Historical Development of Durable Concrete for the Bureau of Reclamation

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Introduction

The Bureau of Reclamation infrastructure stretches across many different climates and environments in the seventeen western states. Many of the dams, spillways, pumping plants, power plants, canals, and tunnels are constructed with concrete. These structures were built from Arizona to Montana, across the plains and in the mountains and deserts. Concrete structures had to remain durable to resist both the design loads and the natural environments of the western climate zones. Many natural environments can be quite destructive to concrete and the earliest Reclamation projects were faced with a variety of durability problems. The state-of-the-art of concrete construction advanced from hand mixing and horse and wagon transporting operations to automated mixing plants, underwater canal construction, and pumping and conveyor placing. This paper first overviews the challenges facing concrete construction in the beginning of the 20th Century. It then traces the Bureau of Reclamation's role in the development of durable concrete to resist the environments of the west.

What is Concrete?

Before we begin, we must first understand what is concrete, the most versatile building material. The American Concrete Institute defines concrete as "a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate; in portland-cement concrete, the binder is a mixture of portland cement and water."[1] The earliest concretes date at least as far back as early Roman times including the aqueducts and the historic Pantheon in Rome. These concretes did not use portland cement as a binder. Rather, they used combinations of lime and pozzolanic sands mixed with broken rocks and shards of pottery.

Most 20th Century concretes are composed of about 75 percent aggregates by volume and about 25 percent "portland cement paste." The paste is the binder and contains cementitious materials and water. The cementitious materials include primarily portland cement and sometimes an additional cementing material such as a pozzolan. Pozzolans are finely ground, calcined (heated to a high temperature) materials that react with lime to form compounds similar to portland cement. Natural pozzolans are heated by events like volcanos. Artificial pozzolans are calcined in a kiln of furnace, such as fly ash. The ratio of water to cementitious materials is about 1.5:1

[1] American Concrete Institute, ACI 116R, Report on Cement and Concrete Terminology, Farmington Hills, MI, 2001.

by solid volume or 1:2 by weight. The individual components are mixed wet for about 5 to 10 minutes, then placed in forms to harden into their final shape.

The chemical process that turns the wet concrete into a hardened mass is called "hydration," a reaction between the cement and water that forms strong chemical bonds. Concrete does not get hard by drying like some clay bricks and lime mortars. It must retain the moisture to allow the cement to chemically hydrate; usually for about one month. The best concrete is one that stays continuously moist at a temperature of about 40 to 70 degrees Fahrenheit, such as the center of a mass concrete dam. The strongest concrete contains just sufficient water to chemically react with the available cement, about 25 to 40 percent water to cement by weight. The weakest concretes are those that contain excess water or prematurely dry out, stopping the reaction from continuing. Pozzolanic materials do not naturally harden through hydration with water, they must have added calcium hydroxide, or lime, to allow the reactions to take place. Fortunately, one of the chemical by-products of cement hydration is calcium hydroxide. Thus, added pozzolan when combined with cement and water makes for even stronger and often more durable concrete. Cement hydration also generates heat and can lead to temperature cracking when the interior mass wants to expand while the exterior contracts as it cools. Thus, any means of reducing the cement content reduces the potential for cracking.

The durability of concrete depends on the durability of its constituents; cement paste and aggregates. A concrete with strong paste may not be durable if combined with poor aggregate, and visa versa. One of the most important parameters is the "porosity" of the paste, which is a function of the amount of water relative to the cementitious materials. Excess water can dilute the cement paste leaving a more porous medium. This can be attacked more easily by deleterious substances and physical processes. The climate is a significant factor influencing the long-term durability of concrete structures. One of the reasons the ancient structures have survived is because they were constructed in relatively dry, temperate climates.

Early Obstacles to Durable Concrete

The turn of the 20^{th} Century presented numerous obstacles to constructing durable concrete structures, one of which was population expanding across America into harsh climate zones. The quality of concrete was impaired by limitations of the quality of the materials and the methods of construction. In some instances, limitations on the quality of the basic concrete materials: cement, sand, and gravel, and the proportioning of ingredients impaired quality concrete construction under the severe exposures and harsh climates of the west. In other instances, the methods of batching, mixing, placing, and protecting the concrete limited the rate of construction and the overall quality of the structures. Lastly, the methodology behind concrete design and construction was just developing and was not well documented or distributed throughout the industry. A number of significant events and innovations during the 20^{th} Century contributed to the development of concrete as a durable engineering material resulting to what is now considered "modern concrete." First, let's look at durability environments and then the state-of-the-art developments related to constructing durable concrete.

Mechanisms of Deterioration in the Western United States

There are about a half dozen environments that aggressively attack portland cement concrete. These include the following:

1. Sulfate environment
2. Alkali-silica or alkali-carbonate environment - "alkali-aggregate reactions"
3. Freezing and thawing environment
4. Acid environment
5. Chloride (corrosion) environment
6. Wetting and drying environment

Concretes that remain durable under these conditions were proportioned in some way to withstand the elements, either accidentally or purposely. Some advances in the development of durable concrete resulted from observations of concretes that essentially used chemically resistant cements or "accidentally" introduced beneficial admixtures, and comparing them with those that rapidly fell to pieces.

The three most critical natural deterioration mechanisms affecting Reclamation structures are *sulfate attack, alkali-silica reaction, and freezing-thawing attack*. These three mechanisms are described in the paragraphs that follow. In many cases, concrete deterioration is caused by a combination of aggressive environments, such as wetting and drying in concert with sulfate attack in some California desert climates or freeze-thaw attack and alkali-silica reaction in the northwest. Here, micro-fractures caused by one destructive element allow moisture to more easily penetrate the paste and contribute to a secondary reaction. One environment common to United States highways and bridges is chloride/corrosion of reinforcing steel and the resulting deterioration. It was not a major deterioration mechanism for Reclamation concretes due to the absence of chlorides, that is, until some rather dramatic failures of precast, prestressed concrete pipe in the 1990's.

Sulfate Attack - Sulfate attack is a chemical degradation of cement paste caused by high concentrations of sulfates in soils and groundwater. Sulfate attack is caused by chemical interactions between sulfate ions and constituents of the cement paste. The disintegration appears to be caused by chemical reactions with cement hydration products and the formation of a secondary compound, ettringite, accompanied by a large volumetric expansion and cracking of the concrete. Sulfate attack was also known as "cement corrosion" in the early 1900's and is very common in the white "alkali flats" of the arid western states and in seawater, particularly tidal zones. Sulfate attack was noted in Reclamation structures on the Sun River project in Montana in 1908, shortly after the formation of the U.S. Reclamation Service.[2] Figure 1 shows the

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[2] Jewett, J.Y., "Cement and Concrete Work of the United States Reclamation Service with Notes on Disintegration of Concrete by Action of Alkali Waters," Proceedings of ASTM, Vol. 8, Philadelphia, PA, 1908, pp. 480 - 493.

disintegration of a concrete canal lining in the Central Valley Project only five years after construction.[3] Early observations in these failures identified certain cement brands as being more resistant to deterioration in these environments than others. “Bad” cements were less resistant and avoided if possible in favor of more resistant “good” cements.
Alkali-aggregate Reactions - Alkali aggregate reactions (AAR) are the chemical reactions

Figure 1 Sulfate attack on a five year old concrete canal lining, Central Valley Project, California. The groundwater sulfates infiltrate the concrete and chemically react with certain cement hydration products. The expansive reaction causes cracking and disintegration of the cement paste matrix. Notice the deterioration near the upper soil strata where the sulfates are more concentrated.

between certain specific mineralogical types of aggregates (either sand or gravel) and the alkali compounds (generally less than 2 percent of the cement composition) of cement in the presence of moisture. “Typical manifestations of concrete deterioration through alkali-silica reaction are expansion; cracking, which frequently is of such nature the designation “pattern” or “map” cracking; exudations of jelly-like or hard beads on surfaces; reaction rims on affected aggregate particles within the concrete; and sometimes popouts.”[4] The reaction products have a swelling nature, leading to tensile stresses that cause cracking within the concrete. The cracking may allow moisture to more readily be absorbed by the silica gel or accelerate freezing and thawing damage.

Alkalies in cement can react with certain “glassy,” siliceous aggregates such as opals, chalcedony, cherts, andesites, basalts, and some quartz; termed alkali-silica reaction or ASR, and certain specific carbonate aggregates called alkali-carbonate reaction.[5] Alkali-silica reaction,

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[3] Harboe, Edward M., “Longtime Studies and Field Experiences with Sulfate Attack,” American Concrete Institute Special Publication No. 77-1, Detriot, MI, 1977.

[4] “Durability of Concrete Construction,” American Concrete Institute Monograph No. 4, American Concrete Institute, Detroit, MI, The Iowa State University Press, Ames, Iowa, 1968, p. 59-60.

[5] Meilenz, R.C., “Petrographic Examination of Concrete Aggregate to Determine Potential Alkali Reactivity,” Highway Research Report No. 18-C, 1958, p. 29-35.

shown in figure 2, was probably first experienced by Reclamation at American Falls Dam in Idaho, completed in 1927. However, extensive freezing and thawing deterioration and poor quality construction practices masked ASR as a primary cause of deterioration at American Falls Dam. Some structures, such as Parker Dam and Stewart Mountain Dam suffered early rapid expansion and distress, then became relatively stable after a few years as the available alkalis and reactive aggregates were consumed early in the process. Other structures, such as Seminoe Dam are showing continued expansion and resulting distress even 50 years after construction.[6]

Freezing and Thawing Deterioration - Freezing and thawing (FT) deterioration is the deleterious expansion of water within the cement paste resulting in destruction of the concrete. Water present in the cement paste expands about 9 percent upon freezing. When confined within a

Figure 2 One of the earliest photos of alkali-silica "gel" common to expansive alkali-aggregate reaction. These gels swell in the confined concrete matrix causing expansion and cracking in the aggregates and concrete. Bureau of Reclamation Concrete Laboratory file photo, about 1940.

rigid, crystalline micro-structure, the expanding ice crystals can exert pressures far exceeding the tensile capacity of the paste, causing cracking and ultimately failure of the concrete. The concrete must be nearly saturated when it undergoes the freezing for this form of deterioration to take place. Repeated cycles of freezing and thawing are common in Reclamation water conveyance structures. Areas subject to cyclic freezing, such as the spillway shown in figure 3, and particularly those in fluctuating water surface levels, or in splash or spray zones are the most susceptible to deterioration.[7] Freeze-thaw deterioration is most pronounced in more porous concrete having a high water to cement ratio and those concretes without purposely entrained, air bubbles; the very same concretes commonly used in early 20th Century construction. Freeze-thaw deterioration was first identified early in Reclamation history under the general term of durability of concrete without specific causes or solutions. The form of damage is present in the colder and mountainous regions and non-existent in the desert southwest. A mixture placed on the All-

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[6] Mohorovic, C.E., and Dolen, T.P., "1998-99 Concrete Coring-Laboratory Testing Program, Seminoe Dam, Kendrick Project, Wyoming," Bureau of Reclamation Technical Service Center, Denver, CO, August, 1999.

[7] Smoak, W. Glenn, "Guide to Concrete Repair," Bureau of Reclamation Technical Service Center, Denver, CO, April, 1997, p. 4.

American Canal would have no problems, but, the very same concrete placed on the Yakima Project would be severely affected.

Developing the State-of-the-Art of Concrete Technology

Even with quality materials, durable concrete could not effectively be mixed and placed in the larger Reclamation structures without new construction practices and equipment. The historical development of durable Reclamation concrete can roughly be divided into four generations with regard to both materials and methods of construction. Each generation contributed to the

Figure 3 Freezing and thawing deterioration of a spillway training wall at Lahontan Dam in California. The "sand cement" concrete placed in 1915 was severely damaged by freezing and thawing in the colder and mountain regions of the west. Notice the shady area is less damaged than the section exposed repeatedly to cold temperatures followed by the

knowledge base of the developing state-of-the-art. The first generation of Reclamation concrete technology covers from its inception in 1902 until about World War I. These practitioners were the first "pioneers" of Reclamation concrete construction. The next generation, from 1918 until the late 1920's, began developing concrete as an engineering material. The Boulder/Hoover generation began in the late 1920's and continued up to World War II. This generation solved many of the fundamental problems encountered in massive concrete construction and many of the standardized quality concrete construction practices. They uncovered the mysteries of sulfate attack, alkali-aggregate reaction, and freezing and thawing durability, leading to the first truly engineered, modern, durable concretes. The post war generation incorporated the basic concepts of modern concrete to a multitude of applications for dams, pumping and power plants, canals, and tunnels under a variety of differing site conditions. This is the first long-lasting, concrete infrastructure.

The Early Years - The Concrete Pioneers - The first generation of concrete practitioners developed the technology largely through trial and error and continued observation. The earliest concrete was composed of poorly manufactured cements, unprocessed aggregates, and was mixed by hand or small mixers. The materials themselves; cement, sand, and gravel were subject to great variability. The concrete mixture was proportioned by "recipe" based on previous experience, not necessarily as an engineered material. Many early Reclamation projects were somewhat isolated geographically and there was less communication beyond regional boundaries. A change in location or structural design was not necessarily followed with an appropriate change in concrete mixture design, resulting in spotty performance. Labor was cheap, equipment and cement were expensive. The resulting mixtures contained the least amount of cement necessary to meet low strength requirements, at least by today's standards. Concrete was largely transported by wheelbarrows and compacted in place by manual tamping, spading, and rodding. The production rates were very slow, resulting in frequent "cold joints" or unplanned flaws that allowed seepage and subsequent deterioration.

A major change in building technology, the introduction of steel-reinforced, concrete structures, at first did not improve concrete quality. Pre-1900 structures were more massive and used a stiffer concrete that was tamped into place. The resulting concrete was less permeable and somewhat more resistant to the elements due to its low porosity; water simply had difficulty entering the matrix to cause damage. Reinforced concrete structures took advantage of the tensile strength capacity of the steel and the size of structural members were reduced. In addition to thinner structures, the reinforcing steel interfered with the placing and tamping practices. As a result, water was added to the concrete mixture to make it more fluid and thus easier to place. However, more cement was not necessarily added, and the weaker more porous concretes started falling apart in the field in only a few years.[8] The favorite phrase of concrete construction workers "add more water" likely came about during this era and a century later concrete technologists still shudder at the request!

The earliest Reclamation construction projects did not have the benefit of a developed methodology and specific equipment for concrete construction. Construction practices gradually improved during the first Reclamation construction era. Many structures fortunately utilized techniques that have helped them resist degradation. Theodore Roosevelt Dam in Arizona utilized a masonry facing and cyclopean concrete methods: large "plum stones" were placed followed by smaller cobbles and boulders and then the concrete was added to fill the remaining voids. This construction technique left large stones across the construction joint surface that reduced shear planes. The mixtures had a low cement content on a per cubic yard basis that reduced thermal cracking and the cost.[9]

One construction advance called "chuting," shown in figure 4, resulted in poor quality concrete. An "improvement" over the back-breaking manual hauling by buckets, long chutes were used to transport concrete to the forms. This permitted a centralized concrete batching and mixing location and larger batches could be fed to sometimes intricate, gravity-fed, chute systems. Water was added to make the concrete flow down relatively flat sloping chutes. The extra water diluted the cement paste in the concrete. These mixes were much weaker and had poor

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[8] Engineering News Record Editorial, "Some Doubts About Concrete," Volume 90, February, 1923.

[9] Department of the Interior, Bureau of Reclamation, "Dams and Control Works," Third Edition, Washington, D.C., 1954, pp. 57-60..

durability. To discourage this practice, engineers finally specified that the slope of the chutes could not be flatter than about 35 degrees from horizontal.[10]
The developing state-of-the-art had a few “hiccups” along the way. “Sand-cement” was introduced to reduce the cost of cement by inter-grinding crushed rock flour during the manufacturing process.[11] The finely ground rock flour was introduced as a “pozzolan” to react with the cement for increased strength, and indeed, the sand-cement mixtures had higher 7- and 28- day compressive strengths compared to the control mixtures. However, the compressive strength development did not continue much after 28 days as is more typical of portland cement plus real pozzolans. Thus, the problem was the finer ground sand-cement reacted faster, but did not act as a pozzolan because the rock flour was not calcined. Arrowrock Dam, in Idaho,

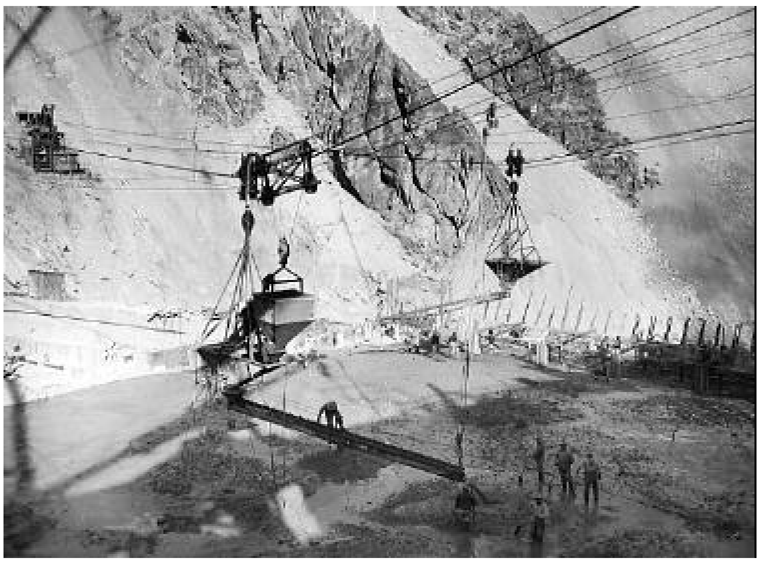

Figure 4 Chuting wet concrete into place - Arrowrock Dam, about 1912. Elaborate chute systems required a very fluid concrete mixture to be placed and spread in the forms. Water was the “admixture” of choice to improve the fluidity! Bureau of Reclamation Historical Photographs.

constructed using sand-cement in 1915, was rehabilitated with a higher strength concrete facing in the mid-1930's to stop continued freezing and thawing damage.[12]

First generation Reclamation concretes were vulnerable to sulfate attack, ASR, and FT deterioration. In spite of these problems, some concretes seemed remarkably durable. Engineers and scientists began examining concrete materials to try to improve the quality. Studies conducted at the Lewis Institute in Chicago beginning in 1914 were to shed new light on the

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10 Walter, L.W., “Thirty Years Experience with Concrete,” Proceedings of the American Concrete Institute, Vol. 25, Detriot, MI, 1929, p. 54.

11 Savage, J.L.,“Special Cements for Mass Concrete,” Second Congress of the International Commission on Large Dams, World Power Conference, Washington, D.C., Bureau of Reclamation, Denver, CO, 1936.

12 Studebaker, Claude, A., “Tentative Report on Gunite at Arrowrock Dam,” U.S. Department of the Interior, Bureau of Reclamation, Boise Project, Boise, ID, January 22, 1937.

engineering properties of concrete.

The Abrams Generation - The first major advance in concrete technology during the 20^{th} Century occurred about 1918 with the publication of Duff Abrams' "Design of Concrete Mixtures."[13] Abrams improved on the recipe proportioning methods through deliberate design practices with proportioning methods and mix design tables. Abrams classic research and his "water to cement ratio law"provided the foundation of concrete mix design still followed today. He found concrete strength and thus quality could be controlled by the relative proportions of water and cement. He also found it was possible to design mixes for the same strength using different materials. Concrete mixes could be designed and proportioned to meet a variety of conditions and structural requirements. Stronger concretes were developed to resist deterioration by the environment. Researchers began investigating the fundamental physical-chemical reactions that were needed to advance the state-of-the-art. One of the first inroads to developing durable concrete took place with the identification of the chemical reaction products of cement hydration, and a method to compute the relative proportions of each constituent in cement by Bogue in 1927.[14] This important step was necessary to formulate different compositions of cement. Without the knowledge of its composition, it was not possible to purposely change materials and manufacturing processes to enhance the performance of portland cement.

Concrete manufacturing methods also improved during the 1920's, including centrally batched and mixed concrete plants and systems to haul and transport concrete to the site, as shown in figure 5. The daily output of concrete plants increased, resulting in fewer cold joints. The horse and wagon was being replaced by the locomotive and trucks. Larger projects were constructed and more mechanized processes were developed. Still, the process of consolidating concrete was left to the common laborer through rodding and spading. The first methods to consolidate concrete with mechanical equipment were just being developed. Better treatment of cold joints was developed during this time, improving the continuity between adjacent placements. For the first time, control tests were used to design and monitor concrete mixtures within specific parameters. Abrams' generation of concrete technologists provided the foundation of knowledge for the next generation, beginning with the decision to construct Boulder (Hoover Dam) on the mighty Colorado River in December, 1928.

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[13] Abrams, Duff, A., "Design of Concrete Mixtures," Structural Materials Research Laboratory, Lewis Institute, Chicago, IL, 1918.

[14] Bogue, R.,H., "Calculation of the Compounds in Portland Cement," Industrial and Engineering Chemical Analysis, Vol. 1, No. 4, October, 1929.

Boulder Dam / The "Hoover Generation" - In 1928, the Boulder Canyon Act ratified the Colorado River Compact and authorized construction of Hoover Dam[15]. The size of the Hoover Dam required a completely new technology for large-scale concrete design and construction. The Hoover generation raised concrete materials technology, design methods, and concrete construction technology to unprecedented heights. This generation of concrete technologists formulated large-scale research and development programs of special cements to meet the specific engineering properties for massive concrete structures. They answered some

Figure 5 Early concrete canal lining. Horse and buggy transporting gave way to central batch plants and the first motorized transporting buggies. Still the concrete placing and compacting processes were performed by laborers with shovels. Bureau of Reclamation Historical Photographs.

fundamental questions about cement chemistry and the effects on mass concrete. Solving these questions required close cooperation and communication between government agencies, manufacturers, contractors, and private and academic research institutions. The application of scientific methods to solve complex durability problems led to what we now know as "modern concrete."

One of the first steps required for concrete for Hoover Dam was to investigate the composition of cement to reduce the amount of heat generated as it hydrated. Extensive research on cement composition resulted in developing a low-heat cement for mass concrete, now known by the American Society of Testing and Materials (ASTM) as Type IV cement. The hydration product "tri-calcium aluminate," abbreviated in a simplified form as "C_3A," was found to be one of the principal compounds that generates heat during the hydration process. Reclamation specified the chemical composition of cement supplied to Hoover Dam in 1933 to assure a low heat of hydration. The low-heat cement also had improved durability because the low C_3A cements had better resistance to sulfate attack. This improved resistance to sulfate attack was the basis for specifying less than 5 percent C_3A for cement used on the Kendrick Project in 1938; another

[15] Bureau of Reclamation, "Brief History of the Bureau of Reclamation," Bureau of Reclamation History Program, Denver, CO, July, 2000, p. 4.

forerunner of the ASTM Type V (sulfate-resisting) cement.[16]
Construction of such large projects as Hoover and Grand Coulee Dams could not have been accomplished without advances in concrete aggregate processing, concrete manufacturing, transporting, and placing. The use of block construction techniques, shown in figure 6, and artificial, post-cooling reduced the potential for thermal cracking. Specialized concrete batch plants with rail transporting and "high-lines" or cable ways, were used to transport and place large quantities in round-the-clock operations. One of the under appreciated advances in

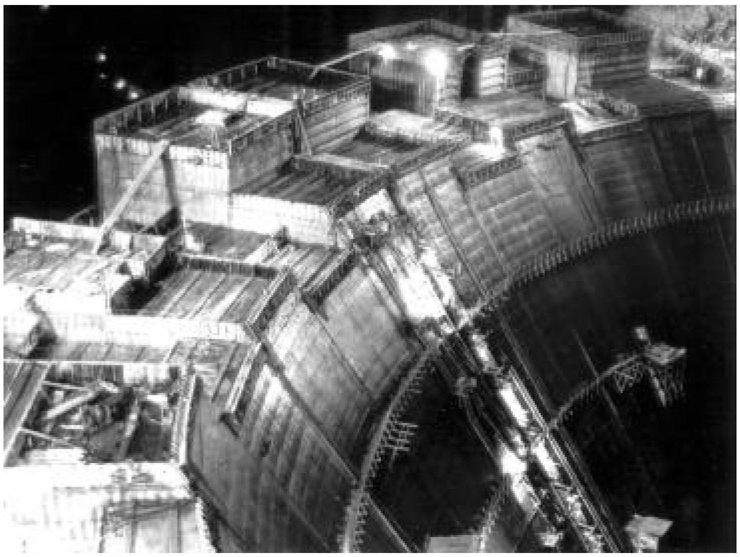

Figure 6 Mass concrete block construction at Hoover Dam, 1930's. The size and scope of this project led to many innovations ranging from advances in cement chemistry to new methods of batching, mixing, transporting, placing, cooling mass concrete. Bureau of Reclamation Historical Photographs.

concrete quality developed by eliminating the back-breaking "tamping" techniques of consolidation with the high-frequency, mechanical concrete vibrator shown in figure 7.[17] Vibrators allowed a lowered unit water content of the mixture and thus lowered the cement content. The concrete generated less heat and became less porous, while costing less.

The size of Hoover Dam required not only significant advances in construction equipment and materials processing, but also in construction project management and process quality control techniques. The designers and constructors of Hoover and Grand Coulee Dams were diligent, meticulous, *and* to some degree lucky. Fortunately, one of the chemical processes that could cause expansion, cracking, and deterioration of concrete; alkali-aggregate reaction, was avoided at Hoover Dam. The cements furnished to the dam had a high alkali content and fortunately, the concrete was mostly free from potentially reactive aggregates; though not by design, because the

[16] Moran, Willis, T. "Bureau of Reclamation Viewpoint on Portland Cement Specifications," 1952.

[17] McCarty, M.I., "High Frequency Vibratory Machines for Concrete Placement," Proceedings of the American Concrete Institute, Vol. 30, ACI, Detroit, MI, September, 1933.

alkali-aggregate phenomena had not yet been identified and studied.[18]

Two of the indirect products of the Hoover generation were the founding of the Concrete Laboratory in Denver, Colorado in 1931 and the first printing of the Concrete Manual in 1936. The Concrete Laboratory and Concrete Manual grew out of the need for a better understanding of the behavior of concrete and the control of concrete construction. Over 100,000 copies of the Concrete Manual have been printed in nine editions and at least four languages. "Concrete schools" were developed for training engineering and field personnel, and have continued to this day. The Reclamation concrete technologists were active participants in ASTM and ACI, serving as both committee chairmen and as president. This commitment to voluntary standards organizations continues today.

Figure 7 The mechanical concrete vibrator was first introduced to the Bureau of Reclamation during construction of Hoover Dam. The laborers job of hand-tamping and spading was replaced with mechanical equipment. However, even though the consolidation process was accomplished by machine, it took a strong person to manipulate these vibrators! Bureau of Reclamation Historical Photographs.

As the United States entered World War II, the last two pieces of the durability puzzle were identified and finally corrected. Aklali-aggregate reaction was encountered by Reclamation at American Falls Dam, and about 150 miles downstream of Hoover Dam at Parker Dam. While American Falls Dam was undergoing rehabilitation from a variety of causes, Parker Dam was just being completed in 1937. Within two years, cracks appeared in the dam.[19] The cracking at Parker Dam was severe enough to warrant a large scale research investigation and a blue ribbon

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[18] Private conversations with William DePuy, Concrete and Structural Branch, Bureau of Reclamation, Denver, CO.

[19] DePuy, G.W., "Petrographic Investigations of Concrete and Concrete Aggregates at the Bureau of Reclamation," ASTM STP-1061, Petrography Applied to Concrete and Concrete Aggregates, ASTM, Philadelphia, PA, 1990, p. 33-46.

panel of consultants. In the end, the chemical reactions between certain altered andesites and rhyolites in less than 2 percent of the aggregates and the alkalies in the cement fostered a deleterious, expansive reaction called alkali-silica reaction, known as ASR[20]. First observed in Pennsylvania in the early 1920's at the Buck Hydroelectric Plant, ASR became a noticeable problem throughout the country in the 1930's and early 1940's.[21] The solution to ASR was to use petrographic techniques to identify those aggregates with the potential for expansion and to specify a 0.6 percent limit of alkalies in the cement.[22] Reclamation quickly instituted the low-alkali limit for concrete with potentially reactive aggregates by April of 1941.[23]

The last major advance in developing durable concrete was the result of both accident and observation in 1938. In New York State, certain highway pavements were observed to have superior performance when a particular brand of cement was used in the concrete. The highway departments began specifying this particular brand of cement for all their highway construction without fully understanding the reason for superior performance. Microscopic examination of the concrete revealed a paste structure containing tiny, entrained, air bubbles brought about by using beef tallow in the cement kilns during manufacturing.[24] This produced the first "air-entrained" cement, accompanied by significantly improved freezing and thawing resistance compared to other cements. The microscopic air bubbles absorbed the expansive forces of freezing ice crystals within the paste, preventing micro-cracking. Though not a direct player in the initial identification of entrained air, Reclamation began testing concrete for freeze-thaw durability in the mid-1930's as a means of evaluating concrete, aggregate quality, and other additives, some of which may have accidentally entrained air. The perceived superior durability of Grand Coulee Dam concrete in the 1930's may have resulted from specifications allowing grinding aids during cement manufacturing that may have entrained some air.[25] Anecdotal evidence points to other accidental introductions of air in concrete in the United States as early as

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[20] Stanton, T. E., "Expansion of Concrete Through Reaction Between Cement and Aggregates," Transactions of ASCE, Vol. 66, December, 1940, pp. 1781-1811.

[21] Kammer, H.A. and Carlson, R.W., "Investigation of Causes of Delayed Expansion of Concrete in Buck Hydroelectric Plant," Proceedings of ACI, Vol. 37, June, 1941, p.665.

[22] DePuy, ibid, 1990.

[23] Dolen, Timothy, P. "Cement History Database," Bureau of Reclamation, Science and Technology Program, Research Project FI908, Decision Support system for Aging Concrete, 2000.

[24] Lawton, E.C., "Durability of Concrete Pavement - Experiences in New York State," Proceedings of ACI, Detroit, MI, Vol. 35, June, 1939, p. 561.

[25] Bureau of Reclamation, "Effect of the admixture, T.D.A., on the durability of concrete," Cement Laboratory Report No. Ce-33, Denver, CO, June 30, 1942.

the 1920's. These concretes were quickly rejected due to lower density and compressive strength! Higginson even refers to the possibility of forms of entrained air in stucco specified by Marcus Vitrivius Pollio in the First Century A.D.[26] Reclamation quickly changed their specifications and changed to air-entrained concrete by 1942.[27] By the end of World War II, Reclamation had finally overcome the three primary causes of concrete durability problems in the west, resulting in what is considered "modern concrete;" an engineered concrete capable of resisting the physical and chemical forces of nature.

The Post-War Generation: "The Constructors" - The post-war generation of concrete technologists applied the fundamentals of modern concrete to "customize" it for a variety of new applications and over a wide range of different environments. This generation began as post-war citizen soldiers returned to the United States and continued through the cold war. These people were the constructors. During the fifties and sixties Reclamation was completing "a dam a year." Large, thick arch dams became high-strength, double curvature, thin arch dams. Projects were constructed across the desert and through 14,000 foot high mountain ranges. Some of the largest water development and distribution systems were completed during this era, the Central Arizona and Central Utah Projects. The concretes used new additives to achieve greater durability, economy, and performance. These concretes should remain durable through the next century.

One of the most significant contributions of this generation improved durability and also made concrete less expensive. The purposeful addition of natural pozzolans in the early 20th Century was done somewhat as a cost-saving measure and later to reduce the temperature rise of mass concrete. The Bureau of Reclamation began investigating a power plant by-product, fly ash, in the 1930's and 1940's as a substitute for natural pozzolans in mass concrete. The first large-scale specified use of fly ash was at Hungry Horse Dam in 1950.[28] Reclamation continued research on fly ash, yielding other benefits such as improving the sulfate resistance of concrete. In the 1970's cement shortages prompted Reclamation to begin using fly ash in normal structural concrete and canal linings to save cement. The U.S. Environmental Protection Agency's implementation of the Resource Conservation Recovery Act, beginning in 1980, strongly encouraged the reuse of

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[26] Higginson, E.C., "Air-Entrained Concrete in Modern Construction," Presented before the Engineering Section of the Colorado-Wyoming Academy of Science, Boulder, CO, May 2, 1952 .

[27] Price, Walter, H., "In the Beginning," Bureau of Reclamation, Concrete Laboratory Technical Conference, December, 1981.

[28] Bureau of Reclamation, Laboratory and Field Investigations of Concrete, Hungry Horse Dam, Hungry Horse project, Concrete Laboratory Report No. C-699, Denver, CO, December 4, 1953.

recycled materials, including fly ash in concrete.[29] The long-term benefits of using fly ash will continue for generations as these concretes are less porous, and more resistant to sulfate attack and alkali-silica reaction, even more than with sulfate-resisting, low-alkali cements.[30]

The advances in construction equipment design dramatically increased concrete production during this time. Large-size canal linings are now placed at ten times the rate as in the early days. Instead of adding water to increase fluidity, superplasticizers are now added to make concrete flow like water, yet be twice the strength of its predecessors. Concrete linings were even placed under water to reduce leakage in unlined canals.[31] Concrete vibrators capable of consolidating 25 to 50 yd^3 of concrete per hour were replaced by 10-ton, vibratory rollers capable of placing 500 yd^3 per hour in roller-compacted concrete (RCC) dams.[32] It is interesting to note that the earliest Reclamation concretes were of such a consistency that they had to be manually "rammed" into place. The era of Reclamation concrete dam construction concluded at Upper Stillwater Dam using RCC of such consistency that was mechanically "rammed" into place!

The Present Generation and Beyond - By about 1990, the last large dams were being completed and a new era was underway. Most of Reclamation's construction program is now devoted to rehabilitation of the existing structures. The Reclamation Safety of Dams Act of 1978 provided the Secretary of the Interior with the authority to construct, restore, operate, and maintain new or modified features at existing Federal Reclamation dams for safety of dams purposes.[33] As the inventory of dams was closely examined, it became apparent that many dams were in need of attention. The safety of dams program recognized dams constructed prior to changes in the state-of-the-art in dam design and construction were candidates for funding under this act. In addition to dam safety needs, many aging Reclamation structures were in need of some type of repair due to the ravages of time. An example is Tieton Dam, figure 8, constructed in Washington in 1925. The concrete lined spillway suffered from serious freezing and thawing deterioration. It was first rehabilitated in the 1970's and again in 1999 with operations and maintenance funding. Concrete canals, power and pumping plants, and appurtenant structures are also being rehabilitated

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[29] Harboe, Edward, M., "Fly Ash and the EPA Guidelines," Presentation to the Division of Design, February, 1984.

[30] Kalousek, G.L., Porter, L.C., and Benton, E.J., "Concrete for Long-time Service in Sulfate Environment," Cement and Concrete Research, Vol. 2, Pergamon Press, New york, 1972, pp. 79-89.

[31] Kepler, W.F., "Underwater Placement of a Concrete Canal Lining," ACI Concrete International: Design and Construction, Detroit, MI, June, 1990 pp. 54-59.

[32] American Concrete Institute, Guide for Consolidation of Concrete, Committee 309, Detroit, MI, 1999.

[33] United States Government, Public Law 95-578, November 2, 1978.

throughout the west. The present generation of concrete technologists benefitted from four generations of research and development. They must continue to apply the hard won practical knowledge of their predecessors to maintain the existing infrastructure well into the 21st Century.

Conclusions

Figure 8 Tieton Dam spillway reconstruction, 1999. Yakima Project, Washington. The challenge for the 21st Century. Identify, protect , and preserve. The spillway was completed in 1925 and suffered from severe freezing and thawing deterioration. The spillway was extensively repaired after about 40 years and reconstructed in 1999. These types of rehabilitation efforts will take center stage in 21st Bureau of Reclamation construction. Construction Records, Yakima Construction Office, Washington.

This paper reviewed the most significant causes of concrete deterioration and Reclamation's role in improving the technology to the current state-of-the-art. Without durable concretes, Reclamation could not have developed the western water resources infrastructure we enjoy today. The development and rapid implementation of these advances kept Reclamation at the forefront of the state-of-the-art through the 20th Century. This has extended the long-term service life of our infrastructure well into the 21st Century. Figure 9 summarizes many of the steps encountered to developing durable, modern concrete. Although the list of accomplishments is long, the author nominates the following as the "top five" contributions to durable concrete in the 20th Century (in chronological order):

1. Abrams' design of concrete mixtures and "water-cement ratio law" - Abrams applied engineering practices to concrete mixtures and he was the first to institutionalize control of the water content to improve concrete quality.

2. Development of special cements to improve concrete quality, such as low-heat and sulfate resisting cements.

3. Development of the internal vibrator to consolidate concrete - this equipment significantly reduced the water content of concrete, making it less permeable.

4. Determining the causes of and solutions to alkali-aggregate reaction and freezing and thawing attack - using scientific methods such as petrographic mineralogical examination and long-term testing to identify the parameters which affected the durability of concrete under these conditions.

5. Incorporating fly ash in Reclamation concrete construction - fly ash improved concrete workability, decreased the porosity of the cement paste, and improved its resistance to sulfate attack and alkali-silica reaction.

The modern concrete of today incorporates all of the advances of the past century. An example of 1 cubic yard of modern concrete will include the following ingredients and their proportions:

Figure 9 Steps leading to the development of durable Reclamation concrete throughout the 20th Century.

Bureau of Reclamation

Steps to developing durable concrete

Poor Quality	***Better Quality***	***Best Quality***	***"Modern Concrete"***
"Pioneers" Hand mixing Low output (cold joints) Poor quality materials ***Sulfate attack*** ***Alkali-aggregate reaction*** ***Freeze-thaw attack*** Recipe mix design Reinforced concrete "Add more water!"	**"Abrams"** W/C ratio Quality materials Mix design Volumetric batching ***Sulfate attack*** ***Alkali-aggregate reaction*** ***Freeze-thaw attack*** "Chuting" "Add more water!"	**"Hoover"** Weigh batching Internal vibration (less water) Block construction Low-heat cement Use of pozzolans Type II,V cement Low-alkali cement Air-entrained concrete Process quality control Concrete Laboratory Concrete Manual "Add more water!"	**"Post War"** Pozzolans (fly ash) Automated Construction (tunnels, canals) Admixtures Concrete Repair Superplasticizers Silica Fume RCC
1902	**1918**	**1928**	**1948** **2002**

Table 1. Bureau of Reclamation "modern concrete" - one cubic yard of concrete.				
Ingredient	Mass (lb/yd^3)	Volume (ft^3/yd^3)	ASTM Specification	Comments
Air	5 percent	1.3	C 260	Air-entraining admixture for freezing and thawing durability
Water *	220	3.5	C 94	Sufficient for 3 inch slump
Cement *	390	2.0	C 150	Type II, moderate sulfate resisting with less than 0.6 percent alkalies to resist alkali-silica reaction
Pozzolan *	100	0.7	C 618	Class F, "R Factor" less than 2.5 for improved sulfate resistance, and decreased potential for ASR
Sand	1080	6.6	C 33	Fineness Modulus of 2.75
Coarse Aggregate	2120	12.9	C 33	1-1/2 inch maximum size aggregate
Total	3910	27		
* Water to cement plus pozzolan ratio = 0.45 for superior durability in sulfate and freezing and thawing environments. Water reducing admixture included.				

The Author's Closure: The Challenge for the 21 st Century - Identify, Protect, Preserve

Reclamation must now face the critical task of maintaining the existing infrastructure to meet the needs of the 21st Century. The aging of concrete structures will require a major investment for continued operation. The most immediate needs are to protect concretes constructed before the "big three" durability issues were solved. Unfortunately, this only narrows the field down to about the 50 percent of our inventory constructed before World War II. Of these structures, those constructed before about 1930 are in need of the most urgent attention. A decision support system for aging concrete is under development to evaluate the earliest structures and present information on their long-term, service life potential.[34] With this information, Reclamation intends to present the status of our concrete infrastructure on a time-line to prioritize funding for protection before deterioration processes damage these facilities beyond repair.

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[34] Dolen, T.P., "Decision Support System for Aging Concrete," Research Project No. FI908, Bureau of Reclamation, Science and Technology Program, 2001.

I was fortunate to have as a mentor one of the great Reclamation concrete technologists of his time, Mr. Edward Harboe. Whenever I had a question, I would stop and talk to Ed because I knew he either had the answer or knew where to find it. Within a couple of hours, Ed would stop by after digging through his files to come up with the results of a long-ago study. In my opinion, many of our questions have already been answered by our predecessors. We must continue to preserve and to pass on the knowledge base that is our history. I would like to dedicate this paper to Ed and the many pioneers of Reclamation concrete construction, with special recognition the late Mr. G.W. "Bill" DePuy, my old boss, who passed away on January 3, 2002.

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