

The first part of this paper covers mass concrete practices that have been employed in dams in the United States during the past 75 years. The second part describes in some detail the concrete construction operations during that period.

Historical Account of Mass Concrete

Raymond E. Davis

FROM THE BEGINNING, WHEN THE CON-
crete of small dams was mixed by hand, when portland cement usually had to be "aged" to stand the boiling test, when the aggregate was bank-run sand and gravel, and when proportioning was by the shovelful, we have made tremendous progress. The art and science of dam building practiced by the principal agencies engaged in such work in the United States has today reached a degree of perfection, a degree of quality control in the selection and proportioning of concrete materials and in concreting operations, that is not approached in any other field of concrete construction.

In what follows, the writer has attempted to cover in chronological order the principal steps from those

very small beginnings to the present, where on large dam constructions there is exact and automatic proportioning and mixing of materials, and concrete in 12-cu yd buckets is placed at the rate of 10,000 cu yd per day at a temperature of less than 50F during the hottest weather. Lean mixes are now made workable by air entrainment and by the use of finely divided pozzolanic materials. Water-reducing and set-retarding admixtures are effective in reducing the required cement content to a minimum as well as in controlling the time of setting. Those concerned with concrete dam constructions certainly should not feel that the ultimate has been reached, but they are certainly justified in feeling a degree of satisfaction with the progress that has been made.

GENERAL DEVELOPMENT

Prior to 1900

Prior to the beginning of the century, much of the portland cement used in the United States was imported from England, and all cements were very coarse by present standards. Quite commonly they were underburned, and to develop soundness a long period of storage was required. For dams of that period the aggregates were usually bank-run sand and gravel, employed without benefit of washing to remove objectionable fines. Apparently, concrete mixes varied widely in cement content and in sand-aggregate ratio. Concrete mixing was usually by hand and proportioning was by shovel, wheelbarrow, box, or cart. The effect of water-cement ratio was, of course, then unknown and generally no attempt was made to control the volume of mixing water. There was no measure of consistency except by visual observation of the mix.

Most of the dams were of cyclopean masonry in which "plums" or spalls were partially embedded in a very wet concrete. The spaces between plums were then filled with concrete, also very wet. It appears that the early dams were without contraction joints and without regular lifts. However, there were notable exceptions where concrete was cast in blocks; the height

of lift was regulated and concrete of very dry consistency was placed in thin layers and consolidated by rigorous hand tamping.

Generally, mixed concrete was transported to the forms by wheelbarrow, although where plums were employed in cyclopean masonry, stiff-leg derricks erected inside the work moved the wet concrete and plums. The maximum rate of placement was only a few hundred cubic yards a day. Generally, there was no attempt at moist curing.

One very notable exception to these general practices was Crystal Springs Dam constructed in 1888, which is located near San Mateo, Calif., about 20 miles south of San Francisco. According to available information, this was the first dam in the United States in which the maximum permissible quantity of mixing water was specified. The concrete for this 154 ft high structure was cast in a system of interlocking blocks of specified shape and dimensions. Fresh concrete was covered with planks as a protection from the sun and was kept wet until hardening had taken place. For this very dry concrete, an old photograph indicates that five hand tampers were employed for each man with a wheelbarrow.

Only a few of the concrete dams built in the United States prior to 1900 remain serviceable today, and most of them are small. Of the 2800 listings in the 1958 *Register of Dams in the United States*¹ there appeared to be no more than 18 that were built prior to 1900. More than a third of these are in the states of California and Arizona where the climate is mild. Of those in the more rigorous

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climate of the East and Middle West except where they were faced with stone masonry, time and weather have taken their toll.

Years 1900 to 1930

After the turn of the century, between 1900 and about 1930, when concrete placement by means of towers and chutes became the vogue, the construction of all types of concrete dams was greatly accelerated. More and higher dams for irrigation, power, and water supply were the order of the day. In this country the portland cement industry became well established, and cement was rarely imported from Europe. ASTM specifications for portland cement underwent little change during the first 30 years of this century aside from a modest increase in fineness requirement determined by sieve analysis. Except for the limits on magnesia and loss on ignition, there were no chemical requirements.

However, much more attention was being given to the character and grading of aggregates and very substantial progress was made in the development of methods of concrete mix design. In general, little attention was paid to quantity of mixing water, and its effect upon the strength of concrete was largely unknown until the publication of the results of investigations made by Duff Abrams² and his associates during the period 1916-1926. As a matter of fact, in dam construction the use of excessively wet mixes which could be easily chuted down flat slopes was the rule rather than the exception for several years after the water-cement ratio law had become well established.

Generally, portland cements were employed without admixture of any

kind. Exceptions were the sand cements employed by the U. S. Reclamation Service, now the Bureau of Reclamation, in the construction of Elephant Butte and Arrowrock dams. The latter, 350 ft high, at the time of its completion in 1915, was the highest dam in the world. The interior mass concrete of this gravity arch dam contained only about 1 bbl of sand-cement per cu yd. It was produced on the job, intergrinding about equal parts of portland cement and pulverized granite to a fineness such that not less than 90 percent passed the 200-mesh sieve. As compared with portland cements then on the market, the sand-cement was of unusually high fineness. Further details will be given later.

Another exception was one of the abutments of Big Dalton Dam, a multiple arch dam built by the Los Angeles Flood Control District during the late twenties. Punicite (a pozzolan) from Friant, Calif., was employed as a 20 percent replacement for portland cement.

During the 1900-1930 period, cyclopean concrete went out of style. For dams of thick section, the maximum size of aggregate for mass concrete was increased to as large as 10 in. As a means of measuring consistency, the slump test had come into use and the testing of 6 x 12-in. and 8 x 16-in. job cylinders became common practice. Mixers of 3 cu yd capacity were in common use near the end of this period and there were some of 4 cu yd capacity.

In the eastern parts of the United States where freezing and thawing conditions were severe, it was not uncommon to employ as much as 1½ bbl of cement per cu yd for the

entire concrete mass. In the West and other areas of mild climate, portland cement content as low as 1 bbl per cu yd was employed. And the practice of using a richer mix such as $1\frac{1}{2}$ bbl per cu yd for the exterior concrete exposed to weather with a 1 bbl mix for the interior had come into use in areas where the climate was severe.

An exception was Roosevelt Dam built during 1905-1911. It is a rubble masonry structure faced with rough ashlar blocks laid in portland cement mortar using a cement manufactured in a plant close to the dam site. For this structure the average cement content has been calculated to be approximately $\frac{3}{4}$ bbl per cu yd. For the interior of the mass, rough quarry stones were imbedded in a 1:2 $\frac{1}{2}$ mortar containing about 9 bags of cement per cu yd. The voids between the closely spaced stones in each layer were filled with a concrete containing 6 bags of cement per cu yd in which spalls were spaded by hand. These conditions account for the very low average cement content. The rate of construction was laboriously slow, and Roosevelt Dam represents perhaps the last of the large dams so built in this country. Further details concerning this unusual construction will be found later in this paper.

Years 1930 to 1961

By the end of 1929, although sloppy concrete placed by chuting was often employed (frequently with 3 in. maximum size aggregate and generally of high water-cement ratio), on the larger and more closely controlled constructions, cement and carefully processed aggregates were proportioned by weight, and mixing water by volume. Slumps as low as 3 in. were employed without vibration and

concrete was being transported at least on one job from mixer to form in 8-cu yd buckets. An era of rapid development in mass concrete construction for dams was in progress.

From a study of the records and actual inspection of a considerable number of dams, it appears that there were differences in condition which could not be explained. Of two structures that appeared to be of like quality subjected to the same environment, one might exhibit excessive cracking and other signs of distress while the other after a like period of service appeared to be in perfect condition. Meager records of a few dams indicated wide variation in temperature due to hydration of cement and that the temperature rise was associated with the degree of cracking. For the purpose of learning more about the significant properties of mass concrete in dams and factors which influence these properties, ACI Committee 207, Mass Concrete, was organized in 1930 (originally as Committee 108). Bogue and his associates under the PCA fellowship at the National Bureau of Standards had already identified the principal compounds in portland cement, and Hubert Woods and associates were engaged in investigations to determine the contributions of these compounds to heat of hydration and to strength of mortars and concretes.

By the beginning of 1930 Hoover Dam was in early prospect. Because of the unprecedented size of the structure, investigations much more elaborate than any that had been previously undertaken were carried out to determine effect of composition and fineness of cement, cement factor, temperature of curing, etc., on heat

of hydration of cement, compressive strength, and other properties of mortars and concretes. The first use of a low-heat cement in the United States was in Morris Dam which was started near Pasadena a year before Hoover Dam was started. The results of these investigations led to the use of low-heat cement in Hoover Dam. The investigations also made possible a more rational design of the pipe cooling system employed in Hoover Dam for the first time.

For Hoover Dam, the construction plant was of unprecedented capacity. Batching and mixing was completely automatic. The record days' output for the two concrete plants (equipped with 4-cu yd mixers) was over 10,000 cu yd. Concrete was transported in 8-cu yd buckets by cableways; large internal vibrators were used. Within a period of about 2 years, 3,200,000 cu yd of concrete was placed.

Hoover Dam marked the beginning of an era of improved practices in large concrete dam construction. Completed in 1935 at a rate of construction then unprecedented, the practices there employed, with some refinements, have been in use on most of the large concrete dams which have been constructed in the United States since that time. Further details will be given later.

Cement content — During the late twenties and the early thirties it was practically the unwritten law that no mass concrete for large dams should contain less than 4 bags of cement per cu yd and some of the authorities of that period were of the opinion that cement factor should never be less than 6 bags per cu yd. For Norris Dam, which was completed by the Tennessee Valley Authority in 1936 and for which the cement factor of the interior

of the dam was 4 bags per cu yd, the degree of cracking was objectionably great although the strength of wet screened 6 x 12 in. job cylinders at the age of 1 year was nearly 7000 psi. Later, 18 x 36-in. cores of 4 bags per cu yd concrete cut from the first stage of construction of Grand Coulee Dam at the age of 2 years exhibited strengths in excess of 8000 psi. Judged by composition, the cement was of the moderate heat type corresponding to the present Type II. Considering the magnitude of the calculated stresses within the structure, it was evident that such high compressive strengths were quite unnecessary and that a reduction in cement content on similar future constructions might be expected to substantially reduce the tendency toward cracking.

For Hiwassee Dam completed by TVA in 1940, the 4-bag barrier was broken. For that structure the cement content of the mass concrete was only about 3 bags per cu yd, an unusually low value for that time. Hiwassee Dam was singularly free from cracks, and there began a trend toward reducing the cement content which is still continuing. Because of low concrete strengths at early ages, the use of low-heat portland cement in the construction of dams has been almost entirely discontinued for large gravity dams, notably those built by the Corps of Engineers. The Type II cement content of the interior mass concrete has been in the order of $2\frac{1}{2}$ bags per cu yd and even as low as $2\frac{1}{4}$ bags per cu yd. In high dams of the arch type where the stresses are moderately high, the cement content of the mass mix is usually in the order of 3 bags per cu yd. An example of a large gravity dam for which the

Type II cement content for mass concrete was $2\frac{1}{2}$ bags per cu yd is Pine Flat on the Kings River, east of Fresno, Calif., completed by the Corps of Engineers in 1954. An example of a high arch dam for which the total quantity of cement and pozzolan is in the order of 3 bags per cu yd is Glen Canyon Dam on the Colorado River, North of Flagstaff, Ariz.

Pozzolan — It was earlier stated that prior to 1930, the use of a pozzolanic material (pumicite) was given a trial in Big Dalton Dam by the Los Angeles Flood Control District. For Bonneville Dam completed by the Corps of Engineers in 1938, a portland-pozzolan cement was employed for all of the work. It was produced by intergrinding a cement clinker with a pozzolan processed by calcinating an altered volcanic material at a temperature of about 1500F. The proportion of clinker to pozzolan was 3:1 by weight. (The price was 72 cents per bbl [376 lb] at the cement plant in Redwood City, Calif.) This type of cement was selected for use at Bonneville on the basis of results of tests on concrete which indicated large extensibility and low temperature rise. This is the only completed dam in the United States known to the author in which a portland-pozzolan cement has been employed.

In the intervening years, however, the use of pozzolan as a separate cementing material to be added at the mixer, in the ratio of 1 part pozzolan to 2 or 3 parts of Type II cement has come to be regular practice by the Bureau of Reclamation and more recently by the Corps of Engineers. Examples of dams in which pozzolans have been or are being employed are: (1) Davis (Colorado River), (2) Friant,

(3) Hungry Horse, (4) Hartwell, and (5) Glen Canyon. In corresponding order the pozzolans employed were: (1) a finely ground calcined opaline shale, (2) a pumicite employed without processing either by calcination or by grinding, (3-4) a low carbon fly ash and (5) a finely ground pumice.

Some experiments conducted by the Corps of Engineers indicate that for interior mass concrete, where stresses are moderately low, a much higher proportion of pozzolan to cement may be used when there is an economic advantage in so doing and still obtain the desired strengths at the later ages.

For example, the results of laboratory tests indicate that a mass concrete containing 1 bag of cement and the equivalent of 2 bags of fly ash with air entrainment has produced a very workable mix, for which the water content was less than 100 lb per cu yd. The 1 year compressive strength of wet-screened 6 x 12-in. cylinders was in the order of 3000 psi. For such a mix the mass temperature rise would be exceedingly small. For gravity dams of moderate height, where the materials would be precooled so that the concrete as it reaches the forms will be, say, 15F below the mean annual or rock temperature, there seems to be the possibility that neither longitudinal nor transverse contraction joints would be required. That is, the maximum temperature of the interior of the mass as hydration took place might not be appreciably greater than the mean annual temperature.

Precooling — To reduce the maximum temperature of mass concrete during the hydration period, the practice of precooling concrete mate-

rials prior to mixing was started in the early forties and was extensively employed in the construction of large dams during the late forties and fifties.

The first serious effort undertaken toward precooling appears to have been in the construction of Norfolk Dam during 1941-1945 by the Corps of Engineers. During the warmer months the plan was to introduce crushed ice in the mixing water. By so doing, the temperature of freshly mixed mass concrete could be reduced by about 10F. On later jobs not only has crushed ice been used in the mixing water, but coarse aggregates have been precooled either by cold air or cold water at the batching plant. Recently, both fine and coarse aggregate in a moist condition have been precooled by vacuum. At the present time, it has become almost standard practice in the United States to employ precooling in regions where the summer temperatures are high to assure that the temperature of fresh concrete as it is deposited in the work does not exceed about 50F.

On some large dams, a combination of precooling as just described and post cooling by pipe refrigeration, as at Hoover Dam, is being used. A good example of this practice is Glen Canyon Dam where during the summer months the ambient temperatures may be considerably greater than 100F. The temperature of the precooled fresh concrete has not exceeded 50F. By means of pipe refrigeration, the maximum temperature of hardening concrete has been kept below 75F. Further details concerning Glen Canyon will be presented later.

Another interesting development of the fifties has been the abandonment of the 28-day strength as a de-

sign requirement. Maximum stresses under load do not usually develop until the concrete is at the age of 1 year or more. Under mass curing conditions, with the cements customarily employed, the gain in concrete strength between 28 days and 1 year is generally large. It has become common practice for the designer of dams to specify the desired strength of mass concrete at the age of 1 year or even in some cases at the age of 2 years. In other words, the 28-day strength of 6 x 12 in. wet screened cylinders, except as an index to later age mass concrete strength, is obsolete as a value for use in design.

Entrained air — It became standard practice about 1945 to use purposely entrained air for concrete in most structures that were exposed to severe weathering conditions. This practice was applied to the concrete of exposed surfaces of dams as well as to concrete pavements and reinforced concrete in general. However, because of the very favorable effect of entrained air upon the workability of lean concrete mixes and also upon the bleeding of fresh concrete, approved air entraining agents introduced at the mixer have been employed in the construction of practically all dams built in the United States during the past decade.

Purposely entrained air has been the answer to the problem of obtaining satisfactory workability of mass mixes of very low cement content. Most specifications for mass concrete now require that the quantity of entrained air, as determined on samples of wet screened concrete for which the maximum size of aggregate is 1½ in., shall be in the order of 5 percent.

If reactive aggregates are employed,

it is considered good practice to use both a low alkali cement and a poz-zolan of proven quality. This has been the practice in recent large dams built by the Bureau of Rec-lamation.

There follow for certain selected

dams more detailed descriptions of concrete materials and mixes used and concrete construction practices employed. These selections have been made to illustrate a variety of prac-ticles as well as the new or unusual features of the dam.

CRYSTAL SPRINGS DAM

This dam, located about 20 miles south of San Francisco, was built between 1887 and 1890 by the Spring Valley Water Co. It is a gravity type arched dam, 154 ft high and 176 ft thick at the base with a 600-ft crest. The volume of concrete used was 57,200 cu yd.

It is a classic in more than one respect. Built when knowledge of con-crete technology was very meager, it is an outstanding example of a struc-ture free from physical defects after more than 70 years of service. Its excellent quality, however, was no

mere accident, but the result of prac-tices that would be regarded as excel-lent today. It appears to have been the first concrete dam in which the quantity of mixing water (about 5 gal. per bag of cement) was specified. The cement was imported from Eng-land. The specifications required that not more than 10 percent be retained on the No. 50 sieve. A natural sand was employed to which crusher dust was added to increase fineness. The coarse aggregate was a crushed rock, all of which passed a 2½-in. ring.

The mix was composed of 1 bbl

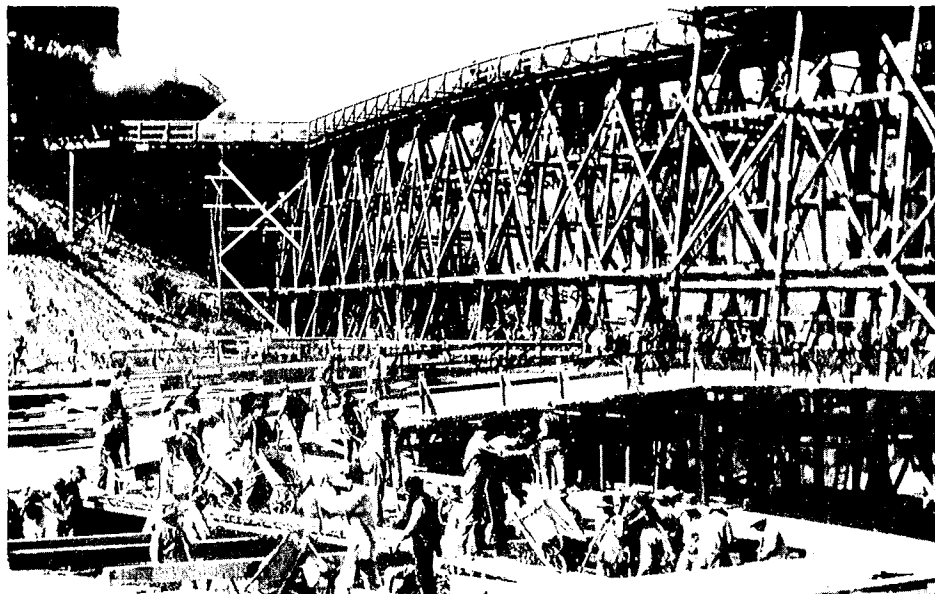


Fig. 1 — Wheelbarrows used in placing concrete for Crystal Springs Dam were charged from cars on the trestle through steel tubes

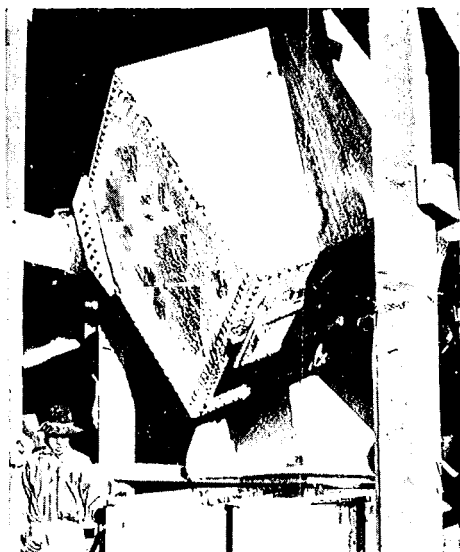


Fig. 2 — Cubical steam driven concrete mixer used in the construction of Crystal Springs Dam

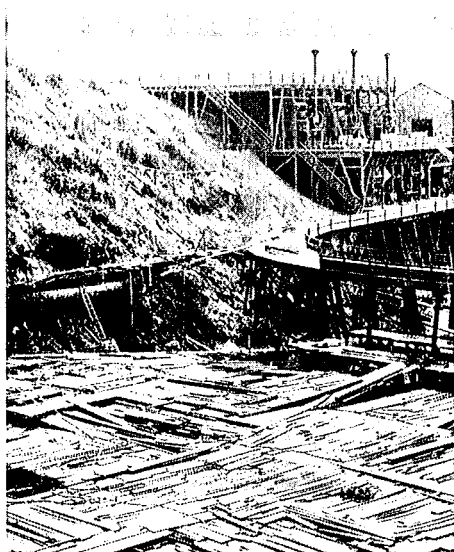


Fig. 3 — Plankcovering used in the construction of Crystal Springs Dam to keep concrete moist

of portland cement, 2 bbl of sand, and $2/3$ bbl of water thoroughly mixed with 22 cu ft of crushed stone. "This amount of material with the proper workmanship makes fully 22 cu ft of first-class concrete in place."³ On this basis, the cement factor must have been about 5 bags per cu yd.

Mixing and placing

Mixing for this dam was done in cubical wrought iron boxes which were rotated with power furnished by a steam engine (Fig. 2). According to the records kept by Hermann Schussler, chief engineer of the Spring Valley Water Co., "the concrete after being thoroughly mixed is to be transported to and put into its place in the work under construction within 15 min. after mixing." It was spread in layers not more than 3 in. thick and "thoroughly rammed by hand until the new layer was completely consolidated with the former one and all

the interstices between the rock fragments are completely filled by the cement mortar."

The structure is composed of small interlocking concrete blocks having an average volume of 35 cu yd. They were staggered as to depth so that neither horizontal nor vertical joints were continuous. The height of lift was 7 to 9 ft. The new concrete of each lift was covered with planks and kept sprinkled with water (Fig. 3). Both horizontal and vertical construction joints were roughened with picks and swept with stable brooms. The tamping of each layer was evidently most vigorous. An old photograph shows five workmen tamping for each workman transporting concrete by wheelbarrow. It is said that Chief Engineer Schussler, when he visited the job, would reward the workman who seemed to be tamping the hardest by tossing him a silver dollar.

The mixture must have been very

harsh, there being barely enough mortar to fill the void spaces between the pieces of crushed stone. The excellent quality of the concrete accounts for its having gone through the 1906 earthquake without damage, which must have been very severe at the dam site, with the San Andreas

fault along which slippage occurred only a quarter of a mile away. The excellent performance of the dam is accounted for by the interlocking block structure, careful selection of materials, the complete consolidation of the concrete by tamping, and proper curing.

THOMPSON MAIN DAM

This is one of 12 dams built between 1905 and 1907 (nine of which were of concrete and three were rock fill) which created a reservoir on the St. Louis River near Carlton, Minn., at the westerly tip of Lake Superior. The main dam which is across the river proper is about 1200 ft long including the overflow spillway section which is 365 ft long. The dam is located in a region of long, hard winters, and the exposure must be rated as severe.

Universal portland cement was employed in all of the work and cement shipments were tested for time of setting and tensile strength of mortar briquets at ages of 1, 7, and 28 days and 1 and 2 years. Comparative tests were made using Ottawa sand, lake sand, and various pit sands. Tests were also made on 6 x 6 x 48 in. concrete beams using various sands and lake and pit gravels.

On the basis of tests conducted in the field laboratory, one of two mixes

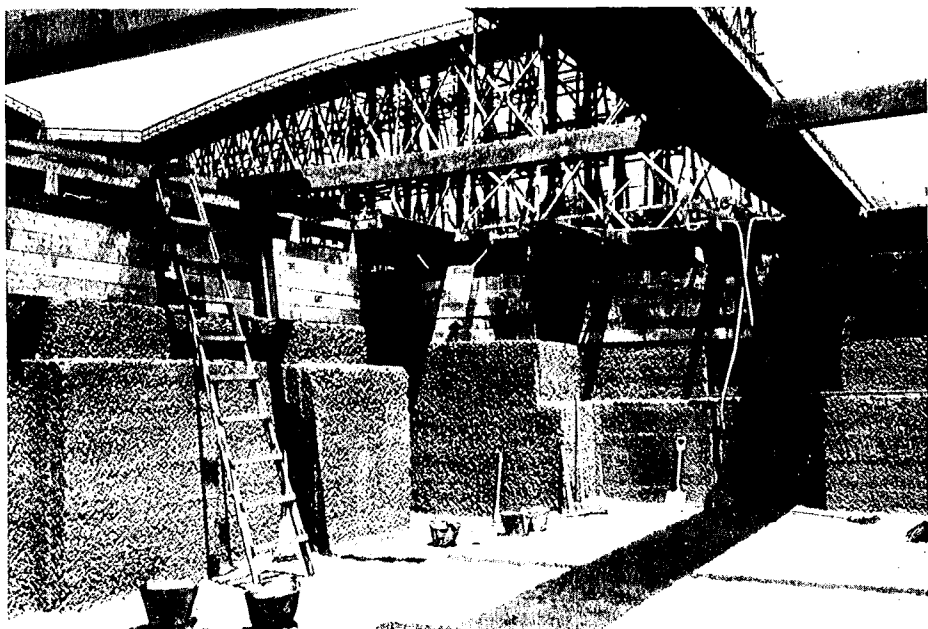


Fig. 4 — Block ready for reception of fresh concrete at Crystal Springs Dam

were employed in all of the work. One of these was in the volume proportions of 5 bags of cement, 20 cu ft of pit gravel, and 4 cu ft of lake gravel. For the other, the proportions were 5 bags of cement, 21.6 cu ft of lake gravel, and 8 cu ft of lake sand.

Mixing

According to the resident engineer, "water was determined by trial to make the concrete the consistency of thick mush which by the slump test would be perhaps four inches. As we had no way of telling the amount of contained water in the materials in the stock pile, it was very much cut-and-try to get the right consistency."⁴ The object was to produce a concrete which would not be too difficult to compact by tamping yet would not be of such high water content as to exhibit bleeding. Concrete was mixed in a 1 yd cubical mixer, 1 min dry and 3 min after water was admitted to the mixer. Mixing water was measured by use of a calibrated barrel. There was no construction joint cleanup, but horizontal construction joints were covered with a layer of 1:2 mortar before concreting was resumed. Transverse contraction joints between blocks were coated with asphalt. Compaction was performed by use of 20 lb wooden tampers.

Sand and gravel in bottom-dump ballast cars were delivered to stock piles from a trestle. Beneath the stock piles was a tunnel and belt conveyor which elevated the aggregates to the storage bins above the mixer. These storage bins were equipped with steam pipes to be used in cold weather. Measured by volume, the aggregate was dropped into measuring hoppers

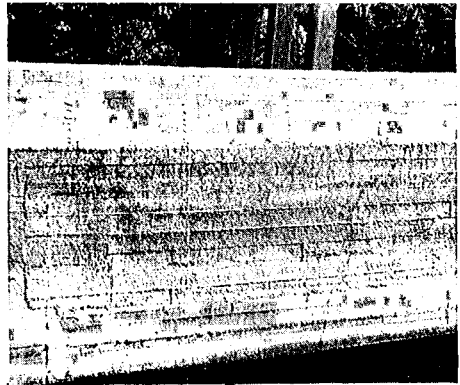


Fig. 5 — View of a portion of the upstream face of Crystal Springs Dam taken 47 years after completion

and then discharged into the mixer. From a storage warehouse cement was transported by belt conveyor to a measuring hopper. No data concerning concrete beam strengths are available, however, in 1928 a core from an old test beam from the original construction exhibited a compressive strength of 5850 psi.

One must conclude that here is an example of an old dam still in service which has given a good account of itself over a period of more than 50 years in a severe climate. It appears that by good fortune a combination of materials was employed which resulted in a low water-cement ratio. Aside from the lack of cleanup of horizontal construction joints, the workmanship must have been excellent considering the time at which the construction took place. Seepage along these joint surfaces is responsible for heavy deposits of calcium carbonate on the downstream face. There has also been considerable raveling at joints in the downstream face due to freezing and thawing.

ROOSEVELT DAM

Roosevelt Dam (Fig. 7) is on the Salt River in Arizona about 80 miles from Phoenix. It was built between 1906 and 1911 by the U.S. Reclamation Service which corresponds to the present Bureau of Reclamation. It is an arch gravity structure of cyclopean rubble masonry faced with rough ashlar blocks laid in portland cement mortar in courses 3 ft high. It is 280 ft high and 723 ft long at the crest. Its volume is 314,800 cu yd: 40 percent rock, 35 percent concrete, 15 percent mortar, and 10 percent spalls. Cement content was calculated to be 0.76 bbl per cu yd.

The portland cement was manufactured in a plant near the dam site which was built and operated by the Reclamation Service for this construction and Granite Reef Dam, 40 miles downstream. Cement was hauled 1700 ft to the mixing plant by tramway. The cement plant capacity was 400 bbl per day.

Aggregate

The fine aggregate was a manufactured sand produced from a mixture of dolomite and a soft sandstone from which the fine fraction of the sand was principally derived. The

sand was processed by roll crushers and screening. The coarse aggregate was a crushed rock which was either a dolomite or a hard sandstone. The sand plant was also built and operated by the Reclamation Service. Sources of aggregates were quarries at the dam site.

Crushing, screening, and mixing plants were in the quarry at the south end of the dam. The mixer had a capacity $1\frac{1}{2}$ cu yd. Cement and aggregates were proportioned by loose volume both for the mortar in which stones were imbedded and for the concrete used in filling the voids or joints between stones.

Placement

There were two 1200-ft cableways over the dam, 350 ft above the river. During the day shift, these cableways were used for the transportation of mortar and concrete to the dam. During the night shift, stone and spalls were moved to the place of storage on the dam from which they were withdrawn during the day shift. Mortar, concrete, stone, and spalls were loaded into 3-cu yd skips. Thus, the skip held two batches of either concrete or mortar. For laying the masonry,



Fig. 6 — Downstream face of Roosevelt Dam built of cyclopean rubble masonry faced with rough ashlar blocks

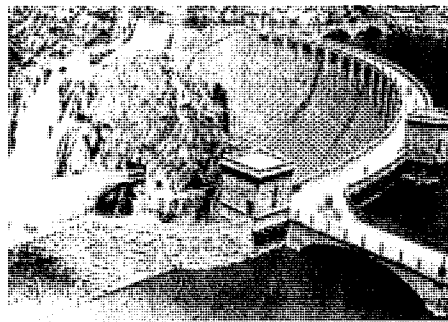


Fig. 7 — Roosevelt Dam with reservoir at spillway elevation

stiff-legged derricks were used with about 11 men per derrick (Fig. 8). After bedding the larger stones in mortar, the vertical joints were filled with a very wet concrete into which spalls were rammed. "For the narrower or deeper joints, the concrete is shoveled in, but a considerable portion of it is dumped from the skip, and then churned with shovels and bars."⁵ There was an inspector at each derrick.

It is reported that about 200 batches of mortar or concrete were placed during an 8-hr shift, which would be at the rate of about 40 cu yd per hr, or 300 cu yd per 8-hr day. The average rate of construction was 16.5 cu yd of masonry per derrick-hr which was regarded as something of a record for this type of construction. This "rapid" rate of construction was attributed to the use of very wet concrete for filling the vertical joints be-

tween the largest stones—"compared with Wachusett Dam (original construction in 1896) where the vertical joints were filled with stiff mortar and spalls laboriously laid by mason with trowel, the rate was not more than 6 cu yd of masonry per derrick-hr, and the dam was not so watertight."⁵

The Roosevelt Dam is of excellent workmanship. Substantially watertight today, even without contraction joints, it is perhaps the outstanding example of large masonry dam construction of that time. Because of the high cost of hand labor, the masonry dam passed out of the picture price-wise and the more economical all mixed-concrete dam completely took over in the United States, though not in other parts of the world. Roosevelt was about the last of the large masonry dams to be built in this country.

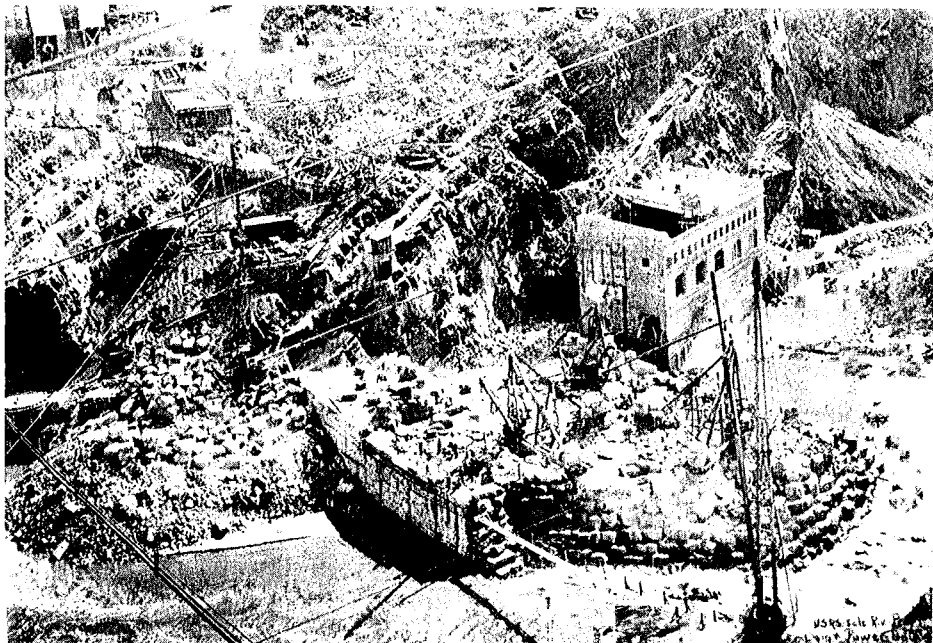


Fig. 8 — Stiff-legged derricks were used for laying the masonry on Roosevelt Dam

ARROWROCK DAM

Arrowrock Dam is located on Boise River about 22 miles north of Boise, Idaho. It was built between 1911 and 1915 by the U. S. Reclamation Service. It is 350 ft high, 223 ft wide at the base, and 1100 ft long. This gravity arch dam had a volume of 636,000 cu yd. It is of special interest not only because at the time of its completion it was the highest dam in the world but because a sand-cement, manufactured by the inter-grinding of portland cement and pulverized granite, was employed in its construction. The dam has rendered excellent service and is notable because of its water tightness.

It is in a locality where freezing and thawing is frequent during the winter months and the water level in the reservoir is subject to large fluctuations. The upstream face is in perfect condition. The downstream face which was subject to frequent icing due to spray from the needle-valve outlets suffered substantial deterioration due to freezing and thawing and

it was repaired in 1937. The deteriorated concrete was first removed. The downstream face was then covered with 18 in. of reinforced concrete in panels about 25 ft square (matching contraction joints in the upper part of the dam).

Sand-cement

The sand-cement was composed of 45 percent disintegrated granite and 55 percent portland cement. The granite was first crushed to a maximum size of about the No. 8 sieve. The cement and crushed granite were then interground so that not less than 90 percent passed the No. 200 sieve. This was done at the job site. The portland cement was required to be delivered to the work so that not less than 75 percent would pass the No. 200 sieve. The oxide analysis indicates that the portland cement, though high in tricalcium aluminate (15 percent), was in the low-heat class so far as tricalcium silicate was concerned (32 percent).

Hourly samples of the interground sand-cement were taken from the discharge of the two mills and a daily composite of these samples was taken for tests to determine setting time, tensile strength, and soundness. It is reported that no sample ever exhibited unsoundness. This is considered significant because at that time there was much trouble with unsoundness of portland cement if it had not been "aged" by storage. These samples tested in 1:3 standard Ottawa sand mortar briquets were required to have a 28 day tensile strength of not less than 275 psi. On the average, the sand-cement exhibited a 28 day tensile strength of 335 psi. It is interest-



Fig. 9 — Construction methods used on Roosevelt Dam illustrates the notable engineering achievement of these early dams

ing to note that, writing off the entire cost of grinding plant, the cost of the sand-cement was \$1.63 per bbl of 376 lb as compared to \$2.36 per bbl for the portland cement.

Prior to the beginning of the work, a test program was carried out to determine the strengths at various ages of standard mortar briquets containing both normal portland cement and sand-cement using the Arrowrock granite. At ages up to 2 years, normal portland cement mortars exhibited higher tensile strengths. At ages of 3 and 5 years, sand-cement mortars exhibited higher tensile strengths.

Concretes

Sand and gravel aggregates were obtained from the river bed at the dam site or from another deposit 13 miles downstream. They were screened into 3 sizes: sand, 0 to $\frac{3}{8}$ in.; gravel $\frac{3}{8}$ to $2\frac{1}{2}$ in.; and cobbles, $2\frac{1}{2}$ to $4\frac{1}{2}$ in. In addition, plumstones were used when available up to a maximum of 20 percent of the concrete volume. They were worked into the fresh concrete by puddling and spading. For the interior mass concrete the sand-cement content was 0.96 bbl per cu yd. For the upstream faces the concrete contained 1.05 bbl of sand-cement per cu yd using an interground blend composed of 66 percent portland cement and 34 percent granite.

The cement was weighed. The proportioning of aggregates was entirely by volume. For the interior mass the mix was 1 part cement, 2.25 parts sand, 5.75 parts gravel, and 3.50 parts cobbles. There are no records as to quantities of mixing water employed, and it appears not to have been measured.

Two 1 cu yd mixers were used. Loading hoppers held two batches

of concrete. Concrete was transported by cableways in 4-cu yd skips. From elevated hoppers it was finally chuted into place, the chutes having angles from 20 to 25 deg with the horizontal. The slope of the chutes is the best indication of the wet consistency of the concrete, although it is reported that after the concrete had been placed "little or no free water stood on the surface."⁶

Placement

The concrete was usually placed in 2-ft layers into which plum stones were occasionally deposited. The most common lifts were in the order of 4 ft but lifts as thick as 8 ft were occasionally employed. The moist curing period (by sprinkling) was not less than 6 weeks. Observation of interior temperatures indicate that the

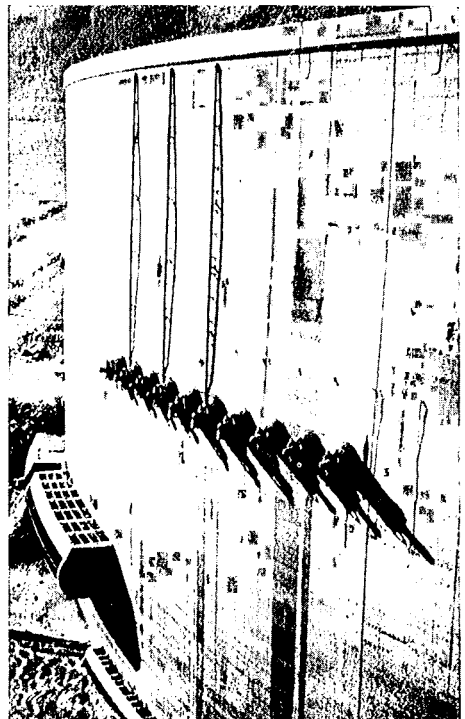


Fig. 10 — Downstream face of Arrowrock Dam

average temperature rise after placement was about 30F and that the average maximum temperature was about 95F.

Horizontal construction joint preparation consisted of cleaning the old surface with wire brooms and then depositing a layer of neat cement grout over the moist surface immediately before starting a new lift. Alternate sections or blocks were normally kept about three lifts or 12 ft above adjacent blocks.

During construction a few 6-in. cubes (from which cobbles had been removed) were prepared for compression testing from samples taken immediately after placement. For the interior mass mix the compressive

strength of cubes averaged 910 psi at 28 days and 1540 psi at 1 year. For the exterior mass mix the average compressive strength of cubes was 1540 psi at 28 days and 2090 psi at 1 year.

In 1930 and 1931, the Bureau of Reclamation drilled fourteen 4¾ in. diameter cores from the dam; nine were horizontal cores from the downstream face, two were vertical cores from the roadway, and one was a horizontal core from the downstream side of the gallery. From these cores compression specimens 9½ in. long were prepared. As would be expected, considering the fact that the maximum size of aggregate was 4½ in., the strengths varied widely. Exclud-

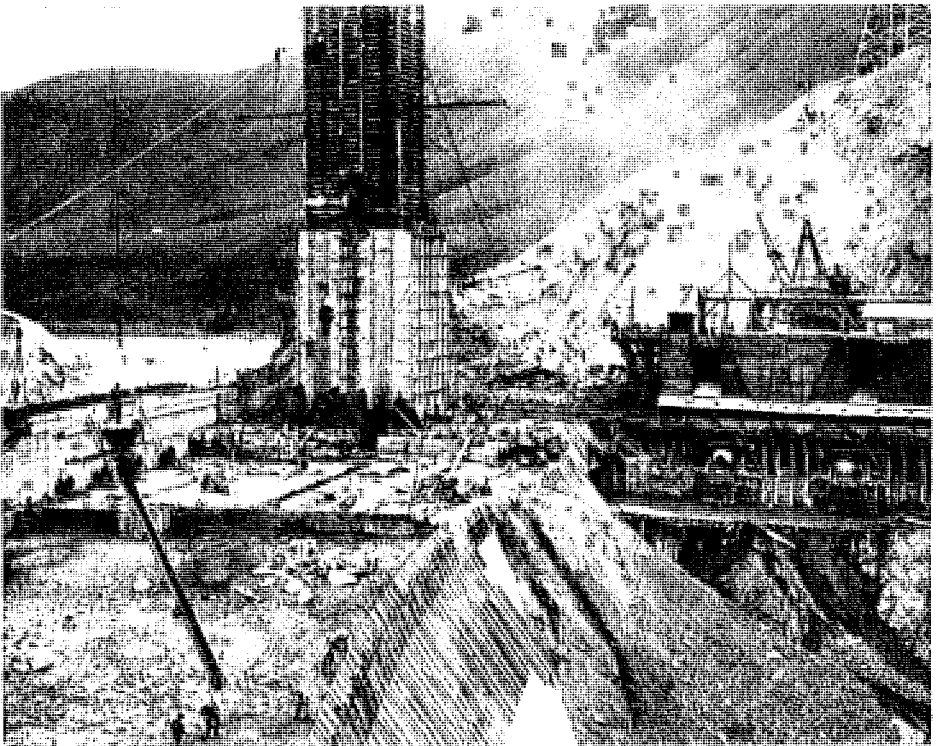


Fig. 11 — Concrete placing for Arrowrock Dam; the two buckets, between the tower and the suspended hoppers above the chutes, drop into pits near the tower where they are charged from cars delivering the concrete from the mixers

ing three absurdly low values (compressive strengths less than 1000 psi) and two absurdly high values (compressive strengths greater than 7000 psi), the average compressive strength was in the order of 2000 psi, a satisfactorily safe value comparing favorably with the average cube strengths at the age of 1 year.

In conclusion, it appears evident

that Arrowrock Dam, with its very low content of portland cement, is a classic example of excellence as evidenced from water tightness and freedom from major cracks. Except for lack of resistance to the very severe freezing and thawing conditions to which the downstream face was subjected, it has been a nearly perfect dam.

EXCHEQUER DAM

Exchequer Dam located on the Merced River, about 100 miles east of San Francisco, was constructed by the Merced Irrigation District between 1924 and 1926. It is an arch gravity dam 325 ft high, 202 ft wide at the base, and 950 ft long. It contains 363,500 cu yd of concrete.

The portland cement employed in its construction was produced at Redwood City, Calif. The calculated tricalcium silicate content, based upon the oxide analysis, ranged from a minimum of 39 percent to a maximum of 59 percent. The tricalcium aluminate content averaged 13 percent. The average amount passing the No. 200 sieve was 84 percent. Its heat-of-hydration must have been high.

The aggregate was a sand and gravel of excellent quality taken from the Merced River. It was screened into four sizes: sand of fineness modulus 2.88, fine gravel passing a 1 in. round screen, coarse gravel passing a 2½ in. round screen, and cobbles of size 2½ to 10 in.

Concrete

The mass concrete contained about 0.82 bbl of cement per cu yd. The aggregate was batched by loose moist volume. Normally, the mixed propor-

tions were 1 part cement, 3.6 parts sand, 2.0 parts fine gravel, 3.9 parts coarse gravel, and 2.7 parts cobbles.

There was no water control. Water was admitted through a valve which the mixer man opened for a time estimated by counting. Based upon slumps which varied from 5 to 10 in., it has been estimated that the water-cement ratio on a volume basis ranged from 0.8 to 1.1, with an average close to the maximum value. While the specified maximum slump was 5 in., job records for 273 samples show that there were no observed slumps of less than 5 in. Only 15 percent of the slumps were in the range of 5 to 6 in. For 61 percent, the averaged slump was 7½ in., and for 24 percent, the average slump was 9½ in.

The specified compressive strength of 6 x 9-in. cylinders was 1400 psi at the age of 28 days. For sets of two cylinders each, the 28 day compressive strength ranged from 1200 to 1800 psi, with an average of somewhat less than 1500 psi. At the age of 1 year under moist curing conditions the average was about 2200 psi.

In exposed concrete of the upstream and downstream faces, the cement content was increased 50 percent to 1.24 bbl per cu yd for which the

specified minimum strength at 28 days was 2000 psi.

Placement

Three 2-cu yd mixers with automatic time controls were employed. It is reported that the mixing time was $1\frac{1}{2}$ min and a batch was produced every 2 min. The concrete was chuted from the mixers to the base of a twin tower near the middle of the dam. From there it was elevated to the top of the tower where it was conveyed to the forms by a system of counterbalanced chutes supported by cables (Fig. 12). According to a competent observer, "The system was comparatively inflexible and did not cover all portions of the area of the dam. Consequently the down pipe at the end of the chute was continually being pulled out at an angle which with the wet concrete resulted in particularly excessive separation; to get into far corners of the blocks it was common practice to wet up the

concrete nearly to liquid consistency . . . in such corners I have often put a shovel down into the entire 4 ft. of the newly finished block." The minimum time between lifts was 7 days.

Construction joints

It was required that horizontal construction joints be brushed and cleaned with an air-water jet. It was reported that the brushing, as it was done here, merely smeared the laitance over the surface. The jetting, performed just prior to concreting, merely removed loose dirt, wood chips, and other contaminations. No thorough removal of surface film and scum was accomplished. Immediately prior to concrete placement a 1:2 mortar was spread over the area where the first bucket of concrete would be placed—usually the downstream corner of the block. It was considered that no more mortar was necessary because the concrete was

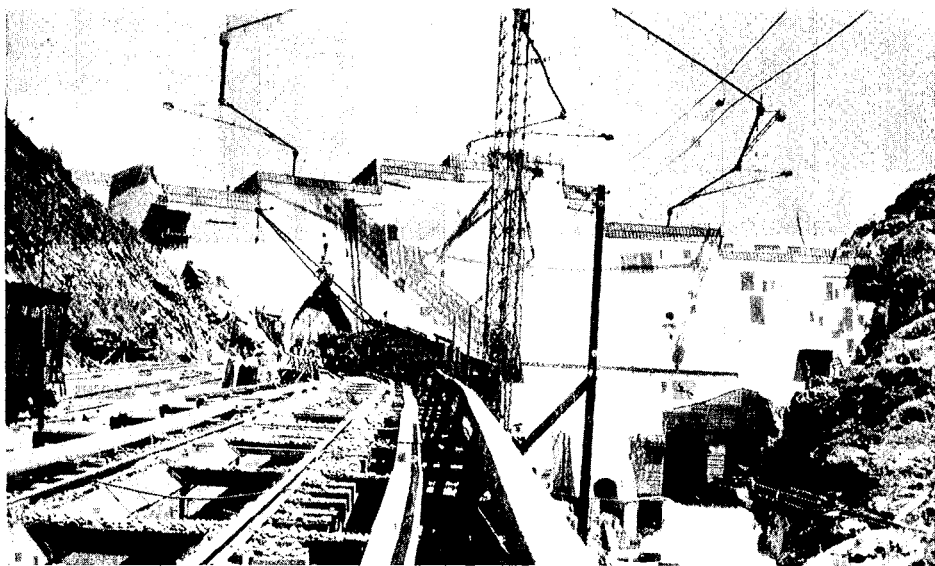


Fig. 12 — Downstream face of Exchequer Dam during construction showing the system of counterbalanced chutes used to deliver the concrete to the forms

so wet that the mortar flowed out ahead of the advancing concrete slope.

This account of the concrete construction practices employed at Exchequer Dam is typical of much such construction in the mid-twenties when concrete had to be very wet and of very high slump to render it placeable by the chuting systems then so widely in use. Also, inadequate horizontal construction joint cleanup was typical.

For the first few years after the dam was completed there was much seepage in the gallery, and at the downstream face many of the horizontal construction joints were wet. Calcium hydroxide liberated during the process of hydration of the cement was leached from the concrete along the construction joints, depositing large quantities of calcium carbonate in the gallery. As the gallery was cleaned from time to time, large

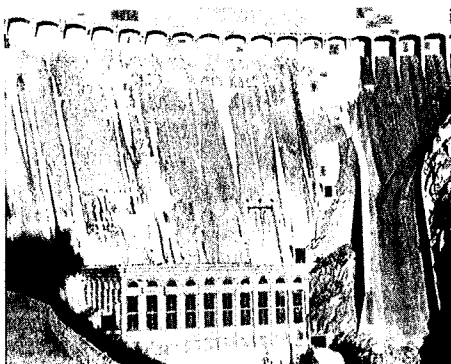


Fig. 13 — Downstream face of completed Exchequer Dam showing deposits of calcium carbonate below horizontal construction joints

quantities of calcium carbonate were removed. Also, there were extensive deposits of calcium carbonate below construction joints on the downstream face (Fig. 13). When inspected in 1957, seepage had apparently ceased. The degree of cracking is only nominal. There is no sign of surface weathering, as would be expected in the mild environment.

MORRIS DAM

Morris Dam, originally known as Pine Canyon Dam, is located on the San Gabriel River about 18 miles east of Pasadena and four miles north of Azusa, Calif. It is a gravity dam, 328 ft high, 277 ft thick at the base, and 750 ft long at the crest. It contains 500,000 cu yd of concrete. It was built between 1932 and 1934 by the Pasadena Water Department.

It is of interest for several reasons. It was the first dam in the United States in which modern low-heat cement was used. The processing of materials and the concreting operations were under very close control. All mass concrete was of very low slump and internal vibrators were

used for the first time. Internal vibration was followed by a final surface compaction using platform vibrators. The construction practice employed would be considered as excellent today as it was in 1932.

Low-heat cements were obtained from four mills in southern California. The composition was very uniform from plant to plant as well as among shipments from the same plant. The tricalcium aluminate content was 5 percent and the tricalcium silicate averaged 24 percent. Among the four plants, the fineness ranged from 92 to 94 percent passing the No. 200 sieve. The average 7-day heat of hydration as determined by the heat

of solution method was 55 cal per g and the average 28-day heat of hydration was 64 cal per g. Both these values are low even for Type IV cements.

The aggregates were processed from a gravel deposit at the mouth of San Gabriel Canyon. The fineness modulus of the sand was 3.0. For the mass mixes, the aggregates were proportioned as follows: 27 percent sand, 21 percent fine gravel (No. 4 - $\frac{3}{4}$ in.), 10 percent medium gravel ($\frac{3}{4}$ - $1\frac{1}{2}$ in.), 17 percent coarse gravel ($1\frac{1}{2}$ - 3 in.), and 25 percent cobbles (3 - 6 in.).

Cement content

For the mass of the dam, including the downstream face, the cement content was 0.95 bbl per cu yd. For the upstream 10 ft the cement content

was increased to 1.10 bbl per cu yd. The average slump of wet-screened concrete was $\frac{1}{2}$ in. The 28 day compressive strength of the full mass mix (14 x 28-in. cylinders) was 2150 psi and the strength at 6 months was 3750 psi. This may be compared with corresponding wet screened concrete (6 x 12-in. cylinders) of 2850 psi at 28 days and 5000 psi at 6 months.

Batching was by weight, with corrections for free moisture of the aggregates, except for water which was batched by volume so as to produce a water-cement ratio of 0.60 for the interior mass mix and 0.54 for the mass mix employed in the upstream 10 ft of the structure. The mixing time for the 4-cu yd mixers was 3 min. The concrete was transported to the



Fig. 14 — Hoover Dam was constructed of columnar blocks with horizontal section as large as 50 x 60 ft

forms by cableway in 4 cu yd bottom-dump buckets.

The very dry mix was compacted by internal vibrators followed by external platform vibrators. The lifts were 5 ft thick. The surfaces of lifts were thoroughly and heavily broomed with wire brooms as soon as the concrete had set enough to be crumbly. They were then cleaned with an air-water jet. Curing was by sprinkling.

The specified minimum time between lifts was 64 hr for the thicker portions of the dam. However, in practice the average time was about 5 days. Some lifts were exposed for several months.

Over a limited area immediately ahead of new placement the old surface was vigorously wire broomed with a 1-in. layer of mortar.

Concrete temperature

Temperatures of fresh concrete at

the time of placement ranged from 60 to 72°F with an average of 66°F. During placement, the average air temperature was 60°F. The individual maximum mass temperature was 118°F and the average maximum was 112°F. The average mass temperature rise due to hydration of cement was less than 40°F. Usually the maximum temperature was reached in 3 or 4 months after the lift was placed.

In 1937, when the dam was full, the leakage was only 0.09 sec-ft. In 1957, the galleries were entirely dry. The structure is substantially free from cracks due to thermal changes. The 1957 inspection indicated that the upstream and downstream faces show less than the ordinary number of shrinkage cracks. Any significant cracks that exist appear to have been caused principally by foundation movements.

HOOVER DAM

Hoover Dam (also for a time officially called Boulder Dam) is located on the Colorado River, 29 miles east of Las Vegas, Nev. Hoover Dam project was started in 1931 and was not entirely completed until 1936. Hoover Dam proper was constructed during the period June 6, 1933 to May 29, 1935. It was built by the U.S. Bureau of Reclamation. It is of the arch gravity type, 727 ft high, 640 ft thick at the base, and 1282 ft long at the crest. The dam proper contains 3,250,000 cu yd of concrete for which the maximum size of aggregate is 8 in. For the dam and its appurtenant works, the total volume of concrete is 4,400,000 cu yd.

At the time of its construction, it

was the highest dam in the world by some 300 ft. Its unprecedented height and mass called for cement and concrete investigations on a scale never remotely contemplated for any dam previously constructed. One of the construction features not previously employed was a system of columnar blocks of varying horizontal section ranging from 25 x 30 ft to 50 x 60 ft (Fig. 14). Circumferential joints were broken but radial joints were continuous. Also for the first time, post-cooling by pipe refrigeration was employed, the cooling coils in each columnar block being placed in the bottom of each lift.

Low-heat cement

The beginning of construction, be-

fore low-heat cement became available, it was found necessary to employ normal portland cement composed of the products of five cement plants in southern California. Later, a low-heat cement was employed, except during cold weather when a blend composed of 60 percent low-heat and 40 percent normal portland cement was used. The low-heat cement was also a blend of the products of the five cement plants of southern California.

For the blend of low-heat cements, the average fineness expressed as specific surface was 1930 sq cm per g as determined by Wagner tur-

bidimeter. Specifications required that the specific surface be not less than 1700. The average tricalcium aluminate content was calculated to be 5 percent and the average tricalcium silicate content was calculated to be 23 percent. The average heat of hydration was 55 cal per g at 7 days and 64 cal per g at 28 days.

The aggregate was obtained from a river deposit upstream from the dam site and was considered to be of excellent quality. It was composed of a variety of rock types. In the coarse aggregate sizes limestone predominated and was followed by granite and basalt. In the sand sizes, about

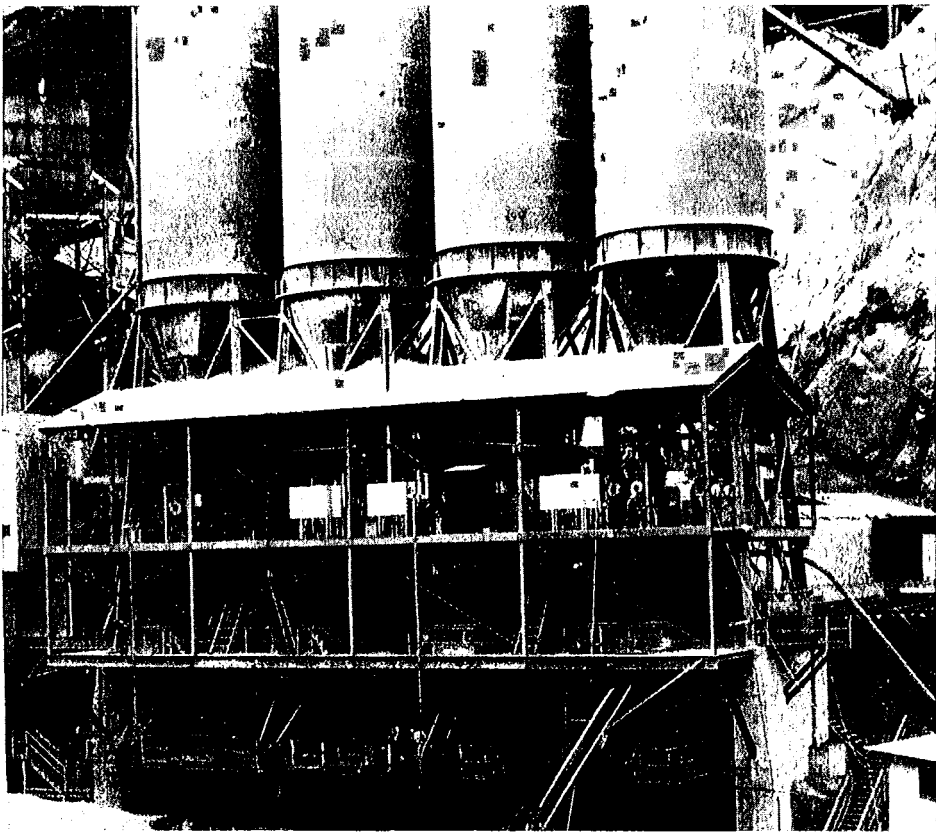


Fig. 15 — High level concrete mixing plant and cement blending plant used for the construction of Hoover Dam

65 percent was quartz. The aggregate was separated into sand and four sizes of gravel: $\frac{1}{4}$ - $\frac{3}{4}$ in.; $\frac{3}{4}$ - $1\frac{1}{2}$ in.; $1\frac{1}{2}$ - $2\frac{3}{4}$ in.; and $2\frac{3}{4}$ - 8 in., the latter size being designated as cobbles. The sand was processed by wet classification which gave close control of its grading. The fineness modulus of the sand was about 2.7.

All of the interior mass concrete contained 1 bbl of cement per cu yd. For this mix, the sand content was about 25 percent of the total aggregate. For the coarse aggregate, the proportions were about 21 percent for each of the three smaller sizes and 37 percent for the cobbles.

There were two mixing plants equipped with 4-cu yd mixers with torque meters to register consistency. The mixing time was $2\frac{1}{2}$ min. The single day record for the combined plants was 10,400 cu yd and for one of the plants was 7500 cu yd. The average slump as the concrete was discharged from the mixers was about $3\frac{1}{2}$ in., being greater at the beginning of the work than at the end.

The concrete was discharged from the mixers into 8-cu yd buckets which were transported by car to locations where they could be picked up by cableways and carried to the point of placement in the dam. The height of lift was 5 ft. Each lift was built up in layers, 18 to 20 in. thick. The concrete was compacted by internal vibrators and hand spading.

Construction joints

The usual cleanup of horizontal construction joints was by air-water jet before the time of final setting. The object was to remove laitance and expose the smaller pieces of aggregate. Elaborate investigations of different methods of construction joint

cleanup had demonstrated that removal of surface material so as to expose a large percentage of coarse aggregate was entirely unnecessary. Here wet sand blasting was employed for the first time to cut the surfaces that were too hard for effective cleanup by air-water jet and also to clean up construction joint surfaces just before placing the new lift. Just ahead of concrete placement for a new lift, old concrete surfaces were treated by vigorously brushing onto the surface a sand-cement grout or mortar of the same composition as the mortar constituent of the mass concrete.

All concrete surfaces were moist cured by sprinkling for a period of not less than 14 days, except when they were earlier covered with fresh concrete.

Cooling

Usually, cooling of the mass concrete was started about a month after placement. The average maximum temperature of mass concrete in the lower portion of the dam where normal cement was employed was 138F, that of concrete containing the blend of normal and low-heat cement was 124F, and that of the concrete containing straight low-heat cement was 105F. The average maximum temperature rise was 41F for the concrete containing normal cement, 38F for that containing the blend, and 32F for that containing straight low-heat cement.

Before grouting was undertaken the concrete was cooled so that there would be a gradient varying from about 70F near the downstream face to 40F along the lower third of the upstream face. For control of the cooling operation, an elaborate installation of electric resistance thermom-

eters was required. In the primary cooling operation, clarified river water, which had been passed over a cooling tower, was employed; the final cooling was with water that had been cooled in the refrigeration plant to a temperature of 40F.

BONNEVILLE DAM

The Bonneville Power and Navigation Project is located on the Columbia River about 40 miles east of Portland, Ore. The principal item of the project is the spillway dam which consists of a gravity concrete base forming the fixed crest and supporting a series of concrete piers and steel lift gates which extend 50 ft above the fixed crest. It was built by the Corps of Engineers between 1935 and 1938.

The height of the spillway section to the top of the fixed crest is 74 ft, the base width is 200 ft. The spillway dam is divided by transverse contraction joints at intervals of 60 ft and by one longitudinal contraction joint at the bucket, 65 ft upstream from the downstream toe. That is, there is an upstream portion 135 ft wide which carries the piers and a downstream portion 65 ft wide which carries baffles. The over-all length of the dam is 1250 ft. The spillway section excluding abutments is 1070 ft long and carries eighteen 50-ft gates, separated by seventeen 10-ft piers. Contraction joints are midway between the piers. The spillway dam proper contains 500,000 cu yd of mass concrete and 100,000 cu yd of reinforced concrete.

Because of its great width, as compared to height, it was considered to be more than ordinarily susceptible to longitudinal cracking due to

The compressive strength of 6 x 12-in. cylinders wet screened from the mass mix at the age of 28 days averaged 3500 psi for low-heat cement, and 4000 psi for the blend of 60 percent low-heat cement and 40 percent normal cement.

thermal change as the mass cooled from the maximum temperature after placement. To avoid the hazard of floods, the dam was built in three steps; the nominal working seasons being from September to April.

Cement

This was the first time that a portland-pozzolan cement was used in a dam in the United States. The decision to use such a cement was reached after extensive investigations of concrete mixes containing three types of cements—a modified cement corresponding to present-day Type II, a low-heat cement corresponding to Type IV, and a portland-pozzolan cement produced by intergrinding clinker of Modified Type II composition in the amount of 75 percent and a calcined pozzolan in the amount of 25 percent.

The results of the investigations indicated that the concretes containing the portland-pozzolan cement were of higher tensile strength and greater extensibility. Under low temperature conditions at the early ages, they exhibited greater compressive strength than corresponding concretes containing low-heat cement; and it was estimated that the heat of hydration of the portland-pozzolan would be about the same as that of low-heat cement.

An average of 97 percent of the portland-pozzolan cement used in the work passed the No. 200 sieve and



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about 91 percent passed the No. 325 sieve, an unusually high fineness for that time. A measure of the activity of the pozzolan was the compressive strength of 2 x 4 in. sealed mortar cylinders composed of 2 parts of ground pozzolan, 1 part of high calcium hydrated lime, and 9 parts of standard Ottawa sand.

The specifications required that the pozzolanic activity be such that the compressive strength of 2 x 4-in. cylinders be not less than 800 psi at 28 days. The average compressive strength was over 900 psi. The tensile strength of standard 1:3 portland-pozzolan cement mortar briquets averaged 330 psi at the age of 7 days and 405 psi at the age of 28 days. The composition of portland cement clinker was typically Modified Type II. During the first season, the tricalcium aluminate content was 5 percent and the tricalcium silicate content ranged from 45 to 50 percent. In later work, in order to produce concretes under low temperature conditions which would have higher strengths at early ages, the tricalcium silicate content was increased to 55 to 60 percent.

Aggregate

The aggregates were principally basalt. The principal source was a gravel deposit upstream from the dam; a secondary source of coarse sand to make up for grading deficiencies was also employed. Aggregates were processed into four sizes: sand having an average fineness modulus of about 2.8; No. 4 - $\frac{3}{4}$ in.; $\frac{3}{4}$ - $1\frac{1}{2}$ in.; $1\frac{1}{2}$ - 3 in.; and 3 - 6 in. During the first season, the interior mass concrete contained 1.0 bbl (384 lb) of cement per cu yd. For exposed surfaces, not subject to erosion, the max-

imum size of aggregate was 3 in. and the cement content was 1.21 bbl per cu yd. For surfaces subject to erosion the cement content was increased to 1.44 barrels per cu yd. The average slump of concrete wet screened from the mass mix was about $2\frac{1}{2}$ in. The average compressive strength of 6 x 12-in. cylinders wet screened from the mass mix was 2740 psi at 28 days and 4430 psi at 1 year.

The mixing plant was equipped with automatic batching and recording units, and the batching and mixing operations were under close laboratory control. The concrete was mixed in four 4-cu yd mixers. The specified minimum mixing time was 3 min.

For the bulk of the dam the concrete was conveyed in 8 cu yd bottom-dump buckets by two cable ways. It was placed in approximately 18-in. layers and was compacted by internal vibration. Placing temperatures ranged from 34 to 72F and during construction the daily air temperature ranged from 26 to 72F.

The surface of each lift was cleaned by air-water jet shortly before the time of the final setting of the cement and again just before the next lift was placed. A bedding layer of mortar was scrubbed over the old surface just ahead of concrete placement. Curing was by water spray for a period of not less than 14 days. During freezing weather the fresh concrete was maintained at a temperature of 50 to 70F for at least 5 days.

On the average, temperature rise within the concrete mass due to hydration of the cement was 36F and the maximum temperature in the different parts of the work varied from 92 to 105F.

HUNGRY HORSE DAM

Located on the south fork of Flathead River near Columbia Falls, Mont., this dam was constructed by the U.S. Bureau of Reclamation between 1948 and 1953. It is of the arch gravity type, 564 ft high, 320 ft wide at the base, its length is 2115 ft long, and its volume is 3,086,200 cu yd of concrete. It is of special interest because it is the first large dam in which fly ash was employed as a pozzolan in all of the concrete work. Also, because the portland cement content was only 2 bags per cu yd for the interior mass concrete. It is still the third highest dam in the United States, although it will have to take

fourth place when Glen Canyon Dam is completed.

The gravel from the aggregate deposit, 5 miles upstream from the dam site, was rough screened into the four customary sizes, including cobbles up to 6 in. It was final or finished screened in a screening plant above the batching bins. Natural sand was stockpiled in three sizes—coarse, medium, and fine. These sizes were blended by weighing feeders on the conveyor belt which carried the sand to the batching plant. This provided at all times a specification sand of the desired degree of uniformity.

The batching and mixing were



Fig. 16—Concrete cars on trackway along bucket loading dock at Hungry Horse Dam

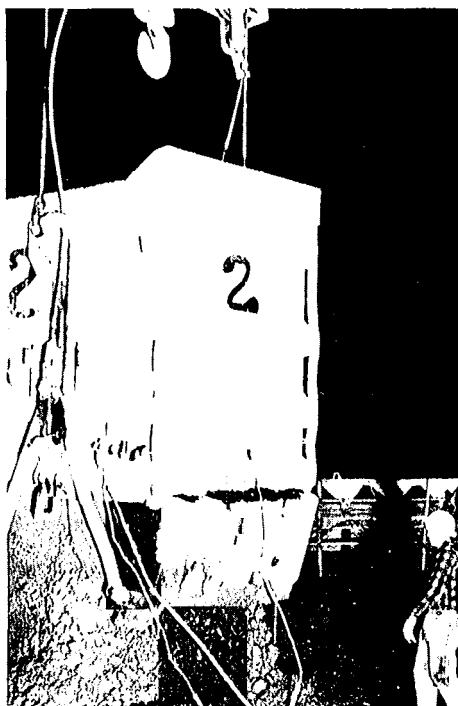


Fig. 17—Concrete for Hungry Horse Dam was placed by 8-cu yd buckets on a 24-hr schedule, the night shift activities being carried out under powerful flood lights and "starlights" which span the canyon

completely automatic. Originally, the plant was provided with four 4-cu yd mixers previously used at Shasta Dam. Later, a fifth 4-cu yd mixer was added. This fifth mixer was employed for special mixes and discharged into a separate hopper. The four mixers that were used for mass concrete were charged from the front end by a rotating hopper and discharged into a central conical hopper at the back end.

Transfer cars of the tilting type were employed for transporting concrete from mixer to platform at the end of cableways, where concrete was discharged into buckets (Fig 16). For three of the cableways, each of 25-ton capacity, 8-cu yd buckets were used

(Fig. 17); for the fourth cableway, of 20-ton capacity, a 6-cu yd bucket was used.

For the interior mass concrete the quantities of materials per cu yd were as follows: 2 bags of portland cement, 90 lb of fly ash, 846 lb of sand, and 708 lb each of the sizes of coarse aggregate. Normally, the water content of this mix was only 135 lb per cu yd, an unusually low value, and the ratio of the weight of water to that of cement plus fly ash was the correspondingly low value of 0.49. An air-entraining agent was used. Normally the slump was less than 2 in. and the concrete was judged to be very workable.

The height of lift was 5 ft, with

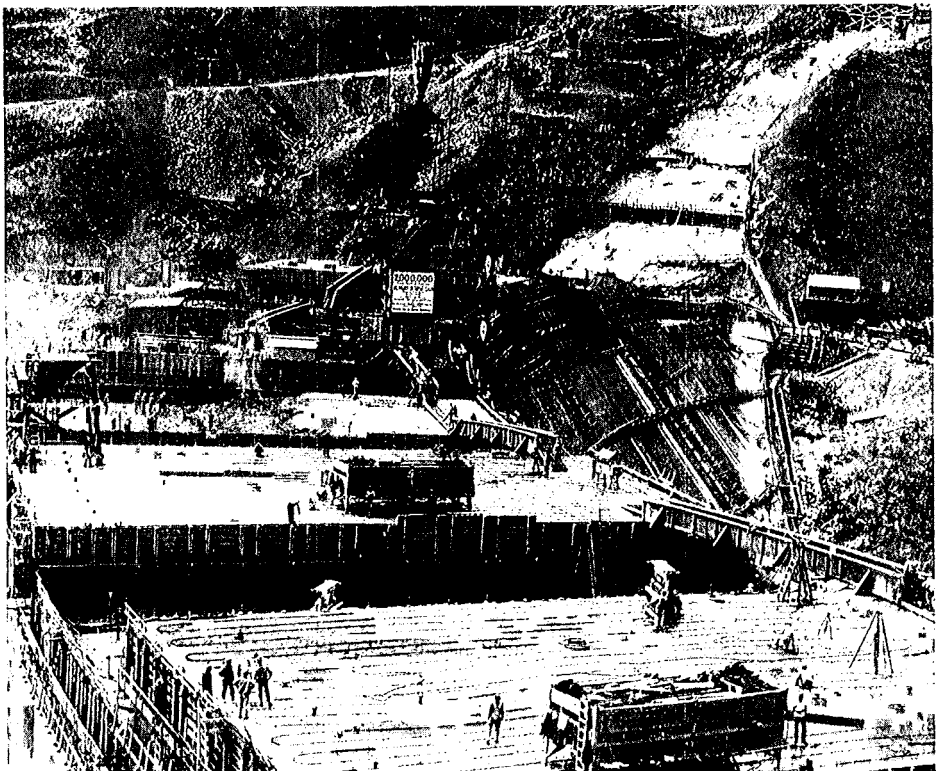


Fig. 18 — Hungry Horse Dam shortly after 2,000,000 cy yd of concrete had been placed

a minimum of 72 hr between lifts. For each lift, the concrete was placed in approximately 20-in. layers. Except in cold weather, concrete was moist cured for a minimum period of 21 days. The average rate of concrete placement was about 6000 cu yd per day. Horizontal construction joint cleanup was by wet sand blasting shortly before placement of the succeeding lift.

The compressive strength of interior mass mixes at the later ages was greater for those containing fly ash than for corresponding mixes containing straight portland cement. Strengths were determined by tests on 18 x 36-in. cylinders which were sealed until time of test and cured under simulated mass conditions. Altogether, 130,000 tons of low-carbon

fly ash was employed for which the specific surface, as determined by Blaine air permeability apparatus, was not less than 3000 sq cm per g.

The portland cement was Type II of moderate heat of hydration obtained from four plants in the general region of the dam.

No attempt was made to precool the concrete materials, but postcooling was affected by a pipe cooling system, as at Hoover Dam, and there was circulated through the pipe system either cool river water or cold water from the refrigeration plant. The three 25-ton cableways, which were the ones normally employed for transporting the mass concrete of the dam from transfer car to the work, had a combined capacity of 7200 cu yd of concrete in 20 hr.

HARTWELL DAM

Hartwell Dam is on the Savannah River between South Carolina and Georgia near Augusta. It is a combination earth-fill and gravity concrete structure built by the U.S. Corps of Engineers between 1957 and 1961. The concrete portion is comprised of a spillway section and a section below which a power plant will be built. The height of the dam is 240 ft. The length of the gravity section is 1900 ft and the volume of the concrete is 877,000 cu yd.

Materials employed in the mass concrete mixes include Type II portland cement, low-carbon fly ash, coarse aggregate in the four usual sizes produced by crushing granite, sand manufactured by rod milling granite, and air-entraining admixture. This dam is of particular interest because precooling of the aggregates,

including sand, was accomplished by use of the vacuum process. Also, because the cement content of the interior mass concrete was only $1\frac{3}{4}$ bags per cu yd and the fly ash content was $\frac{3}{4}$ of a bag per cu yd. The use of this very low cement content ($2\frac{1}{2}$ bags of cement plus fly ash per cu yd), with precooling as necessary to insure a placing temperature of concrete at no time above 55F (the maximum permitted by specifications), must have resulted in a very low temperature rise and a low maximum temperature. The average compressive strength of the interior mass concrete as judged by the results of tests on 6 x 12 in. wet screened cylinders was 380 psi at 7 days, 990 psi at 28 days, 1860 psi at 90 days, 2280 psi at 6 months, and 2400 psi at 1 year.

Vacuum cooling

The vacuum cooling of aggregate was carried out in five steel silos each with a feed trap at the top and a discharge trap at the bottom. For each silo the vacuum was created by the ejection of steam through a venturi tube connected to the silo in such manner as to create negative pressure therein. By exaporation of free water in the aggregates with which each silo was charged, the temperature of the aggregate was reduced to 40F from maximums which during the summer months ranged from 70 to 110F. When each silo had been filled with moist aggregate, the top and bottom traps were sealed and the steam nozzle was opened from 3 to 5 min or until the desired low temperature of the aggregate was obtained. The bottom trap was then opened and the cooled aggregate discharged onto a covered belt con-

veyor which carried the aggregates to the batch plant (Fig. 19).

The coarse aggregate was finally rescreened at the batch plant into four sizes and the rescreened products discharged into bins above the batch plant. Cement and fly ash were removed from their silos by screw conveyor and then transported by bucket elevator to bins above the batch plant. The four 4-cu yd mixers were charged by fully automatic weigh-batchers. After a 3 min. mixing time the concrete was discharged into a central hopper. The central hopper discharged concrete into four 4-cu yd buckets on rail cars which were moved by locomotive to the desired location along a trestle. Two gantry cranes mounted on rails along the trestle picked up the buckets of concrete from cars, lifting them to their desired location in the forms (Fig. 20).

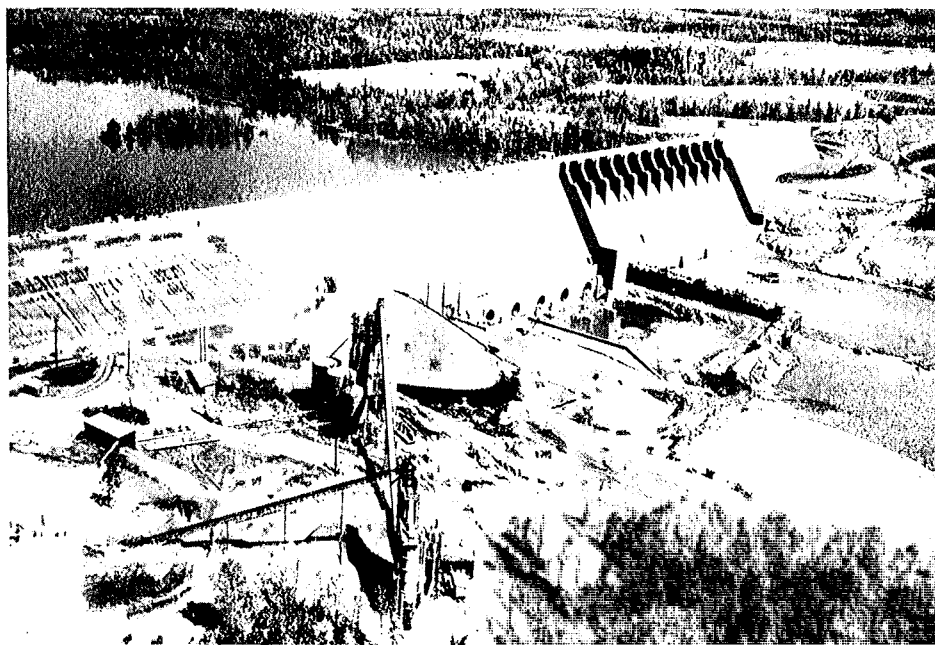


Fig. 19 — Aggregate for Hartwell Dam was vacuum cooled and moved to the batch plant by conveyor.

GLEN CANYON DAM

Glen Canyon Dam is on the Colorado River, 135 miles north of Flagstaff, Ariz. It has been under construction since 1957 by the Bureau of Reclamation. Its height will be 700 ft thereby making it, next to Hoover Dam, the highest dam in the United States. Its base thickness will be 250 ft, its length 1650 ft, and its volume 5,000,000 cu yd. It is an arch type dam.

Materials employed in the mass concrete mixes include a Type II low-alkali cement; a natural pozzolan; a natural sand and gravel; an air-entraining admixture; and a water-reducing, set-retarding admixture. The portland cement is being manufactured in a new plant at Clarksdale, Ariz. The pozzolan is a pumice, obtained from a deposit near Flagstaff,

which is ground to a Blaine specific surface of not less than 7000 sq cm per g.

Aggregate

The aggregate, obtained from a gravel deposit about 9 miles from the dam site, is processed in the usual manner into sand, No. 4 - $\frac{3}{4}$ in.; $\frac{3}{4}$ - $1\frac{1}{2}$ in.; $1\frac{1}{2}$ - 3 in.; and 3 - 6 in. In addition, about 700,000 cu yd within the size range No. 8 to $1\frac{1}{2}$ in. is being further processed by heavy media separation to remove aggregate particles of specific gravity less than 2.5. Aggregate processed in this manner is used in the exterior concrete of the dam as well as in appurtenant works which will be exposed to the weather.

For the mass mixes, the entrained air averages about 5 percent as de-

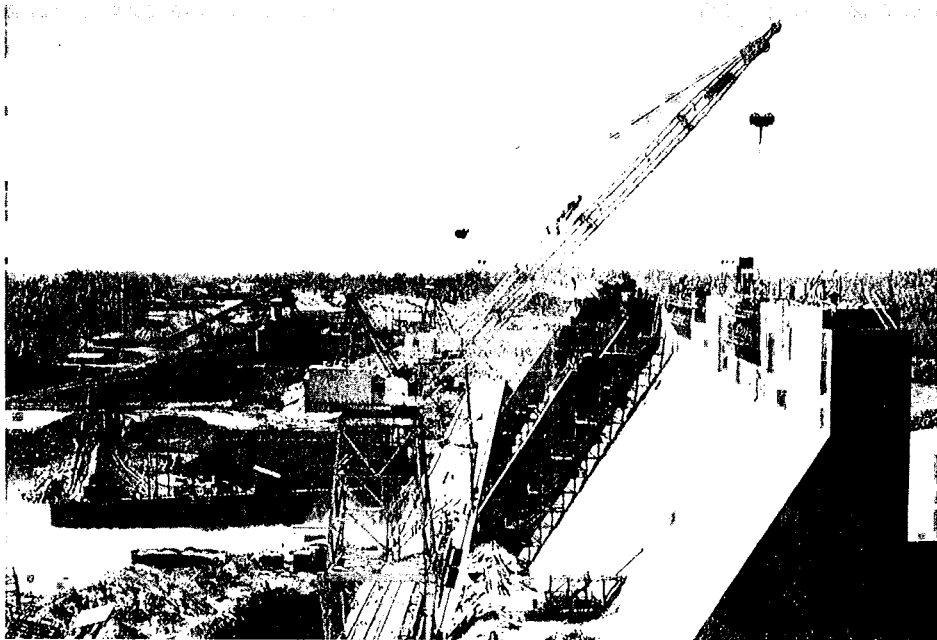


Fig. 20 — Concrete for Hartwell Dam was delivered from rail cars to the forms in 4-cu yd buckets by two gantry cranes

terminated on samples which are wet screened through the $1\frac{1}{2}$ -in. sieve. The water-reducing, set-retarding admixture, which is of the ligno-sulfonate type, is employed in the amount of 0.35 percent of weight of cement plus pozzolan. It is believed that Glen Canyon is the first large dam for which aggregates have been processed by heavy media separation. It is the first dam to be built by the Bureau of Reclamation in which a water-reducing, set-retarding admixture has been employed.

The proportion of portland cement to pozzolan for the mass mixes is in the order of 7 to 3. For the interior mass the content of cement plus pozzolan is the equivalent of 3 bags per cu yd; the mix is designed to produce a mass concrete compressive strength of 4000 psi at 1 year.

A refrigeration plant provides for the precooling of aggregate and for flaked ice added at the mixer. Even during the hottest weather the temperature of the concrete as it is placed in the work has not exceeded 50F.

The batching plant, believed to be the world's largest, is 217 ft high from foundation to the top of the final or finish screening tower. The final screening operation separates the aggregate into eight bins, two of which are for heavy media gravel and one for heavy media sand. The storage bin capacity is 3000 tons. The mixing plant is equipped with six 4-cu yd mixers. The batching and mixing operations are completely automatic.

For the dam proper there are two 50-ton cableways with a hoist speed of 700 ft per min. From the mixer

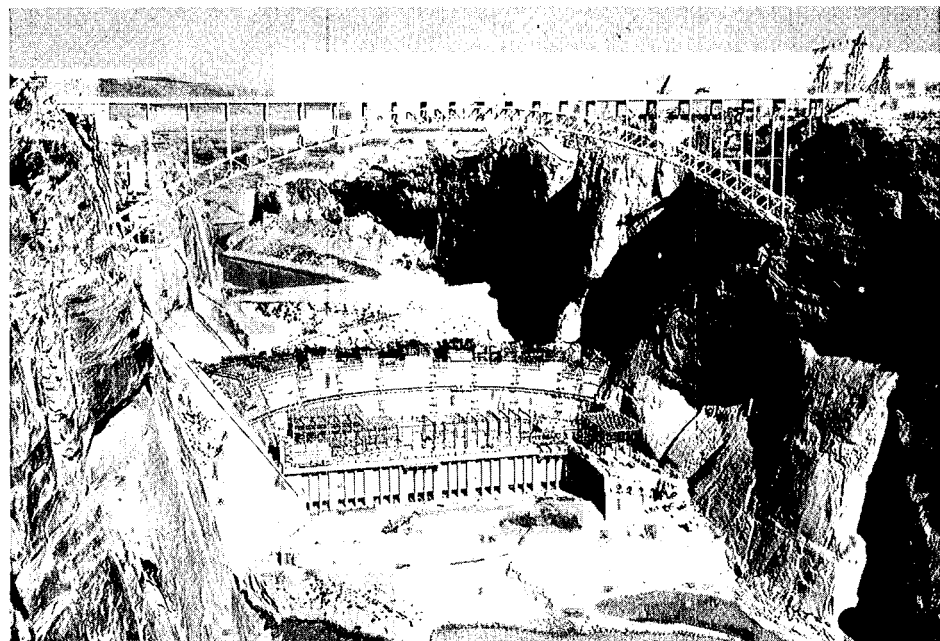


Fig. 21 — Glen Canyon Dam and powerplant as seen from a point about 1 mile downstream from the damsite

the concrete is transported by car and cableway in 12-cu yd buckets. The capacity of the Glen Canyon plant is about 10,000 cu yd of mass concrete per day.

The height of lift is $7\frac{1}{2}$ ft and concrete is deposited in layers 20 in. thick. It is compacted by vibration. The slump is $1\frac{1}{2}$ to 2 in. No loss in slump occurs between mixer and forms. The concrete exhibits most excellent workability as demonstrated by the fact that thorough compaction is obtained at the rate of 100 cu yd per vibrator-man-hr—about double the normal rate for such mass concrete. Joint cleanup is by wet sand-blasting.

Postcooling

Postcooling is accomplished by means of cooling pipes placed in the bottom of each lift. Postcooling is started immediately to keep maximum temperature of the hardening concrete due to hydration of cement below 75F. During this first phase of postcooling, water at 45F is circulated through cooling coils for 12 days.

Later, before contraction joint grouting is begun, brine at a temperature of 30F will be circulated through the cooling coils to reduce the temperature of the concrete in the lower two-thirds of the dam to 40F and in the upper third graduated to 50F at the crest and the downstream face. When the grout has hardened and the concrete mass has reached temperature equilibrium, the arch will have been somewhat deflected upstream. In effect, this amounts to prestressing in a manner which will produce favorable stress conditions in the dam and its rock foundation and abutments when the water load is applied.

A perusal of what has gone before will make it clear that in Glen Canyon Dam there has been reached a new horizon in large concrete dam construction. The materials and methods there used are a far cry from those used in the construction of Crystal Springs Dam, itself regarded as a classic, built more than 70 years ago.

ACKNOWLEDGMENTS AND REFERENCES

Much of the information contained in this paper was derived from unpublished reports of dam inspections made by groups or individual members of ACI Committee 207, Mass Concrete. Greatest credit goes to F. R. McMillan, vice chairman of the committee for many years, for the excellence of many of these illustrated reports, some of the photographs of which have been used as illustrations in this paper, and for his careful review of the first draft of this paper. Thanks also go to Joe W. Kelly for his careful editing of the final draft.

Others who have made significant contributions include Grant Bloodgood, C. A. Pugh, Daniel G. Weir, A. B. West and L. F. Wylie, U. S. Bureau of Reclamation; George D. Burr, City Water Department, San Francisco; Lewis H. Tuthill, Division of Water Resources, State of California; and William R. Waugh and Arthur D. Whitfield, Corps of Engineers.

Construction photographs were supplied by offices of the U. S. Bureau of Reclamation at Boise, Idaho; Phoenix, Ariz.; Boulder City, Nev.;

and Page, Ariz.; and from the U. S. District Engineer's office at Savannah, Ga.

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DISCUSSION

Lewis H. Tuthill*

We are reminded again in this fine paper by Professor Davis, of the great progress that has been made in construction practices during the past 40 years in building concrete dams. These practices have not only improved quality and serviceability, but they have at least been partly paid for by certain economies in materials

and methods. It is unfortunate that so many of the remaining United States dam sites are unsuited, at least economically, for a concrete dam.

Horizontal joints

In Fig. 13 the author shows leakage on horizontal joints at Exchequer Dam. These are a common disfigurement of dams built in the twenties with wet, inferior concrete at the horizontal joint surfaces. A watertight, monolithic bond cannot be

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made on a smeary surface that is a mixture of weak mortar and laitance. The writer often wondered why more of the joints did not leak as he looked at many of these dams in later years. As bucket placing and vibration made it practical to handle and consolidate low slump mass concrete, the quality of concrete at the joint surfaces improved greatly and the potential for dry joints on the downstream face increased materially.

It may be worthwhile to speculate why some horizontal joints in the modern dams still appear to leak. On both faces of a dam, surface shrinkage in a vertical direction opens horizontal cracks, usually on the traces of horizontal construction joints. On upstream faces these cracks will partially or wholly close as the reservoir fills but in many cases they may penetrate sufficiently to permit water to bypass waterstops in vertical contraction joints. This is particularly true when the stops are less than 2 or 3 ft from the upstream face and when they are not backed up by a vertical drain of ample diameter astride the contraction joint.

On downstream faces these cracks at Friant Dam were found to follow the horizontal joint only at the face. Drill cores showed they were normal to the downstream face and only 2 to 3 ft deep. At Friant nearly all of the seemingly leaking horizontal joints had one end of the seep line close to or touching the vertical contraction joint, like level branches from the trunk of a straight tree. Due perhaps to inability of the best of grouting to make a joint completely watertight, particularly in the face of autogeneous shrinkage, the vertical joints filled with water. This water eluded the

upstream waterstop but was held by the downstream groutstop 9 in. from the face. Enough water entered the horizontal shrinkage cracks to spill over on the face of the dam and give the appearance that it had come all the way through the dam in an unbonded joint.

Actually, gravity dams do not need grout in their vertical contraction joints. Any water that got into the joint would be let out near the bottom. Better yet, a generous vertical drain just downstream from the upstream waterstop would prevent water from appearing at the downstream face. Arch dams too, in most cases, could use ungrouted joints if full advantage is taken of concrete cooling.

Carbonate deposits

Another example of disfigured horizontal joints on the downstream face was noted at Shasta Dam, some of them developing before water in the reservoir reached their elevations. Apparently rainwater moving down the slope picked up dirt and lime from the concrete face and entered shrinkage cracks along horizontal joints. As it drained laterally and slowly escaped at low places, a dirty carbonate was deposited which looked as if the horizontal joint had leaked, when obviously it had not. This is a difficult thing to correct during construction but precooling and postcooling the concrete should help to reduce shrinkage in the faces. The writer also saw this kind of staining on the face of a spillway which had never had water behind it.

By taking advantage of modern knowledge and equipment, it is believed possible to get still better bonding and water tightness of horizontal construction joints in mass concrete.

First, whether a grout batch precedes the concrete or not, the clean, sand-blasted surface of the joint should not be wet when the fresh mix is placed on it. It should be on the dry, rather than the wet side of saturated, surface-dry for best results in bond. To keep it from being too dry might take a little advanced attention by the inspector but should cost nothing.

Cost reduction

A possibility for a saving at this point comes in omitting the mortar batch. This is not only expensive in extra cement and added heat generation, but it is an expensive interruption in a fast-moving, well-scheduled concrete placing operation. With the present availability of excellent and effective vibrators for mass concrete, sometimes tractor mounted, it requires very little more than the usual amount of vibration to provide ample assur-

ance that the first layer of concrete on the clean joint has been sufficiently vibrated to bring its mortar in complete contact with the joint surface.

Another opportunity for saving cement and mix-changing time is in omitting richer mixes in the faces of dams that will not be subjected to freezing. This is particularly feasible if a pozzolan is being used because this material reduces permeability to a practical minimum, even in lean mass concrete mixes. Recent examination of the concrete in both faces of the Exchequer Dam, which was the same throughout above elevation 500 (top of power house) and not very good by the standard of today's lean mass concretes, shows the concrete to be as sound today as the year it was placed. There are no significant signs of leaching, chemical attack, or weathering.

AUTHOR'S CLOSURE

The author has read with interest the discussion by Mr. Tuthill and thinks that it is excellent. The writer has emphasized some of the conditions which were passed over rather lightly in the paper but which needed further consideration. All of the points which the writer made are well taken.

With high quality workmanship and mixes which do not exhibit excessive segregation when deposited in the form, the author is sure that the

mortar batch now generally used as a coating to be applied on the old lift of the concrete just before covering with the fresh concrete of the new lift could be eliminated. However, for average workmanship and very dry mixes where there is always likely to be segregation, the author still believes the mortar coating is good insurance against imperfections along the horizontal construction joint.

Where the appearance of usefulness of a concrete structure has been impaired by weathering or disintegration, the cause usually can be traced to failure to follow the rules of good concrete practice. Ten cases, from observations of hundreds of structures, illustrate this point.

Concrete Is What We Make It

F. R. McMillan

THE INTEREST OF THE AUTHOR IN THE study of concrete by observing structures in service started with a series of examinations made in 1924 for ACI Committee E6, Destructive Agents and Protective Treatments. The interest has been a continuing one and many opportunities for such examinations have been presented. The structures visited have been scattered over many sections of the United States and elsewhere. They represent a wide range in type, in quality of materials used, in character of the workmanship exhibited, and in the severity of exposure encountered. Many of them have been re-examined

from time to time, thus providing a valuable extension of the record.

Many illustrations from the structures examined have been used over the years, in papers, committee reports, and discussions to bring out certain characteristics of concrete behavior. In this paper it is proposed to present a series of generalized observations applying to most of the structures examined and a few selected illustrations which together provide a fair cross section of the entire experience. All of the structures used as illustrations were among those examined by Prof. Inge Lyse and the author in 1957 for ACI Committee 207.

GENERAL OBSERVATIONS

Observation No. 1

Where surface disintegration is found, the extent of scaling, spalling, raveling, or other defects is practically never found to be uniform throughout the structure. The variation from point to point in an individual structure is frequently so pronounced that the statement "if all of the structure had been as good as the best of it, the story of disintegration would have been quite different" is justified.

Observation No. 2

Part of the variation in the extent or distribution of surface defects on a given structure can be related to exposure differences. This includes such factors as orientation with respect to the direction of maximum sunshine, prevailing wind, or rain and to the possibility of accumulation of snow. The size and shape of structural units should also be included. The topography of the site can be a factor in determining the extent of surface defects in structures in exactly the same climate.

Observation No. 3

Where there is a decided variation in the depth and distribution of surface defects on a section of concrete in which the severity of exposure is uniform, the intrinsic quality of the materials can be ruled out as the principal cause of the defects. The

author has found it impossible to explain any of these patterns of disintegration commonly attributed to some property of the cement or aggregate except those that influence workmanship.

Observation No. 4

In the many structures examined, the cause of the surface defects observed can be traced to lack of control at all or some of the steps between the arrival of the materials on the job and final finishing of the concrete. These are referred to as workmanship factors. Proper selection of materials and the choice of suitable proportions for the mix can do much to improve the uniformity of various steps.

Observation No. 5

Many unexplained differences in the resistance of concrete to weathering have been encountered. Some of these, it now appears, may have been due to differences in the amount of entrained air. For example, it seems certain that the unexplained excellence sometimes seen in early concrete structures made with extremely fine sands may have been due to this factor. The effect of early curing is often an unresolved question. Rapid drying of the concrete can usually be recognized. Edge raveling and surface scaling are the usual signs of insufficient protection against cold weather.

Observation No. 6

Time is the great leveler. The passing of time will bring out defects, whatever the cause. What may look like the beginning of progressive scaling may later disappear, leaving a sound, uniformly resistant concrete. On the other hand, concrete may look

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very good for a few years but later develop the unmistakable signs of frost acting on porous concrete.

Observation No. 7

Observations 1 to 6, directed more specifically to atmospheric weather-

ing, apply also to structures in constant or periodic contact with water. The most severe condition is where one face is wholly or partially submerged while the opposite face is exposed to the atmosphere.

DELTA AND HINCKLEY DAMS

Delta and Hinckley dams were among the first structures examined in 1924 for ACI Committee E6, the forerunner of ACI Committee 207, Mass Concrete. Notes concerning them were included in the Committee's 1925 report.¹ Because of the importance of the observations on these two dams, the author desires to have the record show that between 1924 and 1957 he visited these structures on four occasions, each time in company of one or more authorities in the field of concrete as follows: June 1928, R. B. Young and B. E. White; Aug. 1939, C. H. Scholer; Aug. 1940, I. L. Tyler; and Aug. 1948, I. L. Tyler, A. G. Timms, and T. E. Coultry. These inspections provided a valuable pictorial record that supports the author's belief that concrete is indeed what we make it.

Delta and Hinckley dams were built by the New York Department of

Public Works to provide storage for the operation of the N.Y. Barge Canal. The dams are only 20 miles apart in the area north of Rome and Utica. Delta Dam, being about 600 ft lower in elevation, probably has slightly less severe exposure. They were built with essentially the same materials and under the same specifications, namely a 1:2.5:5 mix with derrick size cyclopean stones embedded as the work progressed.

Construction Procedure

At Delta Dam (1910-1912) the procedure followed was to place concrete for a considerable portion of the day using bottom dump buckets and a derrick, then to use the same derrick for the rest of the day for placing cyclopean stones. In order to keep the concrete fluid and to get an acceptable embedment, extremely wet concrete was used. The essential

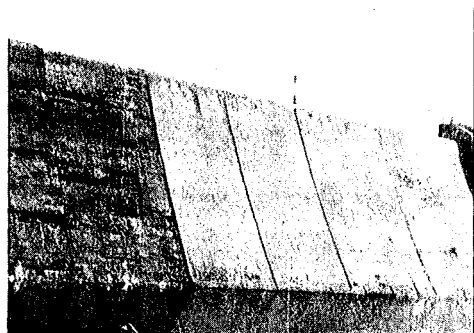


Fig. 1 — Portion of Delta Dam spillway (1928)

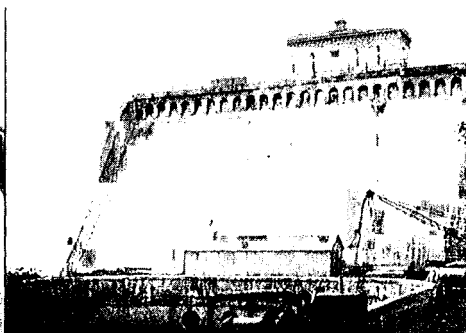


Fig. 2 — Portion of Delta Dam spillway (1957)

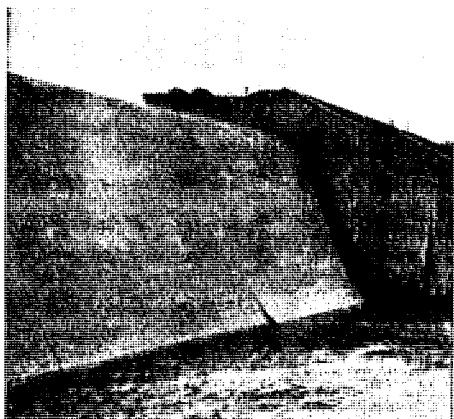


Fig. 3 — South end of Hinckley Dam spillway and abutment wall (1928)

changes in the procedure for Hinckley Dam (1914-1916) were to require a separate derrick for handling the large stones and to require that the amount of water would be the minimum consistent with proper placing in and around the plum stones.

Performance

Delta Dam was completed only shortly before the work at Hinckley was started, but even then it was evident that deterioration had begun.



Fig. 4 — Spillway crest and south abutment wall of Hinckley Dam (1948)

While construction was still under way at Delta, carbonate deposits at the horizontal joints and between joints were prominent on individual blocks standing well above adjacent blocks, which only could have been caused either by rain or by drainage from within the concrete.

The story of these two dams is shown in Fig. 1-11.

In addition to the major repair seen in Fig. 1, Delta Dam, a solid slab over the entire upstream face had been placed. Since 1957, 41,000 sq ft of shotcrete resurfacing has been applied to the downstream face.

The pronounced difference between these two dams at comparable areas is brought out by a comparison of Fig. 1 and 2 with Fig. 3-5.

Three additional photographs of Hinckley Dam (Fig. 6-8) are significant in showing the progressive disintegration with time which occurs when constant vigilance in placing is not maintained. These photographs were all taken from the same spot and, except for a change of camera, show the same area. The negative for the original photograph of this



Fig. 5 — Spillway crest and south abutment wall of Hinckley Dam (1957)

area (1924) is not available but it can be seen in Fig. 3 of the 1925 committee report. The difference between it and Fig. 6 is scarcely noticeable.

Further comment on Fig. 6-8 hardly seems necessary. They amply demonstrate the damage to an otherwise near perfect structure that can result from failure to control the consistency and prevent segregation in placing. However, Hinckley Dam has something more to offer bearing on production of a durable structure. This concerns the design of structural shapes to resist attack from natural weathering.

Fig. 9-11 show one corner of the ornamental coping that extends around the two headblocks. This coping can be seen in some of the previous photographs. The feature to be observed in here is the progressive disintegration that took place from the repeated freezing of the



Fig. 7 — Downstream face of north headblock of Hinckley Dam (1948)

concrete kept wet by the accumulation of snow and ice on the horizontal surfaces. Fig. 11 shows that shotcrete repairs were made after the 1948 photograph was taken.

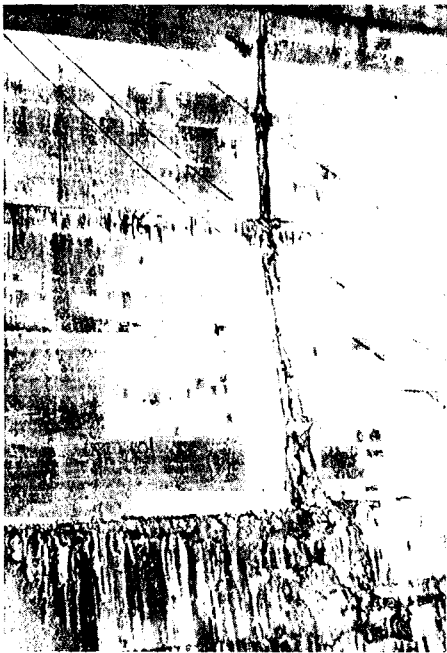


Fig. 6 — Downstream face of north headblock of Hinckley Dam (1928)



Fig. 8 — Downstream face of north headblock of Hinckley Dam (1957)

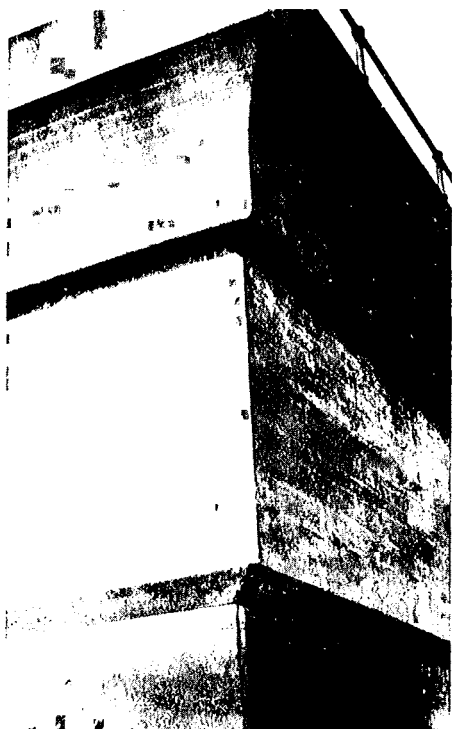
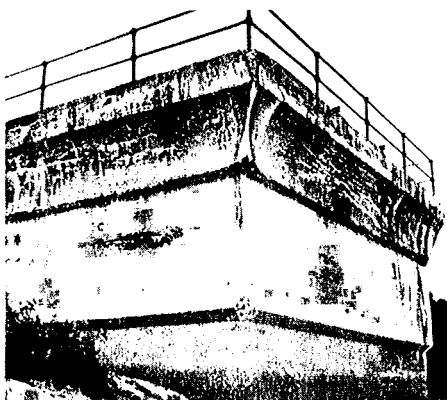


Fig. 9 — (above) Southeast corner of the coping on the south headblock of Hinckley Dam (1924)

Fig. 10 — (below left) Southeast corner of the coping on the south headblock of Hinckley Dam (1948)

Fig. 11 — (below right) Southeast corner of the coping on the south headblock of Hinckley Dam (1957)



Other corners of the coping show the same progressive disintegration from the eighth to the forty-first year. Had the upper edges and corners of these walls been given a rounded shape, such as the spillway crest in Fig. 4, the story would have been quite different.

THOMPSON DAM

Thompson Dam, built between 1905 and 1906 near Duluth, Minn., offers an excellent opportunity to observe differences in durability that can result from failure to get complete incorporation of successive layers of concrete. The construction of this dam is described by H. C. Ash, resident engineer of the project, in the 1929 Proceedings of the Institute.²

Only two photographs are needed to tell the story. Because of an extremely heavy rain, a photograph of the area shown in Fig. 12 was too indistinct for reproduction. Fig. 13, an area of comparable appearance, was taken during a slight letup in the rain.

The feature to be observed is the evidence of seepage along the irregular surfaces between successive layers in some sections and its complete absence in others. Ash's problem in this con-





Fig. 12 — Crest of Arch Dam No. 6 of Thompson Reservoir (1928)

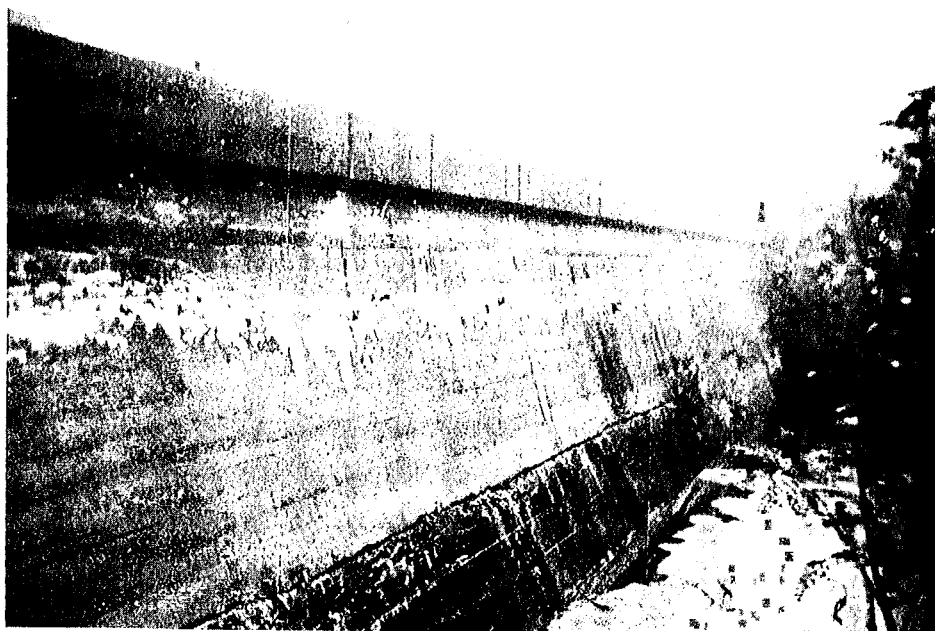


Fig. 13 — Area of similar appearance to that of Fig. 12 (1957)

struction was to maintain the correct consistency which, with the rammers in use, would give complete incorporation of successive layers. The considerable variation in the appearance of the structure from place to place both in 1928 and 1957 serves as a

measure of his success. It also confirms the point of this discussion—small differences in placing technique make important differences in durability. It should not be overlooked that Fig. 13 shows a dam after 51 years in a very severe exposure.

DIABLO DAM

Diablo Dam, built between 1929 and 1930 by the Seattle Department of Lighting, is included here because it introduces a slight variation from the usual method of placing concrete in dams. The dam is described in *Engineering News-Record* for Aug. 29, 1929.

The concrete was conveyed from the mixer by chute to an elevating tower, from which it was transported horizontally by a belt conveyor. The discharge from the belt was passed through an "elephant trunk" to point of delivery. Each 5-ft lift in the dam was placed in several layers 6 to 18 in. deep which required very little hand

spreading. (This was before the days of vibration.)

The *Engineering News-Record* article states that the slump averaged 2½-3 in. Mr. Herbert Faulkner, testing engineer, in a letter dated Dec. 20, 1958, says the slump probably averaged 4-5 in.

The author was on the site July 30, 1929 while placing was in progress. Fig. 14 shows the placing of the last layer in one of the 5-ft lifts. The incorporation of the layer into the one below seemed to be complete and adequate. Fig. 15 taken July 1, 1957 shows the same end of the dam, but

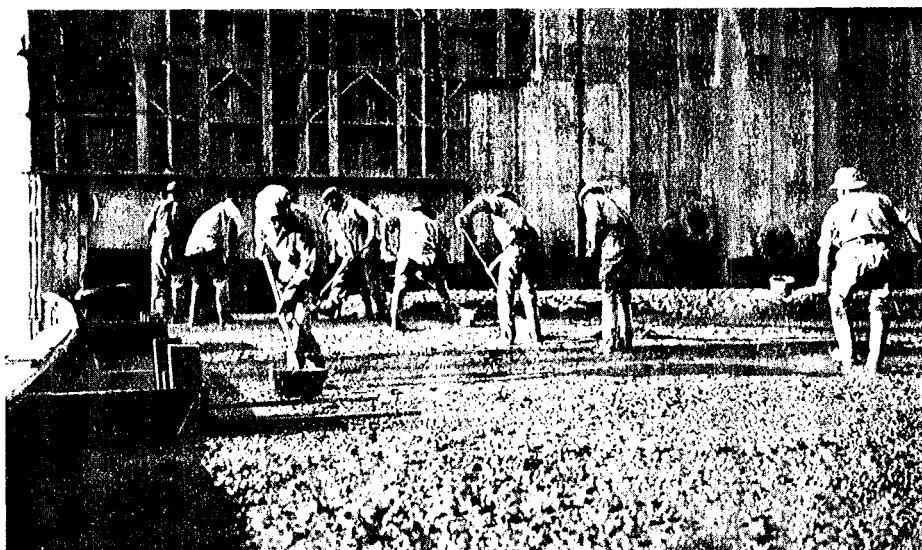


Fig. 14 — Placing the last layer of concrete in one of the 5-ft lifts of Diablo Dam (1929)

the exact elevation for the block at which the previous picture was taken cannot be identified. Of the joints showing in this picture, the majority are marked with only moderate amounts of carbonate. Obviously, there are many which show no de-

posits at all. There are only a few places where faint deposits appear between the fixed 5-ft limits. This indicates that the incorporation of the several layers in a lift was successful even though bonding at the joints left something to be desired.

PINE RIVER DAM

Pine River Dam is included in this series for two reasons: (1) it was the first piece of perfect concrete construction that the author had seen, and (2) the history of its building so obviously accounts for the excellence of the structure that it should not be omitted from this record.

It is one of five small dams built by the U.S. Corps of Engineers between 1900 and 1913 for the control of the headwaters of the Mississippi River. The region is one of long, intensely cold winters. The mean January temperature is 5.4F and the all-time low was -59F. The average growing season is 122 days. Pine River Dam

(finished in 1910) was fourth in a series built by the same foreman, Hans Olson, who had previously been a carpenter foreman on crib dam construction in this area.

The quantities of material used in the concrete were intended to give over-all proportions of 1:3:6 by loose volume. The engineer in charge made tests of mortar to establish the batch quantities of cement and sand, which were changed only when the proportion of coarse particles in the sand changed. Crushed rock (containing 7 to 10 percent fines) was added to give the greatest amount possible and yet have enough mortar to "fill in." The

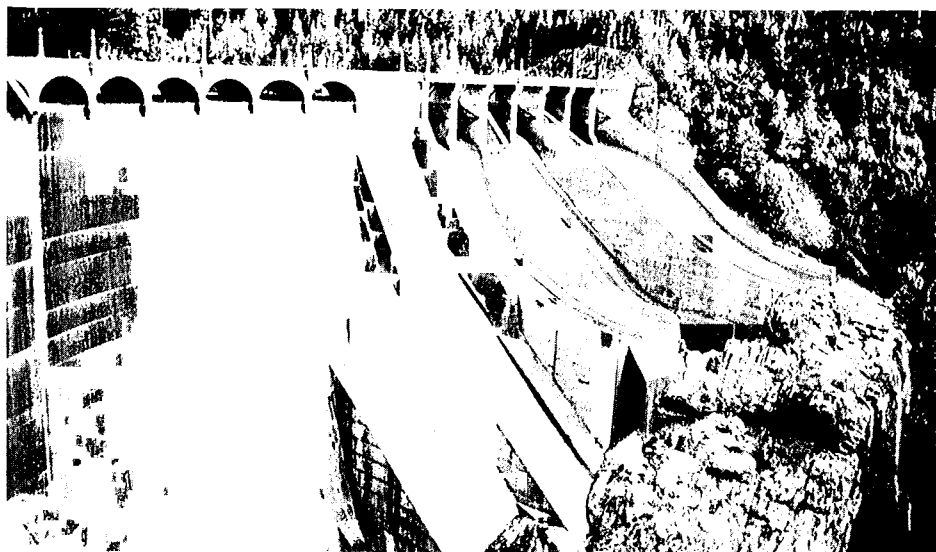


Fig. 15 — Downstream face of Diablo Dam (1957)

concrete was mixed $3\frac{1}{2}$ min (8 rpm) in a cube mixer of 64 cu ft capacity.

Special precautions were taken in the matter of consistency during placing. The U.S. Corps of Engineer specifications required the concrete to be placed in thin layers and thor-

oughly rammed with a 25 sq in. tamper weighing 40 lb. On the first dam Olson started with the heavy tamper and the usual very dry mixture. After some experience and many arguments with the engineers the weight was changed to 25 lb and



Fig. 16 — Downstream face of Pine River Dam (1928)

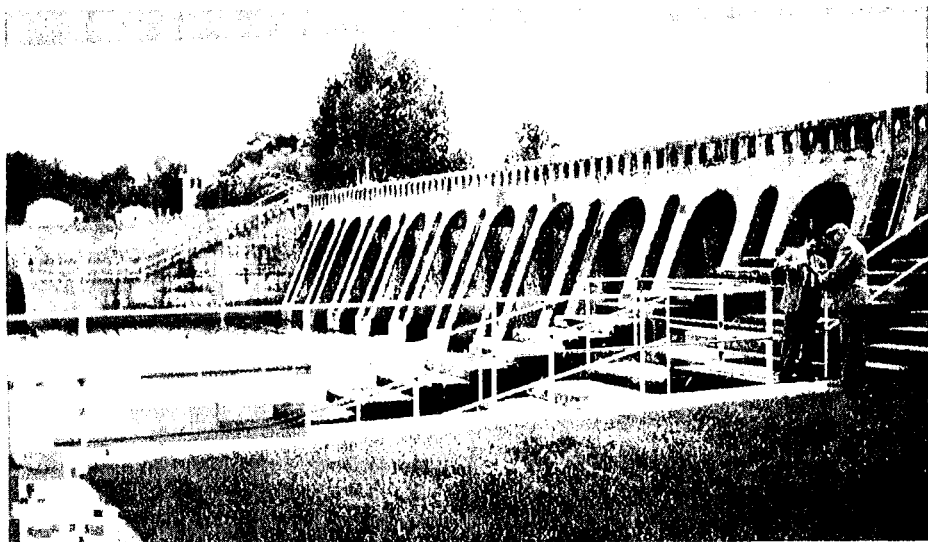


Fig. 17 — Downstream face of Pine River Dam (1957)

a wetter consistency was used. With this he found that as placing progressed the mass grew wetter. To offset this he increased the amount of coarse aggregate to help dry up the mass. In some cases he put in a batch of only coarse aggregate, working it into the mass by ramming and surface working. The procedure continued to improve through the four dams, all of which, after half a century, are fine examples of weather-resistant concrete. But the superiority of Pine River Dam over the other three is easily recognized.

Fig. 16 and 17 show the dam in 1928 and 1957. On close examination of these two views, a number of minor surface changes will be noted. But in the sharpness of the edges and freedom from spalling and major cracking, the general impression one gets from viewing the structure at the site is that of excellence.

During the 1957 inspection, the author was particularly anxious to learn what had developed from certain faint pattern cracks observed in 1933 and 1940. The examination was therefore made in great detail and a



Fig. 19 — Top of wall extending upstream from the right abutment of Pine River Dam (1957)

number of close-up pictures were taken to serve as a basis of record for future developments. Fig. 18-20 show the most prominent defects seen anywhere in the dam. Fig. 21, showing the outstanding excellence of the upstream face, was added to keep a balanced record.



Fig. 18 — Pattern of cracking and carbonate deposits near the downstream end of the left abutment of Pine River Dam showing the far side of the wall in the foreground of Fig. 17 as seen from the log sluice pier

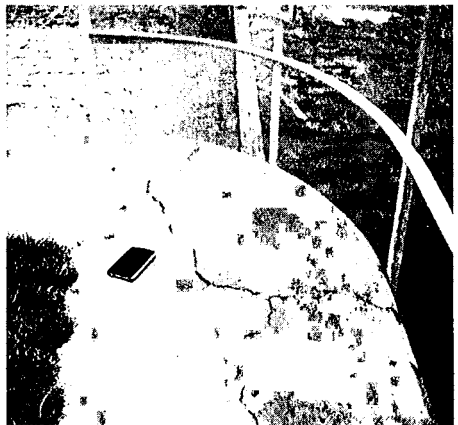


Fig. 20 — Top corner of the right downstream abutment of Pine River Dam looking toward the center of the stream (1957)

FLORENCE LAKE DAM

Florence Lake Dam, situated at a high elevation in the Sierra Nevada Mountains, is an outstanding example of progressive surface deterioration. The quality of the aggregate is an important factor in the surface deterioration. Other factors were an unusually severe exposure and a quality of workmanship that was average for the period—a period, it should be noted, which antedated the use of low water-cement ratios, high frequency vibration, and air entrainment.

Florence Lake Dam is a multiple arch structure with relatively thin sections. The arch thickness is only 18 in. for the upper 40 ft, increasing to a maximum of $4\frac{1}{2}$ ft at the base of the tallest arch (154 ft).

The concrete in the arches had 6 - $6\frac{1}{2}$ bags of cement per cu yd; that in the buttresses (minimum thickness 2 ft 3 in.) was 5 - $5\frac{1}{2}$ bags. In 28 of

the arches the concrete was placed from 1-cu yd buckets handled by a crane using short chutes to reach part of the arch ring. In the remainder of the dam a double counterweighted chuting system was used (slope $2\frac{1}{2}$ horizontal to 1 vertical). Concrete was cured 7 days under wet burlap after the forms were removed. The dam was built in two construction seasons of 1925-1926. Placement of arch concrete was in 4 ft horizontal lifts with a low key to improve water tightness. Tests of cores cut from the dam in 1943, 1945, 1947, and 1949 showed no essential difference in strength for the two construction periods. The average strength of 104 cores was 2740 psi.

The dam site is situated in a typical Sierra Nevada watershed. It is largely glaciated granite with little overburden. Hence there is a minimum of sand and gravel for aggregate. Accordingly, granite spoil from nearby tunnel excavation was used as a source of material. Extensive testing for strength preceded construction. These tests and sonic tests for durability showed satisfactory results.

The walkways along the top of the arches and the entire upstream face were covered with a bituminous compound immediately after completion. This black coating greatly aggravated the daily range in surface temperature and thus added to the severity of the exposure. At this altitude (7329 ft) the air temperature ranges from -20°F to $+95^{\circ}\text{F}$, with many cycles of freezing and thawing per year. Actual determination at the dam in 1928 showed at least 120 cycles for that year.

The disintegration, the character and extent of which is described

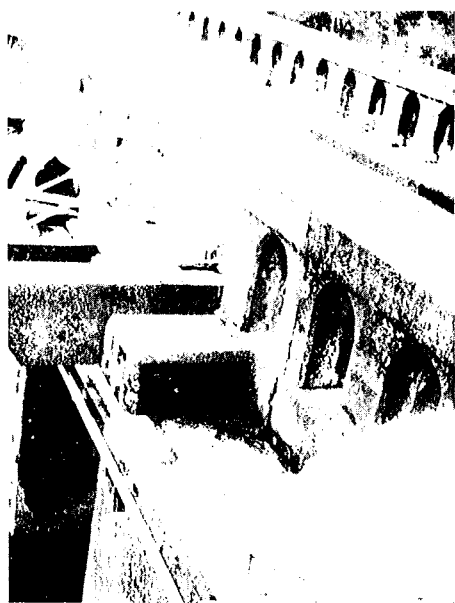


Fig. 21 — Upstream face of Pine River Dam, typical of the entire series of upstream piers, as seen from the right abutment (1957)

below, began to develop early. Some of the first indications pointed to the aggregate as a possible factor. It is important to state here that forty-one 4 in. diameter cores taken in 1961 from lifts showing maximum surface deterioration gave an average compressive strength of 4200 psi, varying from a minimum of 2930 to a maximum of 7130 psi. These relatively high strengths show that the deterioration of the concrete has been confined to surface effects.

The fine aggregate less than $\frac{3}{8}$ in. contained 10 - 20 percent passing the 100-mesh sieve, 75 percent of which was finer than 200 mesh. The maximum size of the coarse aggregate was 3 in. except for three arches in which it was $1\frac{1}{2}$ in.

Because of the early indications of deterioration, some tests and analyses of the aggregate were made. A petrographic analysis made in 1930 "indi-

cated the presence of badly altered feldspar minerals in such quantity as to make its use in concrete for this exposure unsuitable." A test of the sand showed high solubility (loss of weight of 0.022 percent when immersed in water for 6 months).

1929 inspection

The condition of the structure in 1929 can be seen in Fig. 22-24.

Fig. 22 shows the buttresses of the river section to be entirely free from prominent surface defects, while the underside of the arches shows live seepage (dark areas) and prominent surface deposits. These defects are less prominent in the upper portions of the arch than in the lower parts where both the pressure and the time of contact with water would be greater.

The underside of the arches is shown in Fig. 23-24. Note that the white deposits originated principally

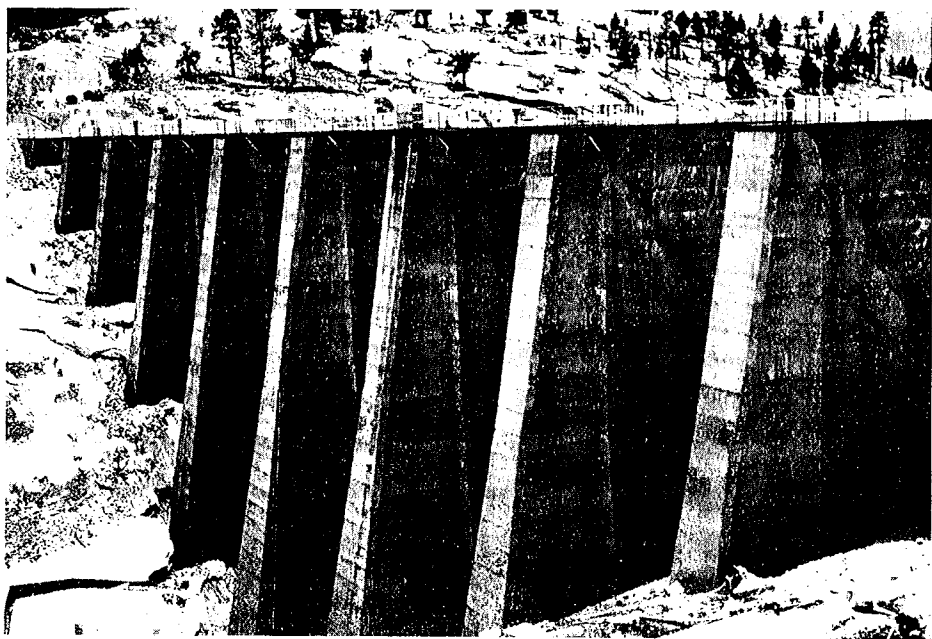


Fig. 22 — Downstream face of river section of Florence Lake Dam (1929)

from seepage along horizontal joints and from random openings at other points. These deposits were mostly hard insoluble calcium carbonate (in sheets or stalactites) but some of the deposits were composed of soft hair-like crystals that could be brushed off easily. The presence of these latter, which had a strong soda taste, suggested the possibility of an unstable aggregate. This suspicion was strengthened by the discovery of a narrow band of similar crystals around the base of a cone-shaped pile of sand, left from the original construction.

The walkways and the visible area of the upstream face were somewhat pitted by pop-outs of aggregate particles. There was also considerable raveling and scaling of the edges. The impression left with the author from the 1929 inspection was that this dam was another case of variations in workmanship which were quickly

brought to light by the severity of the exposure.

With respect to the exposure, it should be pointed out that it was the intention never to have the reservoir full in weather sufficiently cold to freeze the concrete. For operating reasons, the reservoir is usually emptied between September and November. As a special precaution, to protect the concrete in winter from contact with water, a crib diversion structure 1000 ft upstream was used so that the winter flow could be drained through sluice gates in the dam. A sheet of ice has never formed against the dam.

Snow can, and does, pile up between the arches during the winter. This snow has caused some damage to the surface coatings subsequently placed on the upstream face, but otherwise it is considered to be more protective than harmful by reducing the number of cycles of freezing and thawing.

Of importance in connection with the severity of exposure, and bearing on the difficulty of maintaining the integrity of the surface coatings and preventing seepage at the days' work joints, R. W. Spencer, engineering department manager for Southern California Edison Co., states (in a letter dated Jan. 21, 1961) that, due to rapid temperature changes, movements up to 1/16 in. in 2 hr have been recorded when the reservoir was empty.

1941 inspection

With the reservoir empty, the entire upstream face of the dam was visible. Fig. 25 shows the considerable variation in surface damage, both from arch to arch and from place to place within an individual arch. This damage was caused by freezing and thawing immediately below the sur-



Fig. 23 — Downstream face of Arch 53 of Florence Lake Dam (1929)