Effects of Concrete Deterioration on Safety of Dams

Dam Safety Office

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Introduction

The objective of this project was to determine the influences of concrete deterioration on the safety of the Bureau of Reclamation (Reclamation) structures and how deterioration can impact Reclamation's risk evaluation process. In addition, tasks needed to accomplish the objective of evaluating the risks as a function of time for deteriorating concrete structures are identified.

In this report, we discuss:

- The role of risk analysis and assessment in the Dam Safety Program
- Methods to predict concrete deterioration
- The types of concrete deterioration
- The effects of each type of deterioration on concrete properties
- When to consider including deterioration in a risk assessment
- Implementing a deterioration-related risk assessment process
- Potential dam safety failure modes associated with concrete deterioration
- Event trees showing how each type of deterioration could progress to the point of a dam failure
- Using economic models to determine the least cost alternative of repairing a structure versus completely rebuilding the structure at the end of its life

Concrete is a basic structural component of almost all dams and many other water resources facilities. Concrete structures for dams include the intake structures, outlet conduits, and outlet works for most all dams; the service and emergency spillways for both embankment and concrete dams; and the main body or in some cases an impermeable core for concrete and embankment dams, respectively. Concrete deterioration encompasses physical processes that are constantly acting on the concrete with time, or an internal condition that may affect the physical structure of the material itself. Examples of concrete deterioration processes include sulfate attack, alkali-aggregate reaction (AAR), and freezing and thawing (F/T) deterioration.

Risk can be defined by the annual probability of loss of life, loss of economic benefit of the structure, and loss of property and harm to the environment or cultural resources. Currently, the process of performing risk analysis for dam safety includes identifying and quantifying: (1) plausible physical ways in which the dam could fail (failure modes), (2) the events and conditions that could cause failure, (3) their likelihood, and (4) their consequences.

A major component of this report is an evaluation of models to predict the influences of various deterioration mechanisms on the strength and elastic properties of concrete. Although the focus of this report relates to risk assessment, we envision that models to predict concrete properties resulting from ongoing deterioration would be very useful for operations and maintenance planning and budgeting.

The results of this report can serve as a basis for evaluating future research proposals to develop specific tools for use in evaluating risks associated with concrete deterioration.

Conclusions and Recommendations

2.1 Conclusions

Models to predict future concrete properties based on deterioration mechanisms need to be developed to determine how concrete deterioration influences the stability of Reclamation structures.

Basic models exist for only one or two deterioration mechanisms that can be used to predict the impact of deterioration on the long-term physical properties of concrete. While there are many numerical tools to evaluate the structural capacity of a facility, there are no corresponding tools to evaluate the long-term change in capacity of structures because of deterioration of the construction materials.

Work has started on a comprehensive concrete deterioration model under a contract administered by the U.S. Navy. Reclamation can add tasks to that contract and the appropriate funding. This will result in a state-of-the-art model for predicting the changes in concrete properties with time. These predicted changes, along with existing structural analytical tools, will allow reasonable estimation of failure likelihood and how the likelihood changes with time. Ultimately, this will provide more reliable estimates of when risk reduction actions might be justified for deteriorating structures. We anticipate that development of the deterioration model will be the major part of research to address this problem.

Models to predict the impact of deterioration on the physical properties of concrete will need information about the concrete, environmental exposure, and construction conditions. In addition, the properties of aging of various types of concrete, particularly concrete subject to deterioration, are needed to improve predictive modeling.

A database containing material properties information about Reclamation structures has been created. Information on environmental exposure and construction will help identify which structures might be susceptible to deterioration.

Including the effects of concrete deterioration explicitly in the risk assessment framework will be a challenge. This approach will require work to provide information that can be directly applied to the existing risk analysis process.

2.2 Recommendations

We propose that Reclamation:

- Improve techniques used to estimate the impact of deterioration of concrete in risk assessments

- Support the development of software to predict future properties of concrete that is deteriorating
- Support the continued development of an electronic database that will house material properties of concrete and construction information to aid in identifying structures where the risk of concrete deterioration should be considered

The Role of Risk Analysis and Assessment in the Dam Safety Program

> The objective of the Bureau of Reclamation Dam Safety Program is to ensure that Reclamation water impounding structures do not create unacceptable risks to public safety and welfare, property, the environment, or cultural resources. This requires identifying structures which pose unacceptable risks and taking corrective actions to reduce or eliminate these risks in an efficient and cost effective manner.[1]

Risk analysis procedures help organize engineering approaches to credibly identify potential failure modes and related downstream consequences that are often the fundamental information necessary to make decisions related to program objectives.

The Dam Safety Risk Analysis Methodology states that in the context of dam safety, risk is defined as *the probability of loss*. In this case, risk can be defined by the probability of loss of life, loss of economic benefit of the structure, and loss of property and damage to the environment or cultural resources. "Risk arises from undesirable consequences which could occur and uncertainty over whether or not those consequences will actually occur….The process of performing risk analysis for dam safety includes identifying and quantifying three elements: (1) the events and conditions that could cause failure, (2) the likelihood, and (3) their consequences."

The risk equation is expressed as follows:

Risk = P[load] x P[Adverse Response given the load] x Adverse Consequences given the failure

The purpose of this document is to identify how concrete deterioration affects the risk of a water resources structures. Concrete deterioration is a condition that affects the likelihood of failure by degrading the materials properties of a particular structure over time. The process of evaluating the safety of a structure (the likelihood of a failure leading to loss of life) and performing a risk analysis typically assumes a constant state of material properties. However, we know that concrete deterioration is almost always a continual process that is not normally factored into the

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[1] Bureau of Reclamation, *Dam Safety Risk Analysis Methodology*, Version 3.3, Technical Service Center, Denver, Colorado, September 1999.

"snapshot" of time used for the risk evaluation process. The ability to model time-dependent deterioration processes is necessary in order to predict future performance and the associated change in risk or safety. This ability can, potentially, have a large impact on the decision-making process and influence funding to modify a structure to reduce risk.

3.1 Concrete Deterioration and Dam Safety

How does concrete deterioration affect dam safety? One effect of concrete deterioration is the loss of strength in an arch dam. As an arch dam weakens, the probability of an adverse response to a given load increases. There will come a time when the dam is unable to withstand either static, flood induced, or earthquake loadings. Clear Creek Dam in Washington, which was breached, suffered from a variety of deterioration mechanisms and the concrete properties diminished. Analysis of the dam identified a strong probability of failure because of static, hydrologic, or dynamic loading. The dam was breached, rebuilt as a more massive gravity structure, and returned to service. The probability of the catastrophic events did not change; it was the probability of an adverse response of the weakened structure that dictated the remediation efforts.

3.2 Risk Analysis for Cases of Deteriorating Concrete

Reclamation risk analysis procedures typically capture the risk at a particular point in time using an event tree approach. Often, analyses are needed to determine the behavior of the structures under the expected material properties and loadings in order to make probability estimates for nodes on the event tree. In the case of deteriorating concrete, it is useful to estimate how the risks will change with time. This allows for long term planning of remedial actions to extend the life of the affected structure. Realistically, estimating future risks requires tools to evaluate the rate of deterioration and change in properties of the concrete with time. Although development of these types of tools has begun, they are not to the point where useful predictions regarding structural response can be made. If these tools were available, structural analyses could be performed to evaluate the change in structural behavior with time by using the time varying conditions and properties. These analyses could be used to adjust the event tree probability estimates for different points in time to provide an estimate of how the risk will change.

Methods for Predicting Concrete Deterioration

Using physical properties of concrete predicted by models will allow for greatly improved methods of risk analysis. With the ability to estimate future performance, various repair or modification plans can be compared and the optimum risk-based solution developed.

For these models to work, they must incorporate information about the concrete structure, the concrete material used in the structure, and the exposure condition of the structure. In addition, the model must incorporate the reduction of material properties that normally occurs with concrete deterioration. The model should also be able to incorporate data from physical properties tests conducted at various times during the life of a structure or facility.

4.1 Concrete Deterioration Models

Currently, no comprehensive model exists that predicts rate of deterioration (and subsequently the remaining service life) for deterioration mechanisms that affect existing Reclamation structures. This is a very new area for concrete technology. As discussed below, attempts to use computer models to predict properties of concrete exposed to aggressive environments have just started.

4.1.1 Concrete Deterioration Model History

The first public domain software that evaluated durability (deterioration) of concrete was Grace Construction Product's DuraModel, which was introduced in 1997. That model could be used to relationally compare reinforcing steel corrosion protection alternatives. This model addressed only new designs, focused only on chloride ions, and was diffusion-based (one transport mechanism and one ion species). Shortly thereafter, a model with wider industry support, (Life 365[2]) was developed and introduced, for predicting service life and life-cycle costs of reinforced concrete exposed to chlorides. However, like DuraModel, its capabilities are limited. The Corps of Engineers published a method to predict F/T deterioration,[3] but their probabilistic model does not have a process for differentiating between known variations in material properties.

4.1.2 Prototype Model for Predicting Concrete Deterioration and Reclamation's Role

At about the same time as the development of Life 365, work began on a program called STADIUM. It has been in development for about 7 years and represents the work of predominantly three individuals: Dr. Jacques Marchand, Yannick Maltais, and Eric Samson. The work was also part of Maltais's and Samson's Ph.D. work at the University of Laval. However, for all practical purposes, STADIUM is used for only chloride and external sulfate attack and is one dimensional.

To improve the ability of the STADIUM software to handle more deterioration models and a structure's geometry, the software has been recoded and is now called SUMMA. The R.J. Lee Group, under a 2-year Small Business Innovative Research (SBIR) contract with the U.S. Navy, is working on adding capability to the SUMMA model. Work on extending the SBIR contract is underway.

When complete, the developers of SUMMA plan for it to be three dimensional; have strong corrosion, alkali-silica reaction (ASR), delayed ettringite formation (DEF, a form of internal sulfate attack), and carbonation modules; account for both saturated and unsaturated conditions;

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[2] Thomas, M.D.A., and E.C. Bentz, *Life 365–Computer Program for Predicting the Service Life and Life-Cycle Costs of Reinforced Concrete Exposed to Chlorides*. October 2, 2000.

[3] Bryant, Larry M., and Mlakar, Paul F., *Predicting Concrete Service Life in Cases of Deterioration Due to F/T*, Technical Report REMR-CS-35, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. March 1991.

include time dependant variation of exposures, moisture contents, and temperatures; handle cracked and uncracked conditions (but not new cracking as a result of deterioration); include life-cycle cost analysis tools; and provide expert guidance on repair techniques that takes into account the deterioration mechanism.

Through the Navy contract, Reclamation can specify development of new modules. For instance, with appropriate funding, Reclamation could specify development of an F/T deterioration module, an ASR module (suitable for Reclamation facilities), a coupled degradation module (impact of several deterioration mechanisms), and a module that incorporates the consequences of cracking caused by deterioration, as well as other needs.

Currently, the R.J. Lee Group partnership plans to join with representatives from each key organization supporting the SUMMA process and form a SUMMA Development Team. This team has not been finalized but the team would likely consist of Navy, Reclamation, Federal Highway Administration, Corps of Engineers, Grace, HNTB, and Holcim. The team may become an American Concrete Institute, Strategic Development Council consortia. By doing so, the group will be able to work with leaders throughout the concrete industry and have a forum for regular meetings.

The SUMMA Development Team will be responsible for providing direction for SUMMA development. At times, this group will meet to spend necessary time reviewing progress and other issues related to the development process. There may be up to about 10 other organizations contributing to the program, but their involvement with the core SUMMA process will be limited. Their roles will be to provide assistance in specific nuances of the model or field validation and process applications. Reclamation can direct development of specific deterioration models applicable to our structures by being a financial and technical partner of this team.

We estimate that the model is 3 to 4 years away from practical application for most Reclamation uses.

4.1.2.1 Other Uses of a Prediction Model

While this paper deals with the relationship of risk and ongoing concrete deterioration, having a model to predict deterioration of concrete could also play a big role in some operations and maintenance decisions. For example, arresting the surficial deterioration of a concrete stilling basin wall with an air-entrained concrete cap essentially eliminates the potential for freezing in the less resistant zone that is not air entrained and arrests the time-dependent F/T deterioration mechanism. Other repair scenarios and their impact on the service life of a structure could be evaluated and compared, and the least cost alternative selected.

Concrete Deterioration

Concrete deterioration is a progressive reduction in properties that may ultimately make concrete no longer serviceable for its intended use. This may be a physical "removal" of materials from the surface of the structure leading to a reduced cross section or an internal change in strength, modulus of elasticity, Poisson's ratio, or density that reduces its overall structural load-carrying capacity. For example, surface deterioration and loss of material caused by F/T deterioration of concrete can lead to a reduced cross section of a concrete dam. The reduced cross section increases the stresses of the remaining section proportionately to the amount of material removed. As another example, internal expansion of a concrete structure caused by AAR may reduce the strength and modulus of elasticity of the entire structure. Swelling and cracking of concrete outlets or spillways caused by AAR leads to reduced structural performance, and the cracking may accelerate other deterioration mechanisms, such as F/T deterioration.

It is commonly assumed in the absence of any active deterioration that concrete will continue to gain strength for a long period of time. However, this is true only in situations where concrete stays consistently moist and is not subject to deterioration. For instance, laboratory data on controlled experiments (figure 9 of the Concrete Manual[4]) shows that concrete strength generally increases up to the time that moist curing is removed. Following the withdrawal of moist curing, the compressive strength of concrete can decrease. In addition, the combined effect of deterioration and cyclic loading may be very detrimental. Cyclic loads, even at relatively low stresses, may cause permanent strains to accumulate. It is possible that, if the loads are high enough relative to the concrete strength, these strains may intercept the failure curve of the stress-strain plot, resulting in failure at low stresses.

5.1 Concrete Deterioration Processes

There are several known processes of concrete deterioration. These include physical and chemical processes acting on the inherent structure of the cement and concrete and processes related to "flaws" in construction that may impact the safety of the structure. The following sections describe typical deterioration mechanisms acting on Reclamation's concrete infrastructure.

5.1.1 Freezing and Thawing Deterioration

F/T attack is a form of internal disruption of the concrete paste caused by the formation of ice crystals in saturated or nearly saturated concrete. F/T deterioration is particularly severe in the northern and mountain zones. These years may experience 50 to 100 cycles of F/T each year. Deterioration is especially severe in the splash zone of Reclamation hydraulic structures experiencing F/T cycles. Ice expands about 9 percent upon freezing, causing forces of up to 30,000 lb/in^2, which is sufficient to crack concrete if it is not protected against this action. F/T deterioration is a progressive attack, generally from the exterior of the concrete inward. As some of the concrete fails and is removed by spalling, the depth of freezing progresses inward.

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[4] Concrete Manual, 8th edition revised reprint, U.S. Department of the Interior, 1981.

The earliest concretes made by Reclamation were not very frost resistant, failing in as few as 50 to 100 F/T cycles. As the compressive strength of concrete increased, the F/T resistance increased, but the concrete still typically failed in about 200 cycles.

In the late 1930s, it was discovered that entraining tiny air bubbles in the concrete protected it from the expansive forces of freezing water. However, those Reclamation structures constructed up to about 1945 are vulnerable to F/T attack. Modern frost resistant concrete should normally resists well over 1,000 cycles of F/T.

5.1.2 Alkali-Aggregate Reactions

AAR is a chemical reaction between the alkalis in cement and certain "reactive" aggregates that produces a gel that will expand in the presence of water. AAR gel is sufficiently expansive to fracture aggregates and concrete paste and cause the concrete to swell and crack. Dams experiencing AAR have been known to swell as much as one foot in height and length.

AAR occurs in two basic forms: ASR and alkali-carbonate reaction. In the United States, ASR is common in western parts of the country. ASR can occur in concrete containing cements having an alkali content greater than 0.6 percent and glassy siliceous volcanic rocks and other potentially deleterious rock types such as chert, opal, shale, and certain quartzitic rock.

Several Reclamation structures experienced ASR, beginning in the mid-1920s. Reclamation did not fully understand the causes of the deterioration. Some of the notable dams suffering from ASR include American Falls (Idaho), Owyhee (Oregon), Seminoe (Wyoming), Friant (California), Parker (Arizona), and Stewart Mountain (Arizona). Typical deterioration includes swelling and cracking of the concrete, accompanied by a decrease in strength and modulus of elasticity. The cracking also provides avenues for moisture to enter the concrete and contribute to accelerated F/T attack in cold climates. Methods to prevent ASR were identified by 1942 and included identifying potentially reactive aggregates using petrographic techniques, limiting their use, and specifying low-alkali cements and pozzolans.

5.1.3 Sulfate Attack

Sulfate attack is both a chemical and physical attack of the internal microstructure of the concrete paste. Sulfates in groundwater and soil can migrate into the concrete and cause an expansive disruption of the paste, leading to cracking and failure of the concrete. Severe sulfate attack can disrupt and fail concrete in as little as 5 years or less.

Physical sulfate attack involves saturation of porous concrete with sulfates that, under certain drying conditions, can precipitate as crystals within the cement matrix, disrupting its internal structure. Chemical sulfate attack is a chemical reaction between sulfates and cement hydration products that forms expansive compounds and causes dissolution of the paste. Chemical sulfate attack is common in the "alkali flats" of the Western United States, where high evaporation rates cause sulfates to concentrate in the upper soil strata. Most forms of sulfate attack occurred in concrete made with cements high in tricalcium aluminate. Most forms of sulfate attack were eliminated by introduction of sulfate resistant cements in the mid-1930s.

The first documented occurrence of sulfate attack on a Reclamation structure was about 1908. The attack, was on submerged concrete structures near the waterline on the Sun River Project in Montana. Examples of sulfate attack in spillways are documented in tests performed on concrete cores from the south spillway at Guernsey Dam, Wyoming,[5] and Alcova Dam, Kendrick Project, Wyoming. Both dams are located in areas which are now known to have potential for high concentrations of sulfates and were built before the first sulfate resisting cements were specified by Reclamation (also on the Kendrick Project in 1937).

5.1.4 Abrasion-Erosion and Cavitation Damage

Abrasion-erosion damage is a physical wearing of the concrete by water-born sediments, gravels, and rocks. Abrasion erosion damage can be caused both by concrete with low strength and poor aggregates and by design related problems that may sweep rocks and sediments from downstream back into spillway and outlet works stilling basins, resulting in particles abrading the surface in a roller-mill fashion. Abrasion erosion damage can be quite severe in large dams and in the sandy rivers of Kansas and Nebraska. Examples of other stilling basins that have experienced this problem include Grand Coulee (Washington), Canyon Ferry (Montana), Yellowtail Afterbay Dam (Montana), Ridgeway (Colorado), Folsom (California), A.R. Bowman (Oregon), and Choke Canyon Dam (Texas).

Cavitation damage is caused by the formation and subsequent collapse of sub-atmospheric water vapor “bubbles,” releasing tremendous positive pressures on the surface of the concrete. Cavitation damage is a particular concern for high-velocity water flows in spillways and outlets. Cavitation is aggravated by aggregate popouts, construction related offsets, and deposits of carbonates (leaching product from concrete). Dramatic cavitation and subsequent erosion of the emergency spillways at Glen Canyon Dam in 1983-84 required reconstruction of the spillways and installation of “air slots” to aerate the spillway flows. In outlet works, cavitation can be caused by insufficient air supply to gates, defective construction, and sometimes by the way the gates are operated.

Both abrasion-erosion and cavitation damage can be reduced by using high-strength concrete, changing the design and operation of spillways and outlets, and eliminating of significant construction offsets. Modern repair materials with compressive strengths of up to 15,000 lb/in^2 are now used to provide greater abrasion-erosion resistance to areas prone to damage from abrasive particles and rocks.

5.1.5 Other Deterioration Mechanisms

Several other mechanisms may act on Reclamation structures and either cause damage themselves or accentuate other more common forms of deterioration. These forms of deterioration include acid attack, chloride contamination (resulting in reinforcing steel corrosion), wetting and drying volume change, and carbonation shrinkage. Though these forms of deterioration are severe, most Reclamation structures are not significantly affected by them. Reclamation structures are not normally exposed to severely corrosive environments or environments high in chloride, as are many of the nation’s roads and bridges. Damage as a result of corrosion of reinforcing steel is often associated with defective construction practices resulting

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[5] Memorandum from Head, Chemistry, Petrography, and Chemical Engineering Section to Chief, Dams Branch dated June 3, 1982.

in inadequate concrete thickness over reinforcement. The 2003 ICOLD Congress in Montreal, Canada, cited potential safety concerns for corrosion of trunion pins in spillway gates caused by carbonation-induced shrinkage cracking and a subsequent drop in passive resistance to corrosion provided by the high pH of cement paste. In addition, aging concrete and masonry dams in Europe have suffered from increased porosity of the cement paste because of leaching of calcium hydroxide.[6] There is potential for leaching induced degradation in Reclamation dams constructed before about 1920.

5.1.6 Concrete Quality and Construction Practices

Concrete quality and construction practices are frequently related to state-of-the-art developments and improvements in technology. These include improvements in the process of proportioning and controlling concrete mixtures, improved concrete batching, mixing, placing, and consolidating techniques, increased concrete production rates, improved inspection practices, and special cements and admixtures for improved durability. Deterioration can occur in concrete structures constructed before these improvements were made in practices or because of unforeseen mistakes.

One of the most significant improvements in concrete mixture proportioning was the "water-cement ratio law" to control the strength of concrete. The basic provision of the "law" is that lower water content results in stronger, more durable concrete. The development of volumetric and weight mixture proportioning methods allowed consistent control of the mix water and other ingredients into concrete. Excessively "wet" mixtures were common from about 1905 to about 1935. One cause was the inability to consolidate dry mixes with rodding, spading, and manual tamping methods. Another practice called "chuting" involved transporting concrete down elaborate chutes strung up across canyons. If the chute slope was flatter than about 35 degrees, more water was added to "flow" the concrete, resulting in weaker concrete and poor quality construction joints. The introduction of "highline" buckets to place concrete at Owyhee Dam allowed for placing mass concrete with lower water contents. The mechanical vibrator first introduced at Hoover Dam in 1934 allowed for a 10 to 15 percent reduction of water content in mass concrete at a slump (measure of consistency) of 2 inches or less. This also decreased the cement content of mass concrete resulting in less cracking.

One "flaw" which significantly impacts concrete performance is the presence of "cold joints" and construction joints caused by unplanned or planned interruptions in construction. The earliest concrete structures have more of these flaws due to the slow placement rates typical of early Reclamation construction. Many early structures contain concrete placed at rates as low as 25 cubic yards per day, a tenth the rate of modern structural concrete construction and a hundredth the rate of mass concrete construction. The major concern with cold and construction joints is the potential for higher porosity, weakened shear and tensile strength, and decreased durability of these zones. The methods of cleaning construction joints steadily improved as concrete quality and cleanup methods improved through the 1920s and 30s. The introduction of concrete vibrators, high production rates, and high pressure cleaning methods for Hoover Dam signaled a dramatic improvement in construction joint cleanup.

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[6] General Report–Question 82, *Ageing and Rehabilitation of Concrete and Masonry Dams and Appurtenant Works*, 21st International Congress, International Commission on Large Dams, Montreal, Canada, June 2003.

When to Consider Concrete Deterioration During a Risk Analysis

Deciding whether to include concrete deterioration in a risk analysis needs to be based on knowledge of the development of durable concrete and on specific information related to the actual structure under consideration. Improvements in concrete durability followed a developmental "timeline" that can be tracked. Structures can be placed on this timeline to identify whether deterioration might be a concern.

A dam safety risk analysis process must recognize the history of each structure and identify the susceptibility of the structure based on the conditions encountered at the site. The screening process to determine if deterioration should be considered in a risk analysis encompasses some of the following questions:

- When was the structure constructed?
- What are the properties of the concrete (to the extent known)?
- What construction equipment and methods were used and what potential "defects" may have resulted from these methods?
- What are the environmental conditions and loading on the structure?
- What deterioration mechanisms (if any) may be acting on the structure?
- Is the structure resisting these deterioration mechanisms?
- What is the rate of deterioration?
- What dam failure modes are being affected by this deterioration?

To aid teams in answering questions about durability in a risk analysis, durability timelines are presented in Appendix . Appendix presents a discussion of the development of durable concrete and documents timelines for discovering concrete deterioration mechanisms and improvements in concrete construction

The discussions below present information about significant issues that impact concrete durability and deterioration. These issues likely would have an impact in a risk assessment process that considers concrete deterioration.

6.1 Concrete Material Properties

Reclamation's concrete structures encompass a variety of designs, materials (cement, aggregate, and other additives), construction techniques, operating requirements, ages, and environments. Thus, there is no "one size fits all" solution to evaluating the risk due to concrete deterioration. Just as one structure is more vulnerable in a seismically active zone than it would be in a seismically inactive zone, another structure constructed in an F/T environment may be much more susceptible to deterioration than the same structure constructed in a more temperate climate. For example, Arrowrock Dam in Idaho, Lahontan Dam in Nevada, and Elephant Butte Dam in New Mexico were all constructed before 1920 using "sand cement," a mixture of finely ground rock powder substituted for cement to reduce cost. Concrete using this technology has poor resistance to F/T attack. The F/T deterioration at Arrowrock was so severe that the dam and spillway have undergone several repairs, beginning in the mid-1930s and continuing into the 1990s, to protect the concrete from further deterioration. Significant repairs were performed at Lahontan spillway in the 1970s. However, Elephant Butte Dam, with the same type of concrete and similar strengths has not experienced any significant F/T deterioration because of the drier conditions and milder climate in New Mexico. These structures had essentially the same resistance to deterioration, yet it was the climate that dictated the rate of deterioration and need for repairs.

A thorough knowledge of the material properties of the concrete and historical trends in quality concrete construction are critical components of predicting concrete deterioration and its impact on risk analysis. This information should include, to the extent practicable:

- The physical properties of the concrete as it was placed
- The mixture proportions of ingredients used in the concrete
- The physical and chemical properties of the ingredients
- Information about how the concrete was mixed, placed, and cured
- Results of testing that may have been conducted during or after construction

Knowledge of the original concrete properties provides the basis for informed decisions regarding risk. A screening process can be used to identify candidate structures with a higher probability of deterioration and thus potentially increasing risk with age. Structures with a high potential for deterioration should also be candidates for increased long-term risk.

6.2 History of Concrete Service

A risk analysis of concrete deterioration must consider the durability timeline of each structure (the appendix discusses in detail the development of timelines for durable concrete) and identify the susceptibility of the structure based on the conditions encountered at the site.

Implementing a Deterioration Related Risk Analysis Process

Implementing a deterioration related risk analysis methodology is envisioned as a three step process. This basic process would be used for both risk evaluations and operations and maintenance decisions. The first step, initial screening of susceptibility, involves placing the structure on a basic timeline for durable concrete construction as shown in figure 1. The initial screening of susceptibility begins with project completion. This screening identifies the potential for durability related issues. Structural and environmental exposure should also be considered. For example, early thin arch dams are more vulnerable to structural overloading by deterioration simply because there is less mass; i.e., the structural member cross section does not have significant sacrificial concrete to loose, whereas more massive structures could loose significant cross section before overloading becomes a concern.

This process is intended as a screening for vulnerability to deterioration. More complete information for specific structures is necessary before this vulnerability to deterioration is manifested in the field.

The project completion date identifies the potential for vulnerability and begins the process for determining site specific related durability issues. This may include AAR for dams constructed before 1942 or F/T deterioration for dams completed before about 1948. Figure 2 shows a more specific timeline to screen for susceptibility to F/T. Here, the timeline begins with the vulnerability based on age and becomes more specific based on cycles of F/T at the site and the presence of moisture in the concrete during those F/T cycles.

The next step evaluates the likely exposure conditions. For example, F/T exposure is determined by the number of F/T cycles typically experienced at the site and the degree of saturation of the concrete during these cycles. For instance, Mormon Flat Dam on the Salt River Project and Black Canyon Diversion Dam on the Boise Project were completed at about the same time; 1923-24; and, essentially, have the same inherent resistance to F/T attack. However, Black Canyon Dam suffers from extensive deterioration because of its location in Idaho, and Mormon Flat Dam is little affected by F/T (though it may have other durability-related issues) in Arizona.

Figure 3 shows a timeline for screening the susceptibility to AAR and figure 4 shows a timeline for screening the susceptibility to sulfate attack, respectively.

After these screening evaluations, the next step is to evaluate the initial degree of risk. This includes structural analyses based on identification of potential failure modes. Concrete deterioration in itself will not normally result in a dam safety deficiency. Rather, ongoing deterioration can encroach on the static stability, or reduce the stability under hydraulic or seismic overload. The longer the structure is allowed to deteriorate, the greater is its exposure to hydraulic or seismic overload events.

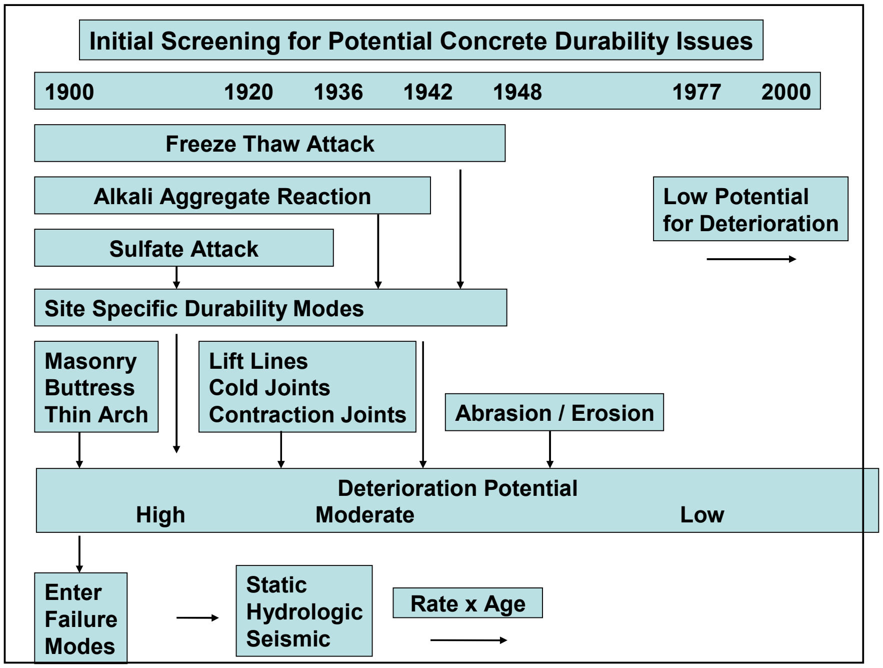


Figure 1.—Initial screening of susceptibility to durability related deterioration mechanisms based on construction completion date.

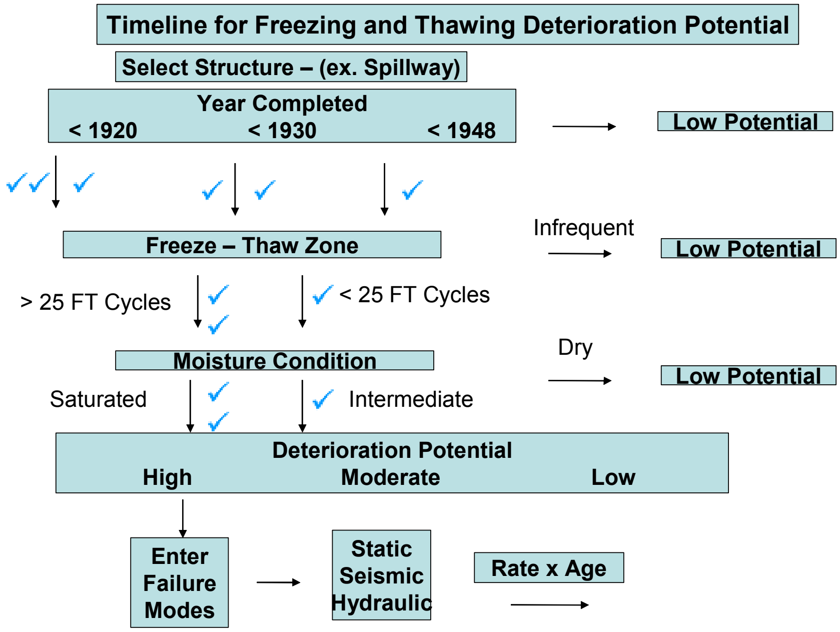


Figure 2.—Decision tree and associated timeline for determining susceptibility to F/T deterioration for concrete structures.

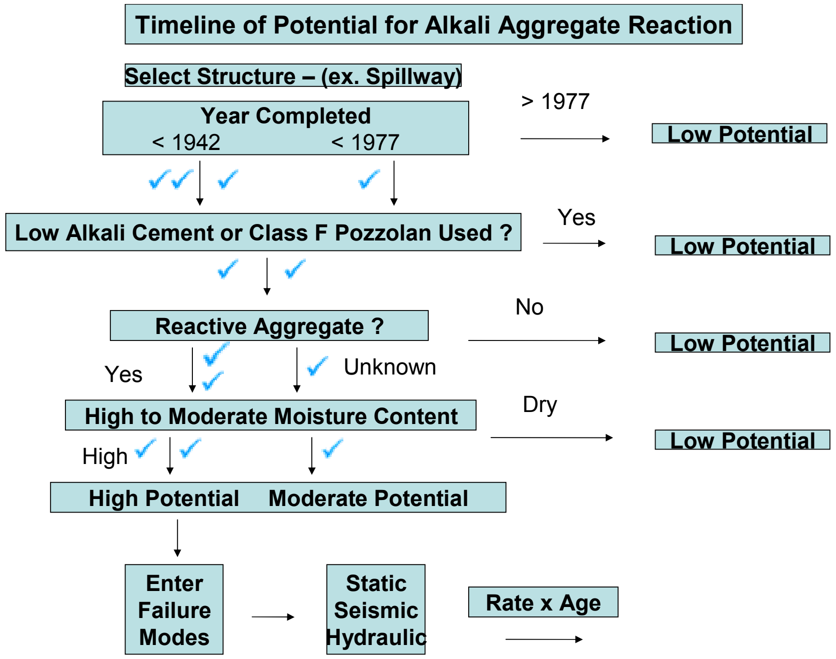


Figure 3.—Decision tree and associated timeline for determining susceptibility to deterioration caused by AAR for concrete structures.

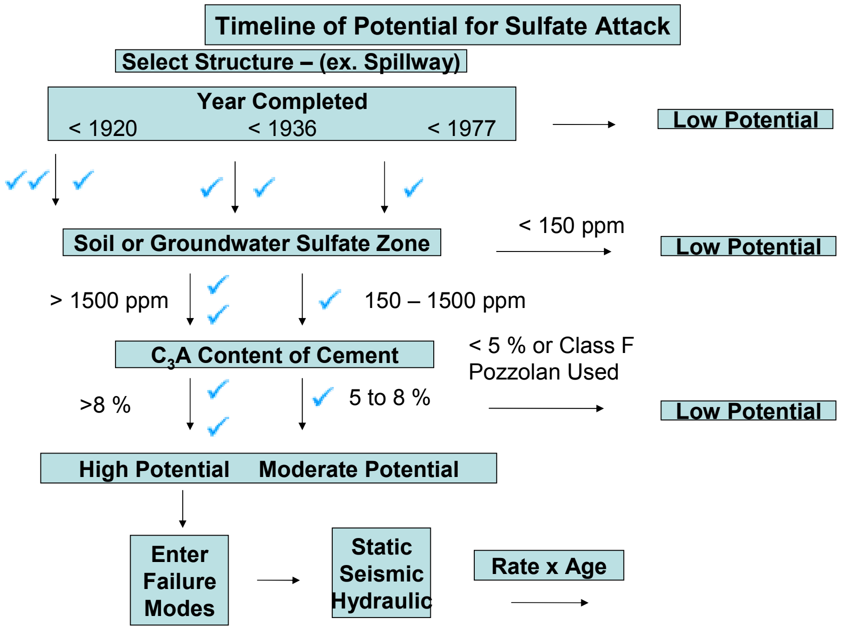


Figure 4.—Decision tree and associated timeline for determining susceptibility to deterioration caused by sulfate attack for concrete structures.

Potential Dam Safety Failure Modes Associated with Concrete Deterioration

For the purposes of this study, dam failure is defined as the uncontrolled release of life-threatening reservoir flows. Generalized failure modes are described below for various types of concrete deterioration and shown in detail on the attached event trees. It should be noted that the failure modes described below are general. Site specific structural conditions and loadings could alter the evaluations. All applicable loadings should be considered. Seismic loadings in particular could result in failure of a structure already damaged by concrete deterioration.

8.1 Freeze-Thaw Damage

This is generally a relatively slow deterioration process. However, as the concrete deteriorates and spalls away, the depth of deterioration can increase and travel into a structure. For instance, it is not unusual to see F/T damage progress into a structure along faulty and leaking joints and lift lines.

8.1.1 Concrete Dams

8.1.1.1 Arch Dams

Loss of section at leaking lift lines or contraction joints leads to overstress in compression or excessive bending. Overstress could also be in tension or shear, especially for seismic loads. Keyed contraction joints may help reduce the problems with bending, but would not necessarily mitigate leakage and loss of section. This could result in the loss of arch action and collapse of the dam. This failure mode could be triggered under static, hydrologic, or seismic conditions, although it would be more likely under seismic loads.

8.1.1.2 Gravity Dams

Loss of section and bond along leaking lift lines leads to increased tension at the heel and cracking. This could result in increased uplift along lift lines and sliding collapse of the dam. Deterioration along leaking contraction joints could aggravate the problem. If the contraction joints are keyed, load could be transferred to adjacent monoliths, if they are not compromised in a similar manner. This failure mode could be triggered during static, hydrologic, or seismic conditions, although it would be more likely under hydrologic or seismic loads.

8.1.1.3 Buttress Dams

Loss of cover on steel reinforcement leads to increased compressive and tensile stresses in the concrete. This could result in collapse of slabs or arch barrels in bending, collapse of struts in compression or buckling, or failure of buttresses in bending or shear. This failure mode could be triggered during static, hydrologic, or seismic conditions, although collapse of struts leading to buttress and dam failure would be likely only under seismic loads.

Reclamation has repaired concrete dams that were damaged by F/T deterioration, ultimately to maintain serviceability of the structure and prevent the above types of failure modes. The repaired dams include Arrowrock (arch), Black Canyon (gravity), East Canyon (arch), Clear Creek (arch), and Santa Cruz (curved gravity). The water district has also made repairs to Thief Valley Dam (buttress).

8.1.2 Spillways and Outlets

8.1.2.1 Spillway Gate Structures

Loss of cover on steel reinforcement of the supporting concrete (piers, drum gate chamber walls, etc.) leads to loss of support anchorage or reduced concrete support strength. This could lead to misalignment of the gate such that it fails during operation (e.g., radial gate arm collapses) or collapse of the gate supports and gates. This failure mode could be triggered under static, hydrologic, or seismic conditions but would be more likely under hydrologic or seismic loading.

8.1.2.2 Spillway Chutes and Stilling Basins

Deterioration of the flow surface leads to cavitation, erosion, or hydraulic jacking (stagnation pressure issues) of the concrete. This could result in the loss of concrete and erosion of the underlying material. Under-cutting or head-cutting could progress to the reservoir and lead to uncontrolled release. This failure mode could occur only under hydrologic loading conditions.

8.1.2.3 Outlet Works

No critical dam safety failure modes could generally be identified associated with these features. Most outlet works have upstream and downstream control gates so that if one gate fails, the flows can still be controlled. Areas of outlet conduits that are normally inaccessible are usually submerged and not subjected to F/T conditions. Areas that are subjected to F/T conditions can be observed and repaired if they reach critical conditions.

Spillways with F/T deterioration that have been repaired to maintain serviceability and to prevent these types of failure modes include Guernsey, Tieton, Arrowrock, Ochoco, Lahontan, Warm Springs (at toe), Gibson, and Seminoe.

8.2 Alkali-Aggregate Reaction

AAR is treated separately here. However, it should be noted that this reaction can accelerate F/T deterioration for structures in cold climates and the two mechanisms should be considered together in these cases.

8.2.1 Concrete Dams

8.2.1.1 Arch Dams

Concrete expansion and generation of large loads at the abutments or thrust block can lead to foundation sliding failure (if weak potential sliding planes exist). This failure mode could occur under static, hydrologic, or seismic conditions, although seismic loadings would be more likely to trigger failure.

Expansion, movement, and cracking of the concrete can result in loss of strength and deterioration of elastic properties. The expansion could lead to large compressive arch stresses that locally exceed the reduced concrete strength locally leading to progressive collapse of the arches because of loss of arch action. This failure mode could occur under static, hydrologic, or seismic loads, but would be more likely under seismic conditions.

Expansion, movement, and cracking of the concrete results in loss of strength and deterioration of elastic properties. This can result in increased bending stresses or adverse cracking patterns (i.e., semi-circular pattern near crest) leading to concrete block movements, loss of arch action, and collapse. This failure mode could occur under any loading condition, but would be more likely under seismic loads.

8.2.1.2 Gravity Dams

Concrete expansion, movement, and cracking results in loss of strength and deterioration of concrete elastic properties. This could lead to loss of bond along lift lines, cracking at the heel, increased uplift pressures, and sliding failure. This failure mode could occur under any loading condition, but would be more likely during floods or earthquakes.

8.2.1.3 Buttress Dams

Concrete expansion, movement, and cracking results in deterioration of strength and elastic properties. This could lead to collapse of slabs or arch barrels in bending, eccentric loading on struts or slabs leading to failure by buckling, or buttress failure by bending or shear. This failure mode would be more likely to be triggered under earthquake conditions.

Concrete dams that have been repaired or replaced to maintain serviceability and prevent these failure modes for various loading conditions include American Falls (gravity), Wild Horse (arch), and Stewart Mountain (arch). The crest of Seminoe Dam was also sealed to slow the rate of deterioration.

8.2.2 Spillways and Outlets

8.2.2.1 Spillway Gate Structures

Expansion and cracking of support concrete leads to loss of anchorage or failure of the supports and collapse of the gates.

Expansion and cracking of support concrete leads to misalignment of the gates and subsequent failure upon operation (i.e., gate arm buckles and hinge pin fails.) These failure modes could occur during static, flood, or earthquake conditions, but would be more likely under floods or earthquakes.

8.2.2.2 Spillway Chutes and Stilling Basins

Concrete expansion results in buckling or misalignment of slabs or walls. Large flows could then get under the concrete and pluck the concrete, leading to erosion of the underlying material and under-cutting or head-cutting to the reservoir and uncontrolled release. This failure mode could occur only during floods.

8.2.2.3 Outlet Conduits

Normally inaccessible outlet conduits within embankment dams subjected to AAR present a special problem. Expansion, cracking, and loss of concrete strength could lead to misalignment or localized collapse of the conduit. This could expose the embankment materials to outlet flow, leading to undetected erosion that could progress to the reservoir and fail the dam. Backward erosion could occur only if the outlet flow continues to bring embankment material in from the upstream direction or if a seepage path is intercepted. If initiation of the failure mode is detected, closing the gates would prevent a breach, unless a breach in the conduit occurred downstream from the gates and intercepted a seepage path that continued to pipe. This failure mode would be the result of normal operations.

The Friant Dam spillway was repaired to improve serviceability and prevent failure under these conditions.

8.2.3 Sulfate Attack

Sulfate attack would normally be a concern only for spillway slabs and walls and for outlet conduits. Since this deterioration process results in concrete expansion, the failure modes described above for AAR would also apply. The Guernsey, Alcova, and Green Mountain Dam spillways have been repaired to improve serviceability and prevent failure caused by sulfate attack.

8.2.4 Abrasion Erosion or Cavitation

Damage can occur to spillway flow surfaces because of insufficient concrete strength or improper hydraulic conditions. This damage can occur without F/T damage, AAR, or sulfate attack. While this isn’t directly related to concrete aging, failure modes associated with this behavior should also be considered during dam safety evaluations. Spillways that have been repaired because of these conditions include Folsom, Fontenelle, Yellowtail, Seminoe, Kortes, Glen Canyon, Flaming Gorge, Blue Mesa, Hoover, Palisades, Navajo, American Falls, Anderson Ranch, and Hungry Horse.

Other Deterioration Mechanisms

9.1 Carbonate of Concrete

Carbonation of concrete resulting in shrinkage cracking and reduction in the pH of the cement paste (i.e., loss of passive resistance to corrosion provided by cement). Trunion pin fails due to corrosion of reinforcing steel or anchors.

9.2. Leaching of Calcium Carbonate

Leaching of calcium hydroxide and loss of strength in dams with high water to cement (W/C) ratios. Leashing could occur in porous concrete of mortar in masonry dams.

Economic Considerations

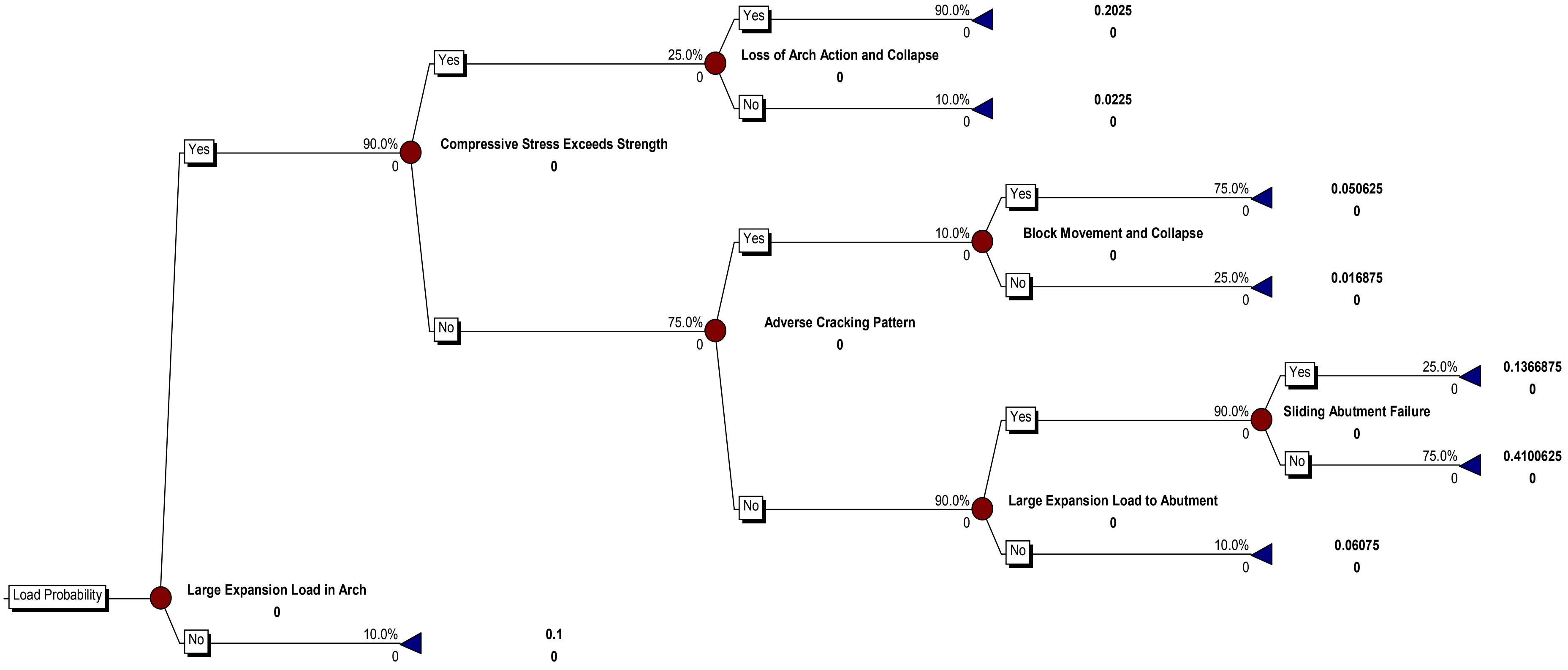
As the old saying goes, "You can pay me now or pay me later." Deterioration resulting from F/T damage, AAR, or sulfate attack will generally continue if left unchecked. Often, serviceability can be restored to original conditions if repairs are made in a timely fashion, but if the deterioration is allowed to progress, it will likely reach the point where the entire structure will need to be replaced. It may be more cost effective to repair a structure early in the deterioration process to save what is there than to wait until the structure needs to be replaced. This should be considered in evaluating the need to repair deteriorating concrete structures. The following example illustrates this concept:

Assume that concrete deterioration in a particular structure, if left unabated, would cause an undesirable risk of failure in 20 years and that replacement at that time, expressed in today's unit costs, would be $20 million. Based on the current federal discount rate of 5.875 percent, if repairs to avoid replacement in 20 years could be accomplished for less than $6,385 million, it would be more cost effective to repair now.

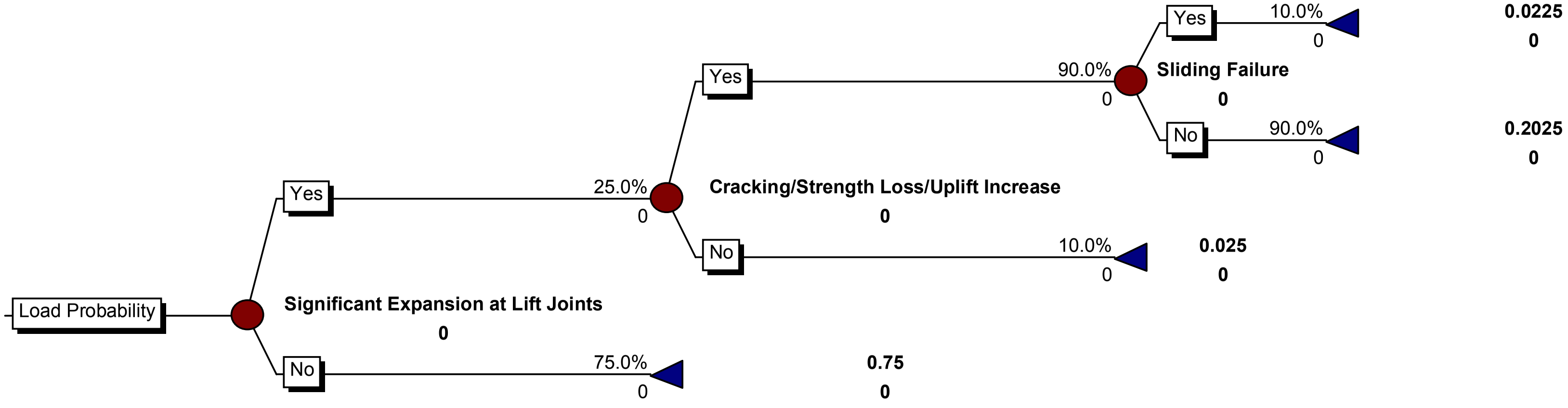
However, in the Safety of Dams Program, a higher level of analysis is required before those repairs can be justified. Even though current repairs may be the most cost effective *structural* solution to accommodate a future human safety issue, there may be *nonstructural* measures, such as a permanent reservoir restriction, dam abandonment, or installation of an emergency warning system, that need to be considered in the economic analysis. For example, in the above illustration, assume that project water is used to irrigate low productivity lands, and that a viable safety solution would be to lower the maximum reservoir elevation by 20 feet at no cost. Calculation of the lost benefits, in present value terms, would be required before the repairs could be considered to be the most cost effective solution. In this context, lost project benefits are considered to be costs. If the lost water benefits are less than the cost of current repairs ($6,385,000), no action would be taken until the structure has deteriorated to the point that a safety issue emerges.

Failure Modes–Examples

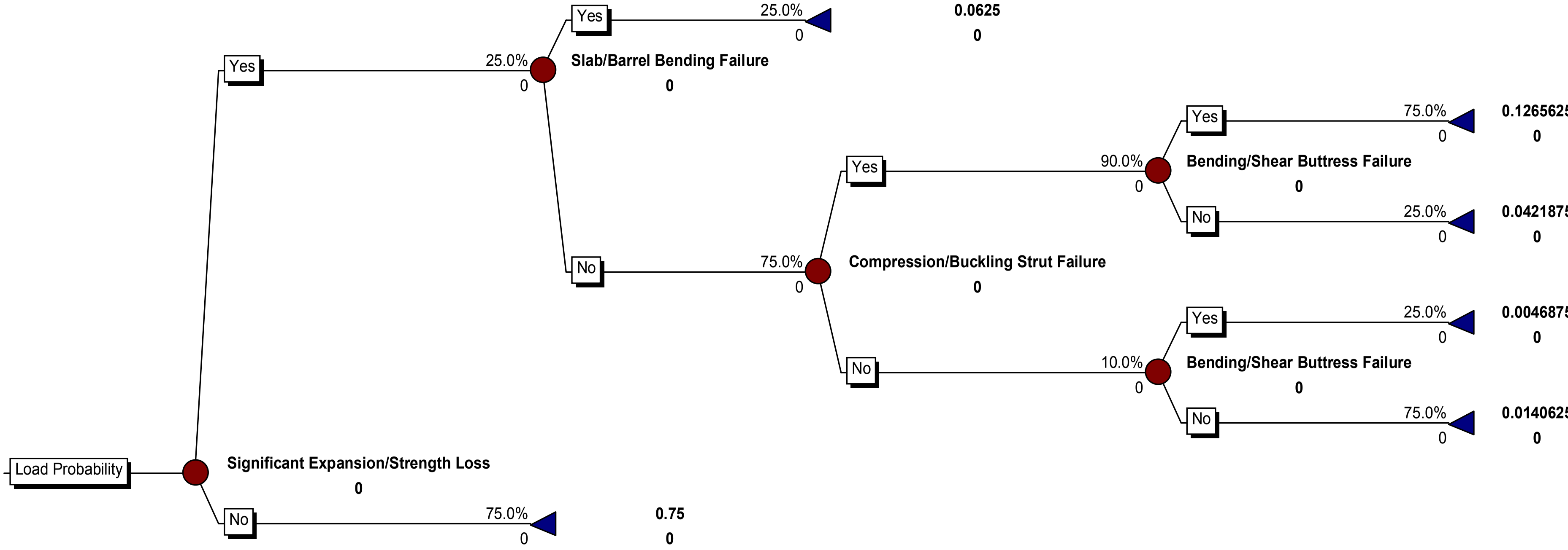
Alkali-Aggregate Reaction
Concrete Arch Dam



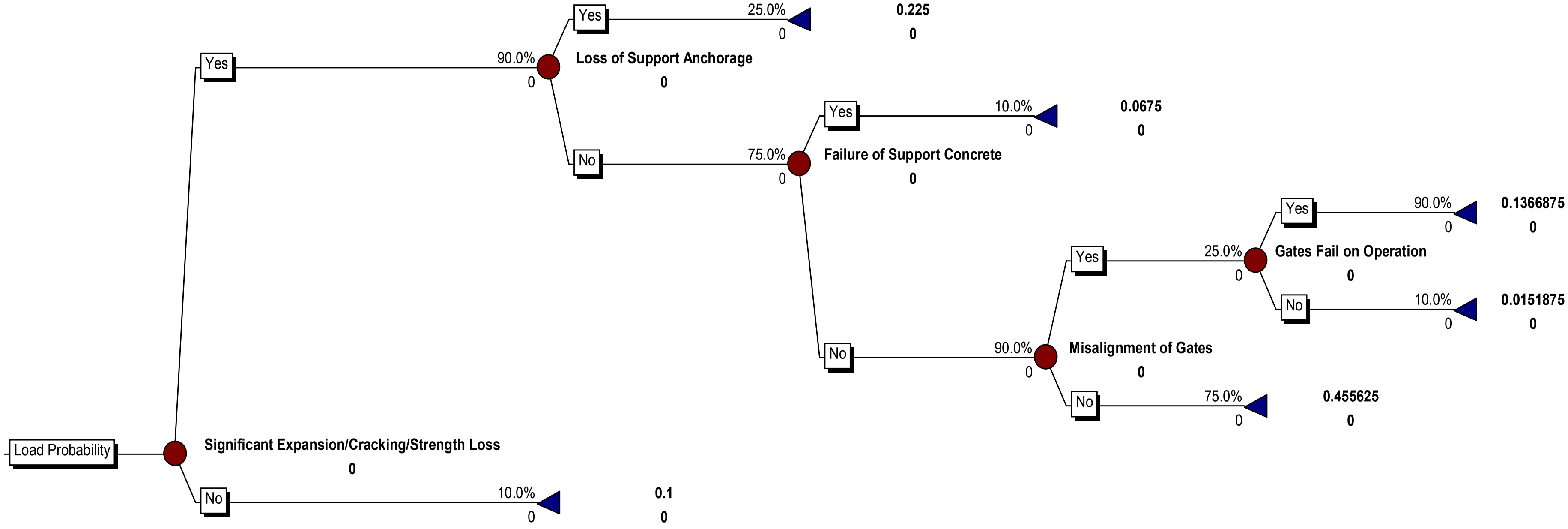
Alkali-Aggregate Reaction
Gravity Dam



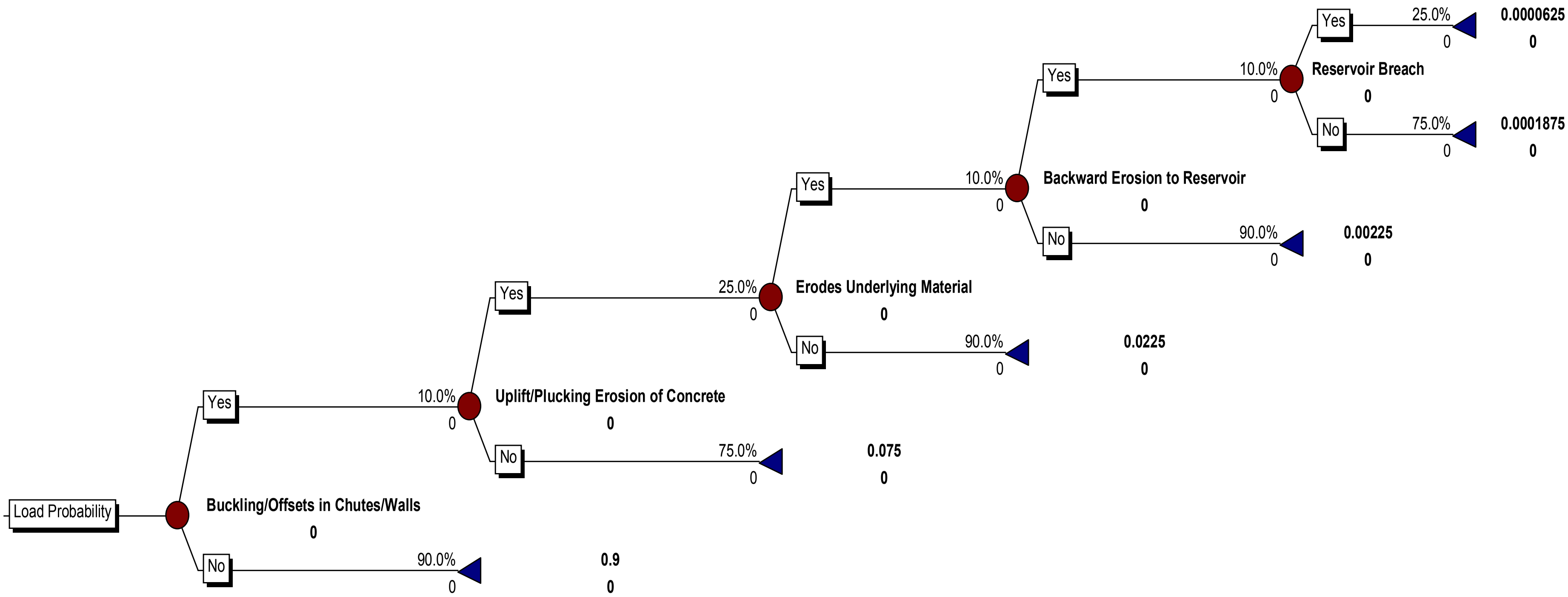
Alkali-Aggregate Reaction
Buttress Dams



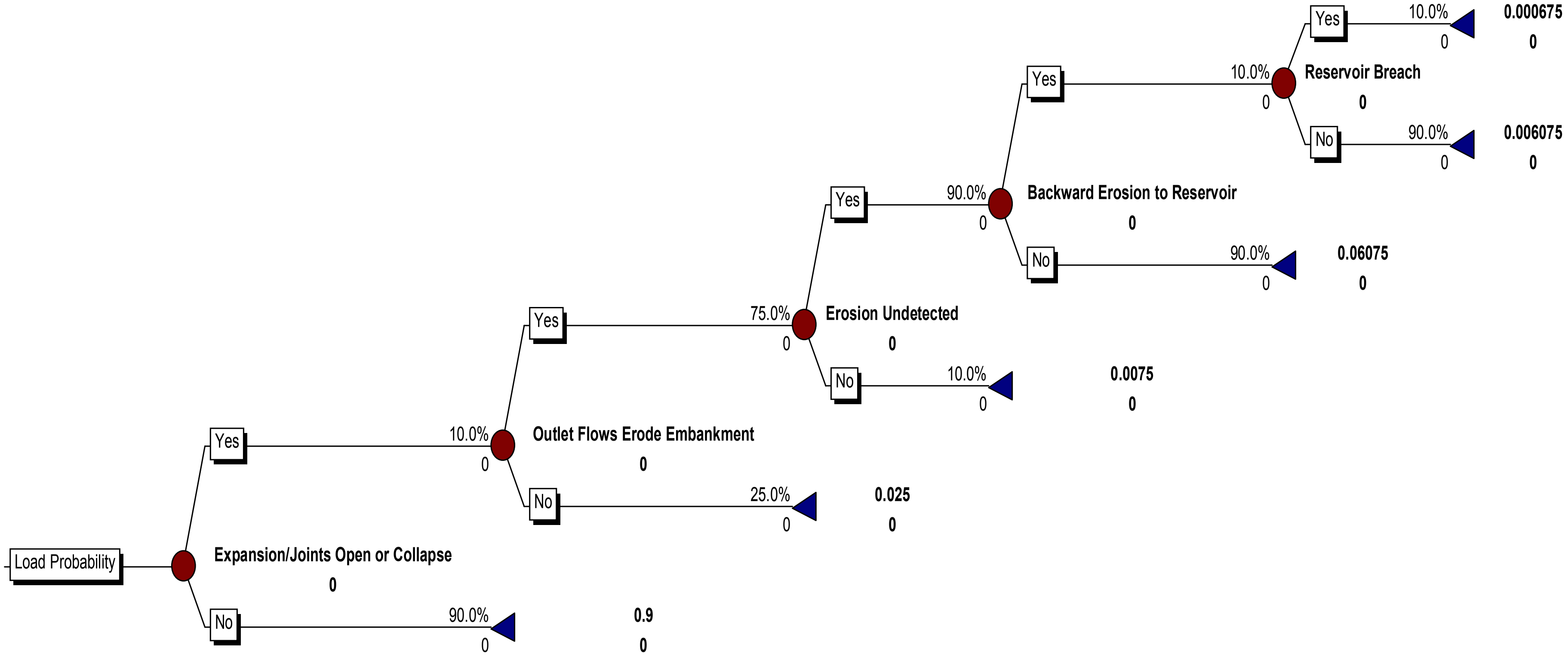
Alkali-Aggregate Reaction
Loss of Spillway Gate Support



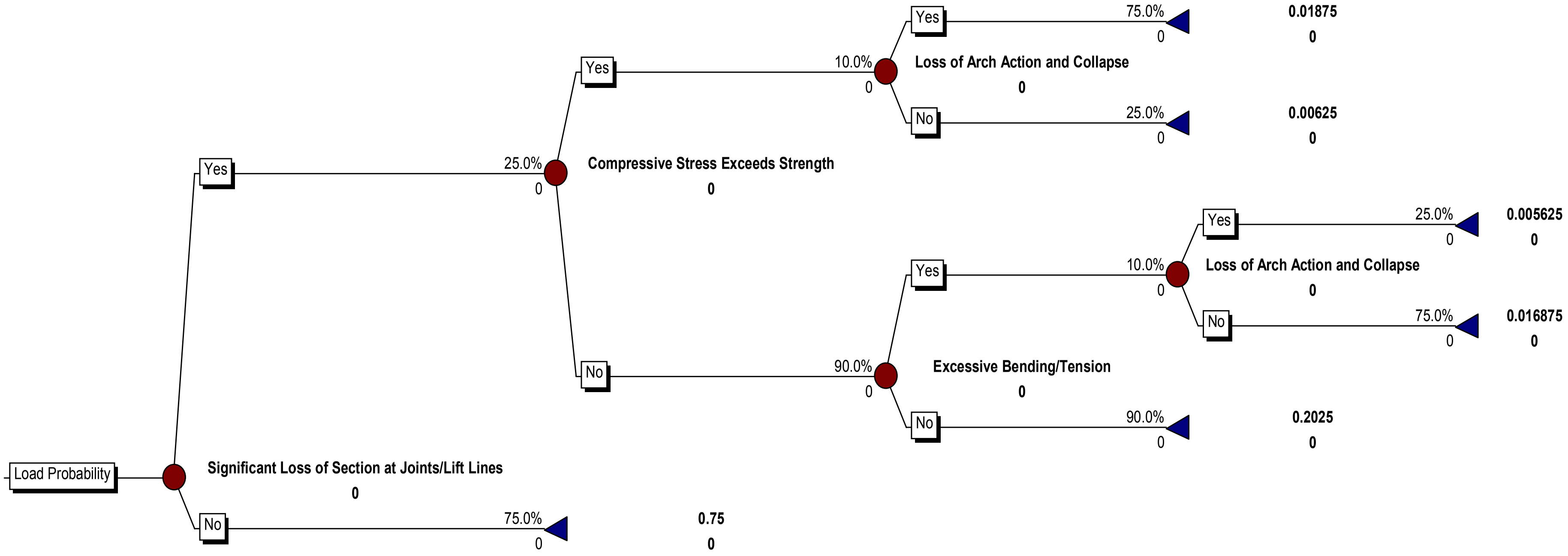
Alkali-Aggregate Reaction
Spillway Chutes and Stilling Basins



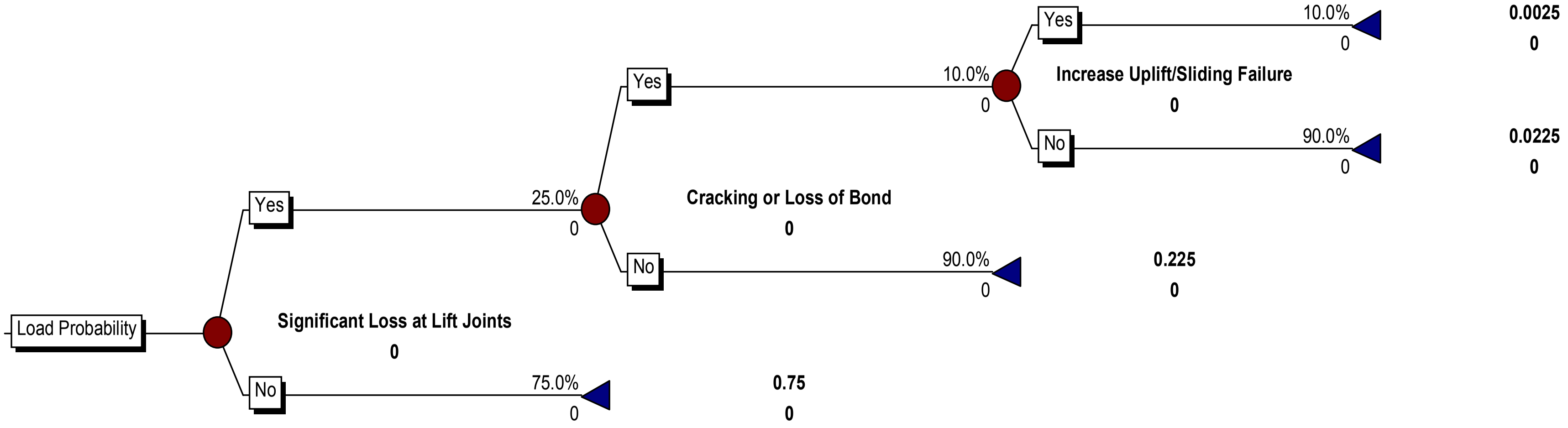
Alkali-Aggregate Reaction
Normally Inaccessible Embankment Dam Outlet Conduits



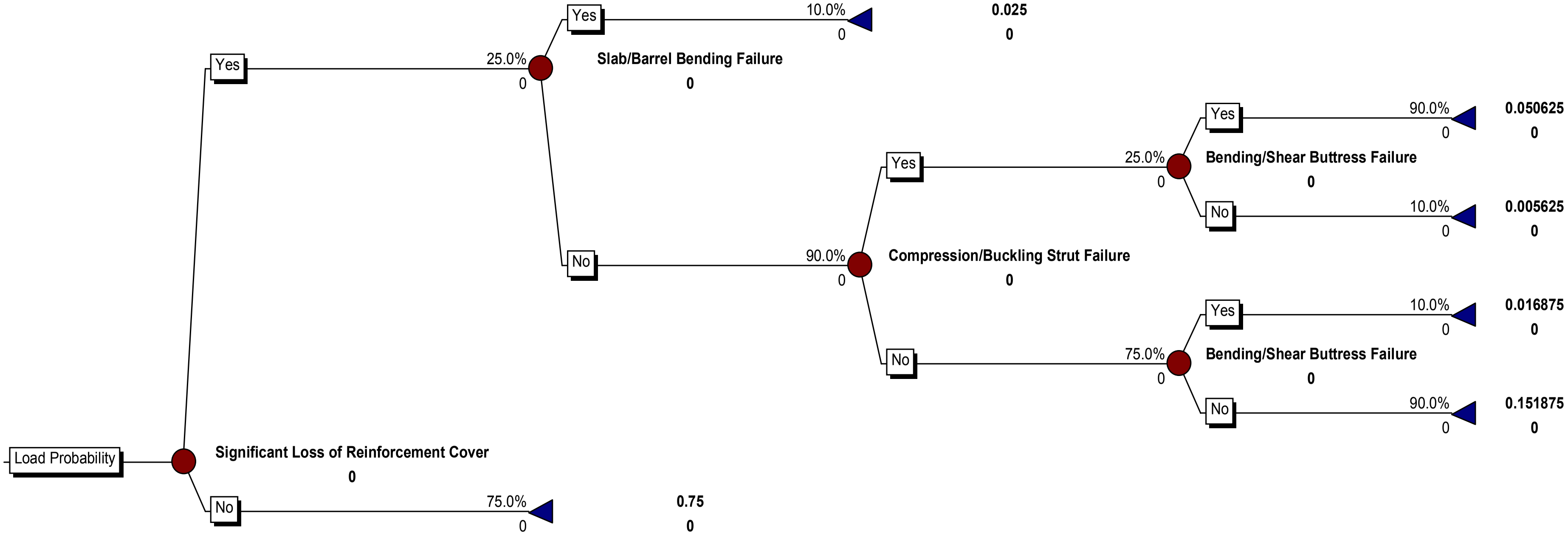
Freeze-Thaw Damage
Concrete Arch Dam



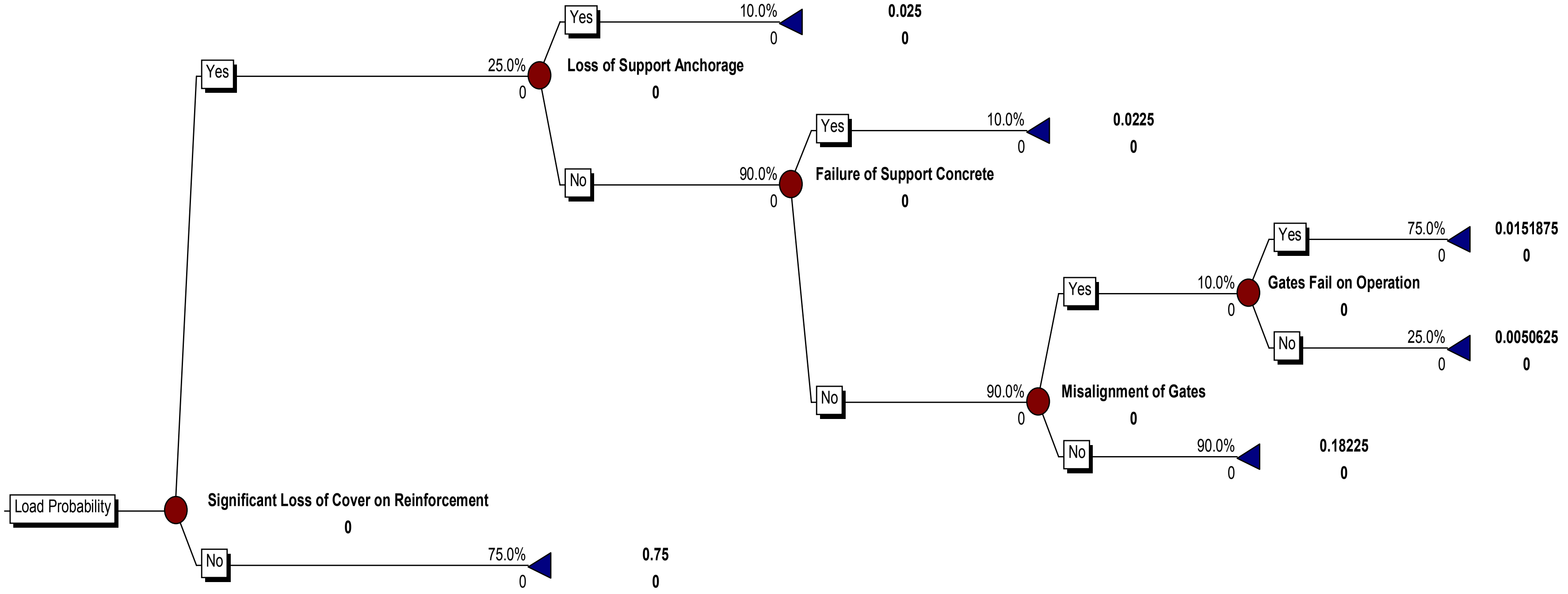
Freeze-Thaw Damage
Gravity Dam



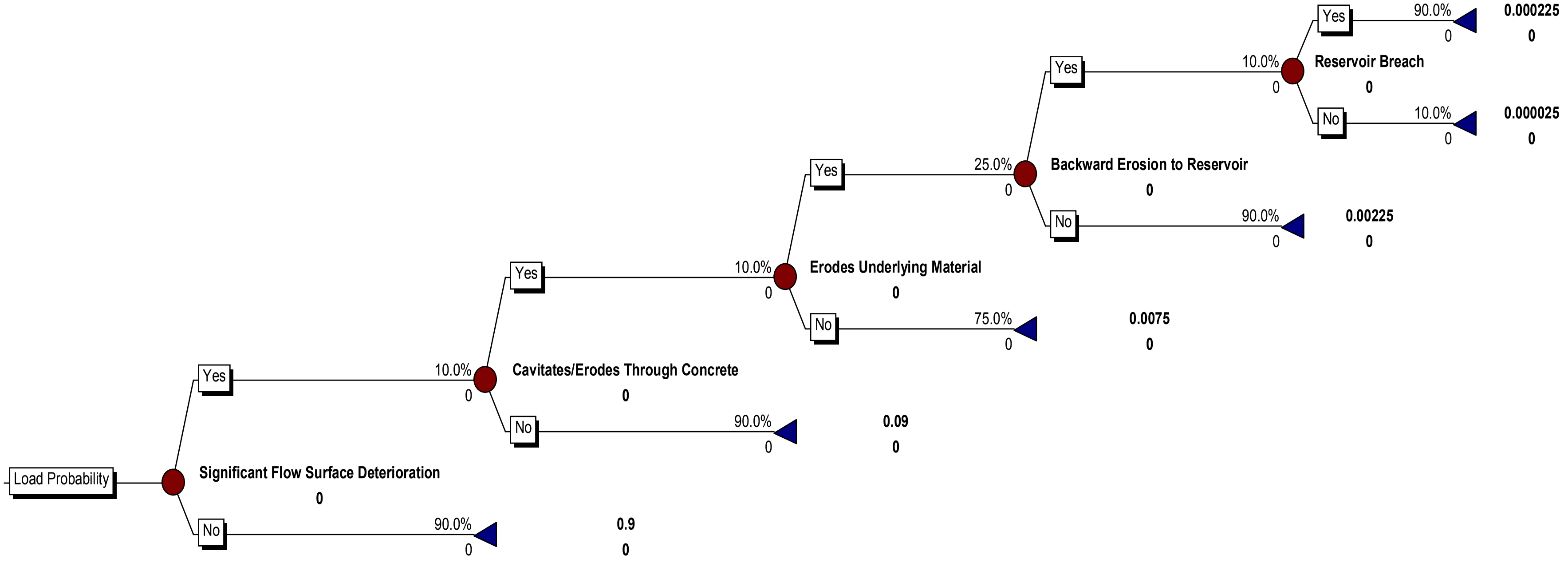
Freeze-Thaw Damage
Buttress Dams



Freeze-Thaw Damage
Loss of Spillway Gate Support



Freeze-Thaw Damage
Spillway Chutes and Stilling Basins



Appendix

Historical Development of Durable Concrete

Timelines for Concrete Deterioration and Improvements in Concrete Construction

Types of durable concrete can be divided into two principal groups: those concretes that are naturally durable as the result of favorable mix ingredients and an environment that does not aggressively attack the internal structure of the material and those purposely proportioned to remain durable in an environment that could attack their internal structure. Examples of naturally durable concrete are ancient structures such as the Roman Pantheon and aqueducts. These structures, composed of aggregates and a cementitious, lime-pozzolanic sand remain durable because they were constructed with methods that minimized the internal porosity of the mixtures, were in some way resistant to chemical attack, and were located in an environment that was less aggressive either chemically or physically. Other examples of naturally durable concrete include some structures in the southwestern United States, such as Hoover Dam. Here, concrete structures are not subject to repeated cycles of freezing and thawing (F/T) and chemically stable cements and aggregates were used during construction. Some concretes, such as were at Grand Coulee Dam, had superior F/T durability compared with other Reclamation concretes of that time. This was because of the exceptional quality of the concrete making materials combined with state-of-the-art mix designs and possibly because of "accidental" additives in the cement manufacturing process that led to greater F/T resistance.[7]

The Reclamation Durability "Timeline"

A ***timeline for the development of durable concrete*** can be used to identify those structures most susceptible to deterioration in aggressive environments. The timeline can be used to categorize Reclamation's infrastructure into those structures constructed before the state-of-the-art advances for durable concrete (and undergoing more severe deterioration processes) and those most likely to remain relatively free from long-term deterioration. Those structures most likely to suffer from deterioration may be in need of timely investment to maintain, upgrade, or replace their current condition. Identifying these deteriorating structures is essential to predict their future condition for evaluating long term safety and for budgeting future investment for increased maintenance expenses or replacement of concrete structures.

When developing a timeline for modern concrete technology, it may not always be possible to identify a *specific date* when changes in understanding resulted in new innovations or a *specific*

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[7] Moran, W. T., Bureau of Reclamation Viewpoint on Portland Cement Specifications*,* Annual Fall Meeting, General Technical Committee, Portland Cement Association, Denver, Colorado, September 29 to October 2, 1952, p. 3.

structure where such changes were first used. Often, a series of independent studies contributed to a collective understanding over a period of time that was punctuated by key discoveries that filled in the missing pieces to the puzzle.

Timelines for Quality Concrete Construction and Concrete Deterioration

The durability of concrete structures follows two timelines. One is the timeline of improved concrete construction methods and equipment. The other is the timeline of improved concrete making materials and methods that can increase concrete's fundamental resistance to deterioration processes. Generally, these two timelines overlap. As the quality of the concrete improved, the resistance to deterioration also improved. Concrete deterioration can proceed more rapidly if the overall quality of construction is poor. For instance, one dam failure mode is related to the quality of concrete construction joints. Bond between lift lines is essential for monolithic behavior of mass concrete dams. The method of preparing lift lines follows a timeline independent of any improved materials timeline and was affected by the general knowledge of construction methods and the available equipment for placing concrete. In addition, poor quality lift lines can aggravate other deterioration mechanisms such as F/T attack by providing a path into the concrete for moisture, which can accelerate some forms of deterioration. The following sections will first address the timeline for improved construction methods and materials affecting concrete quality and follow with the deterioration mechanisms acting on concrete. A timeline for improvements in construction methods and materials is shown in table A1 (at the back of this appendix).

Materials and Methods

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."[8]

Most 20th century concrete is 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-divided, calcined (heated to very high temperatures) particles of siliceous and alumina composition that are not cementitious themselves. Pozzolans react chemically with the calcium hydroxide liberated from cement hydration to form cementing compounds. Natural pozzolans are made during events such as volcanic eruptions. Artificial pozzolans, such as fly ash, are made in a kiln or furnace.. Fly ashes used in Reclamation structures are pozzolans that result from burning coal for power generation. The ratio of water to cementitious materials is about 1.5:1 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

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

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 1 month. The best concrete 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 W/C by weight. The weakest concretes are those that contain excess water or prematurely dry out, stopping the reaction. 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 byproducts of cement hydration is calcium hydroxide. Thus, 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.

Many different construction materials and methods were used to build Reclamation dams. Some of these materials and methods influence both the potential for and the rate of deterioration. For example, in the early 1900s, construction equipment for batching, mixing, transporting, and placing concrete was limited to small capacity mixers, horse drawn buggies, wheelbarrows, and shovels. The production rates were very slow; as low as 25 cubic yards per day, and “cold joints” were often formed throughout the day because of slow progress, and additional “construction joints” were formed when the day’s work was completed. The quality of the concrete mixes and the methods for cleaning lift lines affect the permeability and, thus, the durability of the concrete.

Concrete Materials

Early 1900s’ concrete is relatively weak compared with modern day concrete. Early 1900s’ concrete usually had a compressive strength of about 1,000 to 2,000 lb/in^2, and the mixtures varied considerably from batch to batch. The compressive strength of modern day concrete is usually 4,000 lb/in^2 or higher at 28 days age.

One reason for the lower strengths was lower quality cements. Early cements were not always resistant to chemical attack. The methods of controlling and documenting cement chemical composition were not fully understood. A particular experiment to economize cement was used on a few dams between 1910 and 1920. Some natural “pozzolans” were successfully used to improve concrete quality on the Los Angeles Aqueduct. Construction forces for two concrete dams constructed by Reclamation (Arrowrock and Elephant Butte) added up to 40 percent finely ground sand substituted for cement with the assumption that the sand would act like a pozzolan. Unfortunately, these materials were not calcined and, though the mixes were somewhat more workable and cheaper, they did not provide any significant long-term strength gains. The concretes manufactured from this “sand cement” were not very durable in F/T environments.

In addition, the quality of aggregates used in early concrete was sometimes inferior. The standards for quality aggregates were not implemented until the 1920s. Sand may have contained undesirably fine particles such as silt and clay and was poorly graded. Quality standards for cements and aggregates were in their infancy.

A major advance was the use of various chemical additives (called chemical admixtures) to improve concrete quality. Chemical admixtures were not introduced in concrete until the late 1930s, although some "grinding aids" added to some cements during their manufacture may have accidentally improved the performance of some concrete.

Mixture Proportioning and Batching Methods

Duff Abrams[9] is credited with developing, in 1917, the first consistent method for proportioning concrete of equal strength and workability using different materials. His methods dramatically improved the quality of concrete throughout the United States. Abrams' "water to cement (W/C) ratio law" was the first to consider that the proportions of both water and cement must remain constant to achieve equal concrete compressive strengths. His development of the concept of "fineness modulus" of aggregates allowed the proportioning of concrete mixtures with similar workability using different combinations of sands and gravels. The slump test was developed to maintain concrete consistency from batch to batch and to compensate for changes in moisture in aggregates. The W/C ratio was originally expressed in terms of volume of cement, in sacks, to cubic feet of water. Thus, a W/C ratio of 1, by volume, is 1 cubic foot (62.3 lb) of water to 1 sack (94 lb) of cement. A timeline for durable concrete shows the marked improvement in concrete strength consistency after Abrams' W/C ratio law was introduced.

The change from volumetric to weigh batching in the mid-1920s resulted in improved concrete durability by providing greater control of the moisture content of aggregates. Changing from volumetric to weight proportioning eventually also led to changing from expressing the W/C ratio from volume to weight. This change occurred about the time of the Boulder (Hoover) Dam concrete studies. The W/C ratio of 1 by volume became a W/C ratio of 0.66 by weight (62.3 lb of water to 94 lb of cement).

Concrete Placing Methods

The methods of placing concrete significantly affected the quality of concrete, particularly the water content of the mixture. Before the introduction of reinforcing steel in concrete (before about 1910), concrete structures were relatively massive. The concrete was "tamped" into place in thin layers (about one foot thick) using laborers and the mixture water content was comparatively "dry." The introduction of reinforcing steel to withstand tensile forces in concrete allowed for a reduced cross section for structures. However, with thinner concrete cross sections containing reinforcing steel, there was no room for laborers in the forms, so that dry mixes could not be tamped into place. Water was added to the mix to allow it to be "poured" into forms, greatly decreasing the work for laborers. The added water made the concrete more porous and far less durable in harsh environments. Thus, the expected improvement resulting from the use of reinforcement in concrete significantly decreased its performance until about 1920, when the water cement ratio concept became institutionalized in concrete construction practice. Though mixes compensated for more water after 1920, the practice of adding excessive water to make the concrete flow better was common throughout the 1920s. Unfortunately, adding more water to make concrete placement easier plagues construction to this day.

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[9] Abrams, Duff, A., *Design of Concrete Mixtures*, Structural Materials Research Laboratory, Lewis Institute, Chicago, Illinois, 1918.

Cold Joints and Construction Joints

Both cold joints and construction joints cause inherent “flaws” in concrete that may reduce the bond between subsequent placements and limit the load carrying capacity or allow moisture to penetrate into the concrete where it may attack its constituents. For either condition, the top surface of the joint should be removed and cleaned to provide a bond between the underlying concrete and the next layer. If the joint is not cleaned, laitance (debris) on the surface reduces the transfer of a bond between the lifts. Early Reclamation construction was frequently delayed by mechanical breakdowns and the low output of concrete production facilities. Larger equipment was introduced by about 1920 to keep up with progress and limit the cold joints. But the daily construction joint still presented a bond-breaking flaw.

As the size of the dams increased, more difficulty was encountered transporting the concrete from the mixer to the placement. Elaborate chutes were constructed and suspended by cables across the valleys in the 1920s. Additional water was added to the concrete to make it flow down the chutes; the flatter the chute, the more water was added to the concrete. This left areas of weakened concrete in and between placements. The introduction of large scale cableways to transport mass concrete in the late 1920s improved production and eliminated the need for chuting techniques.

Concrete Consolidation Equipment

One of the most underrated advances in concrete construction equipment was the development of the pneumatic immersion concrete vibrator in the early 1930s. Immersion vibrators made it possible to consolidate large quantities of concrete rapidly and to improve the consolidation of concrete around reinforcing steel in forms. Production rates were increased by an order of magnitude, but, more importantly, the water content of the mix could be reduced and the cement content of the mixture was reduced proportionately. The decreased water content decreased bleeding and the concrete’s porosity and the decreased cement content reduced cost and decreased cracking.

Modern day roller compacted concrete (RCC) in dams has brought us almost full circle to the early days of concrete placement, in the sense that very stiff mixes are “tamped” in place. RCC is placed in 1-foot lifts from one abutment to the other and compacted by 10-ton vibratory rollers. Performance is greatly improved by rapid placement and the elimination of cold joints.

Poor Construction Practices

Poor construction practices can significantly affect concrete durability. Construction practices improved throughout the early history of Reclamation. Reclamation developed standard practices for concrete construction and then instituted these practices through improved specifications, education, and training. Two of the most significant improvements were the publication of the first edition of the Concrete Manual in 1936 and the development of concrete schools for training personnel. Reclamation’s emphasis on quality concrete construction greatly improved the resistance to deterioration.

Repair of Concrete Structures

As the early concrete construction projects began experiencing deterioration, improved methods of concrete repair were developed. Improvements in concrete repair techniques continue today. Notable innovations[10] included "Prepacked Concrete", pneumatically applied mortar, and dry pack mortar in the 1930s and 1940s. Large scale concrete repair projects were undertaken to repair concrete deterioration, cavitation damage, and abrasion-erosion damage in the 1960s and 1970s. These projects introduced new repair methods including epoxy injection, epoxy bonded concrete and modified mortar and polymer concrete.[11] Additional methods introduced in the 1980s and 1990s include silica fume concrete and thin-bonded overlays and coatings[12]. Improvements in concrete repair techniques have taken on a new urgency as our older structures begin to rapidly deteriorate.

Improvements in Durable Concrete–The Durability Environments

There are about a half dozen environments that aggressively attack most concretes. Concretes that remain durable under these conditions were proportioned in some way to withstand the elements either accidentally or purposely. The principal environments acting on Reclamation concretes are summarized as follows:

1. Sulfate environment
2. Alkali-silica or alkali-carbonate environment–alkali-aggregate reaction (AAR)
3. F/T environment
4. Acid environment
5. Chloride (corrosion) environment
6. Wetting and drying environment

The three most critical durability deterioration mechanisms affecting Reclamation structures are sulfate attack, AAR, and F/T deterioration. In many cases, concrete deterioration is caused by a combination of aggressive environments, such as wetting and drying combined with sulfate attack in some California desert climates or F/T deterioration combined with alkali-silica reaction (ASR). In these cases, micro-fractures caused by one destructive element allow moisture to more easily penetrate the paste and contribute to a secondary reaction. Corrosive environments are extremely serious for certain reinforced concrete structures. Fortunately, most of Reclamation's infrastructure is not subject to chlorides and is relatively resistant to corrosion of reinforcing steel. Some Reclamation reinforced concrete water conveyance structures constructed with pre-stressed concrete pipe are suffering severely from corrosion damage to reinforcing steel, as are many other civil engineering structures such as roadways and bridges.

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[10] Bureau of Reclamation, Ch. VII, Repair and Maintenance of Concrete, *Concrete Manual, 5th Edition,* September 1949, pp. 327-345.

[11] Bureau of Reclamation, , Ch. VII, Repair and Maintenance of Concrete, *Concrete Manual, 7th Edition*, 1963, pp. 417-439.

[12] Smoak, W.G., *Guide to Concrete Repair*, Bureau of Reclamation, April 1997.

Sulfate Attack

Sulfate attack is both a physical and a chemical attack of cement paste caused by groundwater with concentrations of sulfate greater than about 150 mg/l or soils containing greater than about 0.1 percent sulfate by mass. According to Mehta,[13] physical sulfate attack and chemical sulfate attack are two entirely different phenomena. Physical sulfate attack occurs when surface evaporation causes sulfate bearing water to rise to the surface of concrete by capillary "wicking" action. Under certain conditions of temperature and humidity, the solution begins to crystallize either at the surface, causing little damage, or just under the concrete surface, causing disruptive cracking of the concrete. Chemical sulfate attack is a disintegration of concrete caused by chemical interactions between sulfate ions and constituents of the concrete paste. The disintegration appears to be associated with the decomposition of the cement hydration products and the formation of a secondary compound, ettringite, accompanied by a large volumetric expansion and cracking of the concrete. Chemical sulfate attack is controlled by limiting the C_3A content in cement to less than 5 percent (by mass of dry cement) for severe concentrations and to less than 7 percent for moderate concentrations and by reducing the permeability of the concrete. Although both forms of sulfate attack are caused by sulfate bearing waters, it is possible to have physical sulfate attack without chemical sulfate attack and visa versa. A timeline for the development of sulfate resisting concrete is given in table A-2 (at the back of this appendix).

Sulfate attack was also known as "cement corrosion" in the early 1900s and is very common in the "alkali flats" of the arid western United States and in seawater, particularly in tidal zones. Forms of sulfate attack were identified in Europe during the 18th and 19th centuries.[14] Sulfate attack was identified in the Western United States in the early 1900s after concrete water conveyance structures failed shortly after construction and other instances of poor durability were observed in marine environments. Reclamation first encountered sulfate attack on concrete on the Sun River Project in Montana and on the Shoeshone Project in Wyoming in about 1908[15] only 6 years after the formation of the U.S. Reclamation Service.[16] It is unclear which type of sulfate attack this was–either physical or chemical attack or both. The identification of the basic relationships of cement hydration in the 1920s led to the ability to quantify the percentages of different compounds in cement,[17] including C_3A, which is a critical constituent of cement. Thorvaldson linked C_3A to sulfate attack about 1927, resulting in sulfate resistant cement being manufactured by the Canadian Cement Company, Ontario, Canada, by about 1933.[18] C_3A was also identified as being a high heat generating constituent of cement during the pioneering

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[13] Mehta, P.K., Sulfate Attack on Concrete: Separating Myth from Reality, *Concrete International*, vol. 22, No. 8, August 2000, pp. 57-61.

[14] Bellport, B.P., Combating Sulfate Attack on Concrete on Bureau of Reclamation Projects, Presented at the 63 rd Annual Convention of the American Concrete Institute, Thorvaldson Symposium, April 7, 1967, Toronto, Canada.

[15] Bellport, 1967, p. 2.

[16] 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, Pennsylvania, 1908, pp. 480–493.

[17] Bogue, R.H., The Hydration of Portland Cement, *Industrial Engineering Chemistry*, vol. 26, October 15, 1929, pp. 837-847.

[18] Fleming, A.G., The Development of Special Portland Cements in Canada, *Journal of Canada Engineering Institute*, Pt II, June 1933.

Hoover Dam studies beginning about 1929. The "low heat" cement specified for Hoover Dam in 1934 was also sulfate resistant cement.[19]

The first Federal specification for sulfate resistant cement was issued in 1936. This represented the start of the deliberate manufacturing of sulfate resistant cements for Reclamation concrete construction. Apparently, the first use of a sulfate resistant cement in Reclamation concrete construction apparently was in 1937 on the Casper Canal, Kendrick Project, in Wyoming.[20] The first "Tentative Issue" of the Concrete Manual,[21] in July 1936, described soils containing greater than 0.1 percent and waters containing more than 0.5 percent sulfates as seriously affecting the resistance of concrete to chemical attack, and the 1st edition[22] identified the influence of the composition of the cement compound on the sulfate resisting qualities.

After Reclamation proposed a standard in 1938, ASTM adopted the Specification for Portland Cement in 1940 that describes the chemical composition requirements for the five standard types of cement still used today. The 5th edition of the Concrete Manual,[23] published in September 1949, included a table of four relative degrees of sulfate attack from "negligible" to "severe," based on sulfate concentration in soils and groundwater and the recommended guidance of cement type. This table was later modified in the 7th edition.[24] Bellport concluded deterioration from sulfate attack in Bureau of Reclamation projects was virtually eliminated by 1967.

Reclamation proposed studies during the 1930s and 40s on the use of pozzolans and specifically fly ash (a pozzolan derived from coal burning powerplants) in concrete as a substitute for low-heat cement and to combat sulfate attack. Reclamation research concluded, in 1975, that fly ash improved the resistance of concrete to sulfate attack.[25] Kalousek, et al., in 1976, predicted the service life of concrete made with Types II and V cement would be about 50 years or less and with pozzolans, including fly ash, could exceed 100 years in sulfate environments. The 8th edition of the Concrete Manual[26] was revised to include different combinations of Types II and V cement plus pozzolan to resist different severities of sulfate attack. About this time, Reclamation specified the replacement of about 20 percent of cement with fly ash in most concrete construction. Classifying different fly ashes by chemical composition to resist sulfate attack was proposed by Dunstan in 1980.[27] The sulfate resistance of these various classifications of fly ash concrete has been demonstrated in the laboratory and verified by more than 30 years of practice.

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[19] Davis, R.E., Carlson, R.W., Troxell, G.E., and Kelly, J.Y., Cement Investigations for Hoover Dam, *ACI Journal*, vol. 29, June 1933, pp. 413-431.

[20] Bellport, 1967.

[21] Bureau of Reclamation, *Manual for the Control of Concrete Construction–Tentative Issue*, Denver, Colorado, July 1936.

[22] Bureau of Reclamation, *Concrete Manual*, 1st edition, Denver, Colorado, 1938.

[23] Bureau of Reclamation, *Concrete Manua*l, 5th Edition, Denver, Colorado, September 1949.

[24] Bureau of Reclamation, *Concrete Manual*, 7th Edition, Denver, Colorado, 1963.

[25] Dikeou, J.T., *Fly Ash Improves the Resistance of Concrete to Sulfate Attack*, Research report 23, A Water resources technical publication, Bureau of Reclamation, Denver, Colorado, 1975.

[26] Bureau of Reclamation, *Concrete Manua*l, 8th Edition, Denver, Colorado, 1975.

[27] Dunstan, E.R., Jr., *A Possible Method for Identifying Fly Ashes That Will Improve the Sulfate Resistance of Concretes, Cement, Concrete, and Aggregates*, vol. 2, No. 1, ASTM, Philadelphia, Pennsylvania. 1980, p. 20.

How long will Reclamation concrete last in a sulfate environment? We don't know. We know that improvements in concrete technology extend the life of concrete exposed to sulfates, but we don't know if the extension is permanent or temporary. The life also depends on the quality of the concrete, the type of cement used, and the concentration of sulfates. Most early concrete without sulfate-resisting cements failed long ago and were replaced with those containing Type II and V cements. Three stages in the development of sulfate-resisting concrete are:

- Those constructed after about 1937 with low W/C ratios and chemically resistant Types II and V cements
- Those constructed after about 1945 with chemically resistant cement and purposely entrained air
- Those constructed after about 1975 with chemically resistant cement, entrained air, and sulfate resisting pozzolan (primarily fly ash)

Figure 5 shows the distribution of alkaline and high salinity soils in the 17 Western States.[28] As can be seen from this figure, most of the Reclamation infrastructure lies in regions of potentially positive sulfate attack from either naturally occurring sulfur or from sulfur introduced by irrigation practices. Figure 6 shows the effects of sulfate damage caused by the concentration of groundwater sulfates in the soils from irrigation[29].

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[28] Bureau of Mines, *Pozzolanic Raw Materials Resources in the Central and Western United States*, Information Circular 8421, U.S. Government Printing Office, Washington, D.C., 1969, p. 16.

[29] Bureau of Reclamation Concrete Library Photo Files.

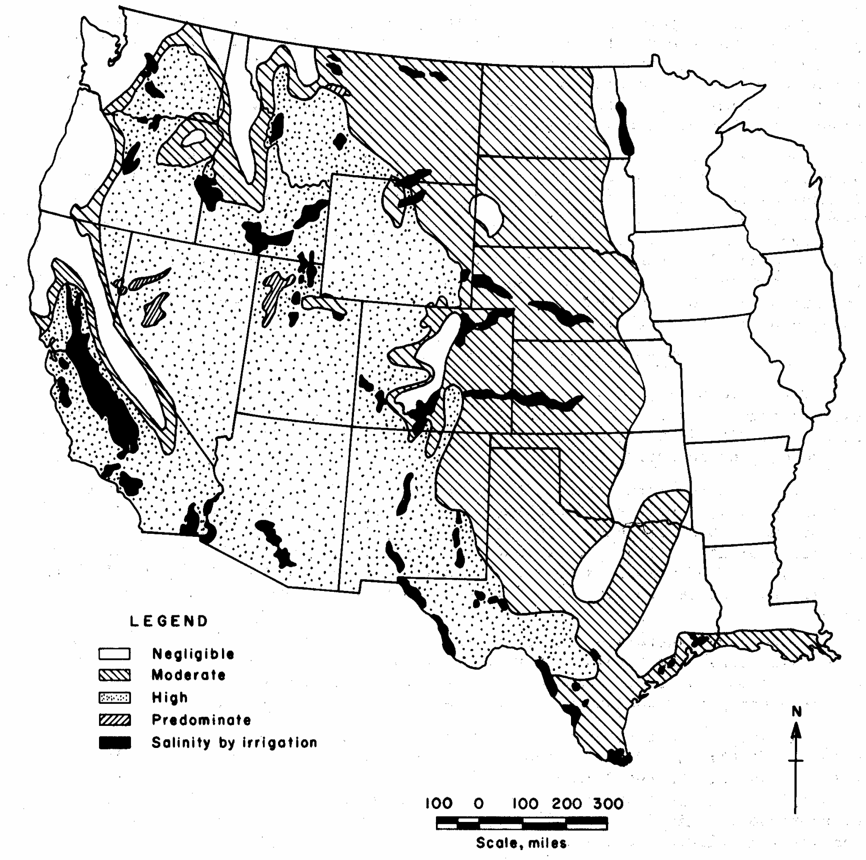

Figure 5.–Distribution of high alkali and high salinity soils in the Western United States with potential for deteriorating concrete by sulfate attack.

Entrained air was introduced in 1945 to increase concrete's resistance to F/T deterioration. Entrained air can also improve the concrete's resistance to sulfates because it improves the workability of the fresh concrete. This allowed Reclamation to place concrete with a lower W/C, which results in less bleed water. Bleed water paths through the concrete significantly increase the permeability of the concrete.

Concrete without entrained air in a sulfate environment may be approaching the end of its service life in less than 50 years. Concrete with entrained air in a sulfate environment should have a service life between 50 years and 75 years. Concretes with entrained air constructed after 1975 with either a type II or type V cement should be resistant to sulfate attach for about 100 years.

Figure 6.—Deterioration of concrete canal lining caused by sulfate attack. Note that deterioration is greatest in the saturation zone because of high groundwater sulfate concentrations.

AARs (Alkali-Silica, Alkali-Carbonate)

Alkali aggregate reactions (AAR) are the chemical reactions between certain specific types of aggregates (either sand or coarse aggregates) and the alkali compounds (generally less than 2-3 percent) of cement. The reaction produces a gel that, in the presence of sufficient moisture, can expand. The expanding gel can exert considerable pressure. This reaction has also been called cement-aggregate reaction.

Laboratory testing of concrete and aggregates in the Monterey Basin of California, beginning in 1936, led to the first published description of alkali aggregate reaction by Stanton in 1940.[30] These studies and others that followed in 1942 led ASTM, Reclamation, and other agencies to limit alkalis in cement to less than 0.6 percent.

The predominate reaction that may occur in Reclamation structures is ASR. A specific type of ASR occurs in the Kansas-Nebraska region. Alkalis in cement react with certain “glassy,” siliceous aggregates such as opal, chalcedony, chert, andesite, basalt, and strained micro

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[30] Stanton, T.E., Expansion of Concrete Through Reaction Between Cement and Aggregates, *Transactions of the American Society of Civil Engineers*, vol. 66, December 1940, pp. 1781-1811.

crystalline quartz.[31] Certain specific carbonate aggregates can react with cement alkalis, and this reaction is called alkali-carbonate reaction.

> Typical manifestations of concrete deterioration through ASR are expansion and cracking (which frequently is of such a nature that the designation "pattern" or "map" cracking is used to describe the cracks); exudations of small jelly-like or hard beads on surfaces; dark reaction rims around affected aggregate particles within the concrete; and sometimes popouts.[32] The reaction products have a swelling nature, leading to tensile stresses that cause cracking in the concrete. The cracking may allow moisture to more readily be absorbed by the silica gel, increasing expansion or accelerating F/T damage.

Typically, most aggregates are relatively inert to this type of chemical reaction. However, the aggregates that can be reactive are fairly widely distributed geographically. The aggregates in question may often comprise only 5 percent or less of the total aggregates by mass. In some cases, coatings on aggregates can cause the reaction. Both the *degree of* and *rate of* reaction can be affected by many factors, including the following:

- Alkali content of the cement (and pozzolan if used)
- Type and amount of reactive aggregate
- Nominal maximum size of aggregate
- Use of a suitable pozzolan
- Temperature and moisture content of the concrete

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

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

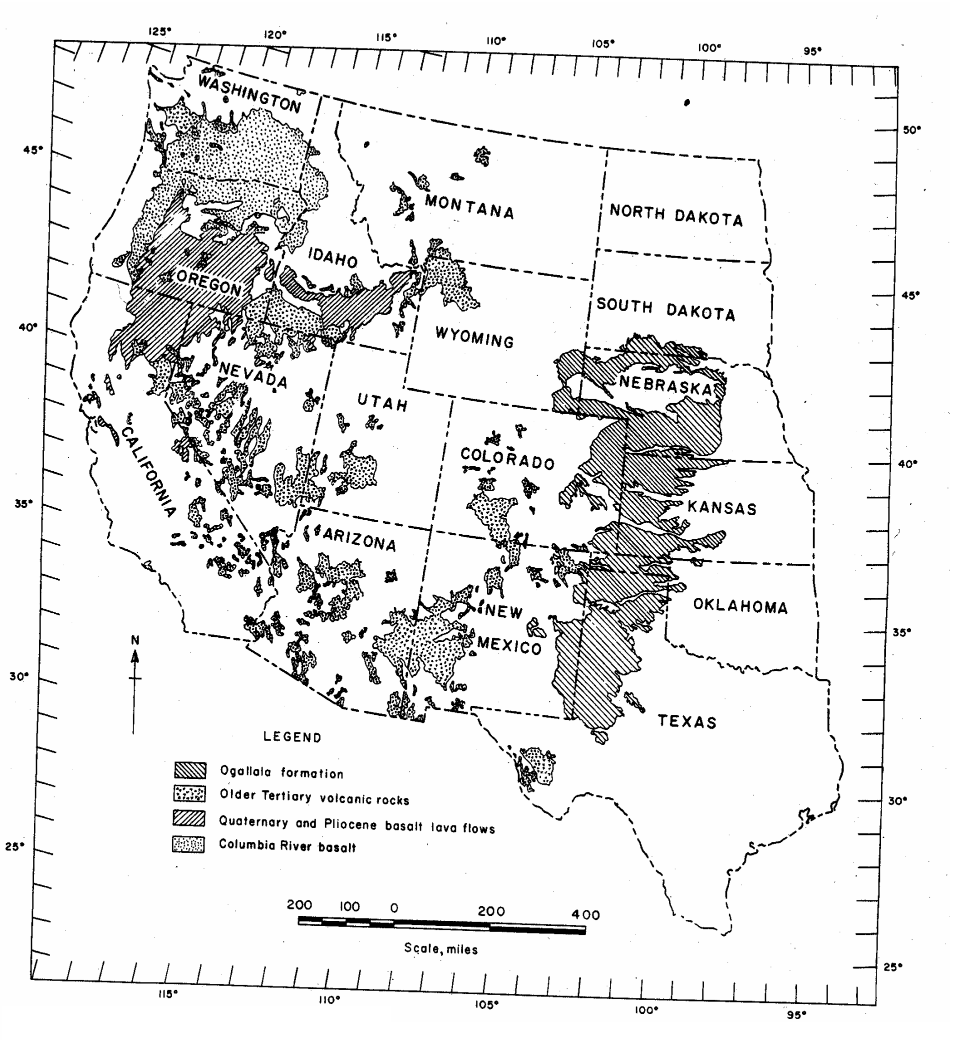

Figure 7.—Distribution of aggregates in the Western United States that may be potentially reactive in concrete.

A timeline for ASR in concrete is shown in table A-3. ASR has been identified in many Reclamation structures. The 3rd edition of the Concrete Manual[33] cited the potential for ASR without giving an explanation of means to control the reaction. In early 1941, petrographic examination of aggregates became the principal means of identifying potentially reactive aggregates. Petrographic examination is still necessary for identifying both potentially reactive aggregates and evaluating ASR in concrete. The limitation of alkalis in cement to less than 0.6 percent was first published in the 4th edition of the Concrete Manual[34] in October 1942. Various test methods were then developed to evaluate ASR in the early 1940s. Investigations into the ASR resistance of concrete containing pozzolans to combat ASR began in the late 1940s and continued through the 1970s. Standard Reclamation practice to use about

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[33] Bureau of Reclamation, *Concrete Manual*, 3rd edition, Denver, Colorado, January 1941, p. 55.

[34] Bureau of Reclamation, *Concrete Manual*, 4th edition, Denver, Colorado, October 1942, p. 51.

20 percent Class F or N pozzolans as a replacement for cement began in the late 1970s. This practice has apparently served a dual purpose by first reducing the cost of cementitious materials in concrete and then providing additional protection from both ASR and sulfate attack.

Potentially reactive aggregates have been identified in virtually every State where Reclamation has projects (figure 7).

Reclamation made a wise decision to require low-alkali cement in virtually all concrete structures after about 1942. Reclamation provided additional protection against ASR in large dams by using pozzolans after about 1942. An ASTM Class F Fly ash (a pozzolan) was used in construction of Hungry Horse Dam in 1949. By about 1980, virtually all Reclamation concrete structures were constructed with Class F pozzolans, resulting in greatly improved performance against both ASR and sulfate attack.

Structures constructed before 1942 and known to be suffering from ASR have recorded significantly decreased material properties. Seminoe Dam, in Wyoming, has had over a 50 percent decrease in compressive strength and elastic properties over the past 60 years.[35] These structures should be periodically monitored for long-term performance. Structures completed after 1942 should remain relatively free from ASR.

Freezing and Thawing Deterioration

F/T deterioration is the result of expansion of water as it freezes in the concrete paste and destroys the concrete. Water present in the paste expands about 9 percent upon freezing. When confined within a 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 at least 90 percent saturated when it undergoes freezing for this form of deterioration to occur. Repeated cycles of F/T are common in Reclamation water conveyance structures, particularly those in fluctuating water surface levels or in splash or spray zones. Temperature monitoring at Warm Springs Dam in Oregon measured about 70 F/T cycles per year over a 2 year period.

A timeline for F/T durability of concrete is given in table A-4. Early studies identifying the relationship between water-cement ratio and concrete compressive strength were performed by Abrams from about 1914 to 1922. This concept also related increased strength to improved concrete quality and durability without specifically identifying the F/T mechanism.

> The water (to cement) ratio seems to be a factor which ultimately governs the strength and wearing resistance of the concrete...wide ranges in temperature, wide variations in moisture content, and probably exposed to other destructive agencies, must have a very considerable degree of resistance if it is to give a good account of itself. It is true that the strength of concrete reflects to a very large degree the ability of concrete to withstand these other agencies. [36]

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[35] Mohorovic, C.E., Dolen, T.P., and Hurcomb, D.R., *1998–1999 Concrete Coring–Laboratory Testing Program, Seminoe Dam, Kendrick Project, Wyoming*, Bureau of Reclamation, Materials Engineering and Research Laboratory, Denver, Colorado, August 1999.

[36] Abrams, Duff A., Proportioning Concrete Mixtures, *Proceedings of the 18th Annual Convention of ACI*, vol. 18, Detroit, Michigan, February 1922, p 174-181.

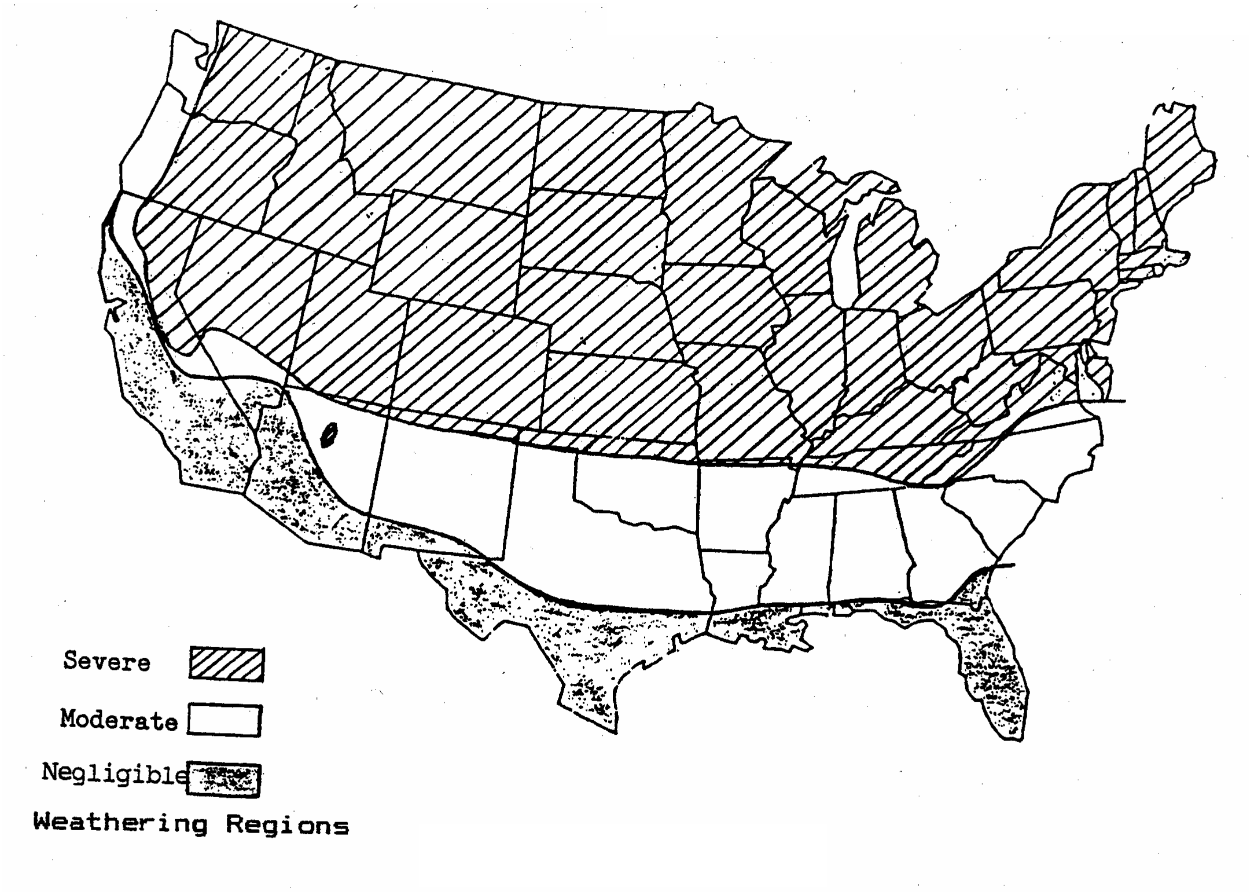

Figure 8.—F/T weathering regions in the United States–Source: ASTM C 33 Concrete and Aggregates.

Deterioration specifically resulting from F/T attack was identified during the 1920s. Early Reclamation mixture proportioning practice related improved resistance to F/T attack to improved compressive strength and using good quality aggregates. By about 1930, most Reclamation concrete began using a low W/C ratio and higher compressive strength to combat F/T deterioration.

The solution to F/T deterioration of concrete was an additive to concrete that formed tiny air bubbles in the paste. In 1939 laboratory studies, Carlson was one of the first to attribute greater durability of concrete to entrained air. The “most resistant concrete proved to be that which contained 10 percent air introduced by 1/10 of 1 percent of a “wetting agent” added to cement (during the manufacturing process).”[37]

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[37] Carlson, R.W., Remarks on Durability of Concrete, *Proceedings of AC*I, vol. 35, Detroit, Michigan, April 1939, p.359.

The first deliberate manufacturing of air-entrained cements occurred by about 1940 after obtaining a better understanding of the function of air entrainment in concrete.[38] These air-entrained cements showed much improved durability in F/T tests when compared with non-air-entrained concretes.

ASTM issued the first tentative specification for air-entrained cement in 1943 for Type I-A and II-A cement. In 1943, the Federal Government issued the Federal Emergency Alternate Specification for air-entrained cement using vinsol resin.

Discussion of the improved durability of air-entrained concrete was not included until the 5th edition of the Concrete Manual. Because of World War II, the 5th edition was not published until 1949. About September 1944, laboratory mixture proportioning programs first provided data for mixtures with the deliberate addition of air-entraining admixtures (AEA).[39] AEA was introduced in field construction at Anderson Dam in September 1945.[40] The ACI standard practice for proportioning concrete mixtures first noted the benefits of air-entraining admixtures in the 1946 edition. The first symposium on Air Entrained Concrete was held by ACI in June 1946.[41]

Reclamation concrete structures constructed before about1945 are vulnerable to F/T deterioration. The original concrete properties and exposure of the structures influences the expected service life of these structures. Concrete structures constructed before about 1930 are suspect because of the lower compressive strengths and inferior placing practices used to transport concrete. These practices often resulted in adding extra water to the concrete. These wetter consistency concretes often showed obvious damage in less than 5 years, and to remain in service,[42] some required major repairs within 25 years.

From about 1930 to 1945, the W/C ratio of most concrete was controlled and the quality of the concrete improved, extending its expected service life to more than 25 years. These structures have relatively good resistance to F/T in moderate climates or less severe exposure conditions. After 1945, virtually all Reclamation concrete contained entrained air and this concrete is resistant to F/T deterioration. The service life of these structures could extend well beyond 50 years

Acid Attack

Cementitious compounds are highly alkaline and thus portland cement concrete is not resistant to acid attack. Concrete can be attacked by a variety of strong acids or compounds that convert to acids. The most common form of acid attack on concrete is *carbonation*, the reaction between

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[38] Kennedy, H.L., The Function of Air in Concrete, *Proceedings of ACI*, vol. 39, Detroit, Michigan, June 1943, p. 529.

[39] Bureau of Reclamation, *Effect Of The Admixtures T.D.A., Darex, And Vinsol Resin On The Properties Of Concrete Made With Buffalo Rapids Aggregate And Cement,* Buffalo Rapids Project, Concrete and Metals Laboratory Report No. C 272, Denver, Colorado, February 1945.

[40] Lane, A.V. and Burke, E.W., *Report on Air-Entraining Agents for the Year 1945*, Bureau of Reclamation, Anderson Dam, Idaho, January 15, 1946.

[41] Symposium on Entrained Air in Concrete, American Concrete Institute, 42nd Annual Convention, Buffalo, New York, February 1942, *ACI Journal*, vol. 17, No. 6, June 1946, pp. 601-700.

[42] Boswell, C.C. and Gieseck, A.C., Maintenance of Heavy Concrete Structures–Minnesota Power & Light Company Practice, *Proceedings of ACI*, vol. 42, February 1946, p. 278.

carbon dioxide (CO_2) and the calcium hydroxide ($Ca(OH)_2$) in hydrated cement paste. CO_2 combines with moisture to form carbonic acid, which then reacts with the $Ca(OH)_2$ to form $CaCO_3$. CO_2 is present in low concentrations in air and reacts to a small degree in most exposed concretes. The primary result of carbonation is shrinkage in concrete and a drop in the pH of the pore water in the paste from about 13 to about 9[43]. The most important consequences of carbonation are shrinkage and the reduction in pH that may make embedded reinforcing steel susceptible to corrosion. Corrosion of reinforcing steel can significantly reduce the life span of reinforced concrete structures.

Carbonation is a slow reaction that occurs over many years. Carbonation may reach a depth of 1 to 2 inches in 25 to 50 years, but may occur faster in poor quality concrete. This could eventually lead to long-term problems in reinforced concrete structures if the carbonation depth exceeds the cover thickness of concrete over steel. Carbonation-induced shrinkage may approach the same order of magnitude as drying shrinkage, about 400 to 800 x 10^{-6} in/in. Concrete subjected to early drying, such as improperly cured concrete, will be most susceptible to the highest amount of both drying and carbonation induced shrinkage.

The most important factors governing the rate of carbonation are the porosity of the cement paste and the curing history of the concrete. The depth of carbonation for a concrete with a low W/(C+P) (water to cement and pozzolan) ratio can be about 15 percent of the depth of a concrete with a high W/(C+P). The rate of carbonation is influenced by the curing history of the concrete. Highest carbonation rates are achieved in sheltered (from rain) environments with humidity between 50 and 65 percent. Deteriorating concrete structures are probably the structures most seriously affected by carbonation because deteriorating concretes may have had higher W/(C+P) ratios and less curing than more recent concrete. Pre-1930 concrete is much more prone to carbonation because of the higher W/C ratio often used in this concrete. Carbonation should not be a significant cause of deterioration in saturated environments.

Reclamation structures are not normally exposed to other types of acid attack. Sulfuric and nitric acids may be caused by acid rain, mine drainage wastes, springs, and decomposition of organics in some reservoirs and peat bogs.

Corrosion (Chloride) Environment

Reinforcing steel in concrete, particularly in pipelines and canals, may be subject to corrosion caused by moisture and exposure to chlorides. (Chlorides in contact with non-air-entrained concrete accelerate F/T deterioration.) Reinforcing steel is normally protected from corrosion by the high alkalinity of the concrete around the steel. However, if chlorides come in contact with the steel, the protection is lost and the steel can begin to rust. Rust occupies more volume than the steel and exerts tensile forces in the concrete, causing cracking. In most structures, the reinforcing steel is well protected from corrosion by providing adequate concrete thickness between the steel and the environment. However, if problems occur during construction, such as allowing the steel to shift in the forms or come in contact with the subgrade in slabs, then the protective cover layer is greatly reduced or lost, exposing the steel to corrosive elements. Chlorides may also come in contact with steel in concrete because the cover is too thin, because of cracking, and because of carbonation-induced shrinkage (accompanied by a reduced pH). A

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[43] Neville, A.M., *Properties of Concrete*, 4th edition, John Wiley and Sons, New York, p.499.

particularly aggressive corrosive environment is developed when chlorides penetrate carbonated concrete containing reinforcing steel. Reclamation structures most seriously affected by corrosion are precast, pre-stressed concrete cylinder pipelines. These structures may have relatively thin concrete cover over highly stressed steel. Small reductions in wire diameter can cause wire failure and explosive rupture of the pipe.

Wetting and Drying Environment

Many Reclamation structures are subjected to alternating cycles of wetting and drying as water levels change. This can cause small expansions and contractions in the concrete. This environment in itself is not detrimental, but it may aggravate or accelerate other conditions such as sulfate attack. The wetting and drying concentrates minerals at the subgrade-concrete interface. Fluctuating water surface levels can increase the number of F/T cycles during freezing weather.

Table A-1.—A Timeline for Improved Quality Concrete and Construction Practices

Date	Event	Result
1905–1910	Introduction of Reinforced Concrete	Change form massive section to thin-reinforced sections
1910	Change from "dry" tamped concrete mixes to wet "fluid" mixtures with high slump (to place around reinforcing steel).	Increased water content for fluidity increases W/C ratio and decreases durability
1918	Proportioning concrete mixtures based on "W/C ratio law." Volumetric proportioning methods.	Better concrete mixture proportioning requirements improve concrete quality.
1920s	Testing aggregates for quality and grading.	Improved concrete durability because better quality aggregates are used; improved mixture proportioning.
1926–1928	Elemental composition of cements.	Improved understanding of cement hydration products improved manufacturing processes.
Late 1920s	Change from volumetric concrete proportioning/batching to weight proportioning/batching.	Better quality control processes and more consistent field concrete
1928	Electric "highline" cableway with buckets for transporting mass concrete.	Increased placing rates (1,000 yd^3/shift 125 yd^3/hr); placement at lower slumps, elimination of "chuting" wet concrete.[44]
1929	"Basic principals of concrete making."	Improved methods of mixing, handling, placing, curing, and field process control techniques are as important as W/C ratio in concrete quality.
1930	Development of low-heat cement.	Reduced concrete cracking, improved sulfate resistance.
1930	Development of block construction techniques in mass concrete.	Reduced concrete cracking.
1933	Use of internal vibration for consolidation of concrete.	Reduced entrapped air and use of lower water content in concrete decreases cement content, reduces cracking, decreases permeability, and improves durability.
1933	Development of post-construction cooling techniques for mass concrete dams.	Massive concrete and arch dam construction free from thermal cracking.
1934	Improved construction joint cleanup in concrete construction.	Improved quality and bond strength of lift lines.
1936	Development of sulfate resistant cement specification.	Improved sulfate durability.
1936	Tentative edition of Concrete Manual	Improved concrete quality for Bureau of Reclamation.

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[44] Cableway Bucket–Concretes at Rate of 1,000 Cu. Yd., *Construction Methods*, March 1931, pp.34-38.

Table A-1.—A Timeline for Improved Quality Concrete and Construction Practices

Date	Event	Result
1937	Use of pozzolans in mass concrete.	Reduced heat of hydration and potential improved resistance to sulfate attack and ASR.
Late 1930s	Use of membrane curing compounds for concrete.	Increased production rate for placing concrete canals and improved curing of concrete where water is not available.
1939	Identification of entrained air in concrete pavements.	Greatly improved F/T durability of concrete.
1942	Specifications for low-alkali cements.	Improved resistance to AAR.
1943	Specifications for air-entrained cements.	Improved F/T resistance.
1945	Introduction of air-entraining admixtures.	Improved control of entrained air in concrete, replaces air-entrained cements for most construction.
1946	First large scale use of pozzolan in mass concrete–Davis Dam	Reduced heat of hydration of mass concrete, reduced cost, improved resistance to ASR.
1949	Fifth edition of Concrete Manual.	Most modern concepts of concrete durability and mixture proportioning incorporated as Reclamation standard practice.
1949	First large scale use of fly ash	Less heat generation in mass concrete, improved resistance to AAR, sulfate attack.
1950	Improved processes for cooling concrete with ice and chillers.	Less thermal cracking in mass concrete, less shrinkage cracking in structural concrete and canal lining.
1958	Development of water-reducing and set-controlling admixtures	Reduced cement content, better control of setting properties
1960–1990	Improved methods of concrete repair, introduction of epoxies and polymer concretes.	Extended service life of deteriorating concrete structures, improved resistance to abrasion-erosion and cavitation damage.
1960s	Introduction of computerized concrete quality control and quality assurance systems.	Improved concrete quality, decreased variability.
1970s	Introduction of high-range, water-reducing admixtures.	High strength concrete, “flowable” concrete
1970s	Introduction of mobile, crane-mounted concrete pumping trucks and conveyor systems.	Placement of concrete in difficult locations.
1970s	Investigations in mass concrete placing by roller-compaction techniques.	Reduced cost of concrete dam construction.
1980	Introduction of 15 to 25 percent cement replacement with fly ash in Federal concrete structures.	Reduced cost of cementitious materials in concrete. Potential for sulfate attack and ASR in Reclamation structures essentially

Table A-1.—A Timeline for Improved Quality Concrete and Construction Practices

Date	Event	Result
		eliminated.
1980s	Introduction of silica fume mineral admixtures	Extremely high-strength concrete and repair materials.
1985–1987	Construction of Upper Stillwater Dam using roller-compacted concrete (RCC) technique.	Rapid placing of mass concrete; 1.5 million yd^3 of RCC placed in 11 months of RCC construction. Use of 70 percent pozzolan in mass concrete.
1987	Construction of concrete cut-off walls through embankment dams.	Control of seepage through embankment dams.
1988–1990	Investigations in placing concrete canal lining underwater at Coechella Canal. Introduction of underwater concrete admixtures.	Reduced leakage in unlined canals–placement of concrete canal lining without taking canal out of service.
1990s	Introduction of extended set-retarding admixtures	Improved quality for remote construction sites
1989-2000	Rehabilitation of concrete dams and spillways using roller-compacted concrete	Rapid reconstruction of concrete dams and embankment dam spillways.

Table A-2.—A Timeline for Sulfate Durability

Date	Event	Author(s) / Project
1908	Sulfate attack encountered in Reclamation projects	Jewett, J.Y., Sun River–Montana, Shoshone Project–Wyoming
1910–1927	Early studies on sulfate resistance of concrete in alkali soil environments	Burke, et al.–1910; Bates, et al.–1913 Manson, et al.–1920; Thorvaldson, et al.–1923
1927	Identification of C_3A as compound in concrete related to sulfate attack	Thorvaldson, et al.
1928	Development of methods to calculate composition of cement compounds.	Hansen, Brownmiller, and Bogue–1928
1927–1933	Studies show low-heat cements and some pozzolan cements resist sulfate attack	Davis, et al. Bureau of Reclamation–Bolder Canyon Studies
1931–1933	Manufacturing of sulfate-resisting cement in Canada.	Fleming–1933
1933–1935	Laboratory and field studies identify limits for C_3A in concrete and sulfate concentrations causing deterioration.	Davis, et al. Tuthill–Metropolitan Water District, California
1935	Fly ash introduced as pozzolan in concrete.	Davis, R.E.
1936	*Special Cements for Mass Concrete* published.	U.S. Dept. Of Interior, Bureau of Reclamation
1936	First Federal specification for sulfate resistant cement (by chemical composition) Tentative ASTM standard for sulfate resisting cement issued.	Bureau of Reclamation, National Bureau of Standards, ASTM, et al.
1936	Tentative edition–*Concrete Manual* published, caution issued for sulfate concentrations greater than 0.1 percent in soils and 0.5 percent in water.	Bureau of Reclamation
1937	Reclamation issues specification for modified cement with C_3A content less than 6 percent–first specified cement for sulfate resistance. Specification with C_3A limit of 5 percent.	Bellport, 1967; Casper Canal, Kendrick Project, Wyoming Heart Mountain Division, Shoshone Project, Wyoming
1938	Reclamation proposes standard specification for sulfate resistant cement to ASTM.	Bureau of Reclamation
1940	ASTM issues standard specification for Portland cement (five types of cement).	ASTM
1942	Fly ash used on first Reclamation structure.	Harboe, Hoover Dam Spillway Repairs
1949	Table for selection of cement type based on sulfate concentrations in soil and water.	5th edition–Bureau of Reclamation, *Concrete Manual*

Table A-2.—A Timeline for Sulfate Durability

Date	Event	Author(s) / Project
1966	Revisions to sulfate concentrations for sulfate resistant concrete.	7th edition–Bureau of Reclamation, *Concrete Manual*
1967	Deterioration caused by sulfate attack virtually eliminated.	Bellport, 1967
1948–1972	Studies on effect of pozzolans (Class N, F, and C) and sulfate attack. 50 year predicted service life of concrete with sulfate-resisting cements, 100 years or more with sulfate-resisting pozzolans.	Kalousek, et al, Bureau of Reclamation
mid 1970s	Cement shortage throughout United States, substitution of 15 to 25 percent pozzolan for cement allowed as an option on Reclamation projects.	Central Arizona Project
1975	*Fly Ash Increases Resistance of Concrete to Sulfate Attack.*	Dikeou, Bureau of Reclamation
1976	Performance of lignite and sub-bituminous fly ash in concrete–A Progress Report, *Vulnerability of Lignite Fly Ashes to Sulfate Attack.*	Dunstan and Kalousek, Bureau of Reclamation
1978 to present	EPA regulations require federal agencies to permit use of pozzolan in government concrete construction.	Central Arizona Project
1980	*A Possible Method for Identifying Fly Ashes That Will Improve the Sulfate Resistance of Concretes* – Introduction of "R Factor" for chemical composition of sulfate resisting fly ashes.	Dunstan, Bureau of Reclamation
1983 to present	Bureau of Reclamation policy for use of fly ash in concrete construction, allowable substitution of fly ash plus Type II or V cement for equivalent or increased sulfate resistance in concrete.	Harboe, 1984
1967 to present	No reports of significant sulfate attack on Reclamation projects confirms past research and development of sulfate resisting concretes.	

Table A-3.—A Timeline for AARs (ASR–Alkali Carbonate Reaction)

Date	Event	Author/Project
1912	Buck Hydroplant completed.	Kammer and Carlson, 1941
1922–1929	Identification of deterioration of concrete by unknown expansions, “concrete growing.”	Buck Hydroplant
1927	American Falls Dam completed.	Bureau of Reclamation, Minidoka Project, Idaho
1935	Identification of certain aggregates causing volumetric expansion in concrete.	Holden, Buck Hydroplant
1936 to 1941	Laboratory investigations to determine cause of expansive reactions in concrete, 1938. Pavement failures in Salinas Valley, California, 2 years after completion.	Stanton, et al., State Department Of Highways, California
1937	Parker Dam completed.	Bureau of Reclamation, Colorado River Storage Project, Arizona
1940	Stanton reports on ASR causing deterioration of concrete.	Stanton, California Dept. of Highways
1940	AAR identified at Parker Dam and American Falls Dam, laboratory and field studies conducted on cores from Parker, Gene Wash, and Copper Basin dams.	Bureau of Reclamation and Metropolitan Water District of Southern California
1941	General description of AAR, petrographic examination of potentially reactive aggregates initiated for concrete aggregate investigations.	3rd edition–*Concrete Manual*
1942	Identification and publication of maximum limits of 0.5 to 0.6 percent alkalis in cement to prevent potential reaction with certain aggregates.	4th edition–*Concrete Manual*
1942	Use of mortar bar expansion test to quickly evaluate aggregates for ASR.	Bureau of Reclamation (and others)
1946 to 1949	Pozzolan use to combat ASR at Davis Dam. Studies on effect of pozzolans to combat ASR.	Davis Dam Project, California 5th edition–*Concrete Manual*
1949	*Studies on Use of Pozzolans for Counteracting Excessive Concrete Expansions Resulting From Reactions between Aggregates and Alkalis in Cement.*	Stanton, T.E., *ASTM Symposium on Use of Pozzolanic Materials in Mortar and Concrete*
1948 to 1953	Identification and laboratory studies of a particular AAR in Kansas-Nebraska region.	Engineering Experiment Station, Kansas State College and Portland Cement Association
1957	Identification of alkali-carbonate reaction.	Swenson, E.G., ASTM Bulletin No. 57
1958	Investigations/identification of strained quartz contributing to ASR.	Meilenz, R.C., Highway Res. Report No. 18-C
1942 to 1970s	Laboratory studies on use of fly ash to increase durability of concrete, improve resistance to sulfate attack and ASR.	Bureau of Reclamation

Table A-3.—A Timeline for AARs (ASR–Alkali Carbonate Reaction)

Date	Event	Author/Project
1972	American Falls Dam replaced due to concrete deterioration including ASR.	Bureau of Reclamation
1978 to present	EPA regulations require Federal agencies to permit use of pozzolan in government concrete construction.	Harboe, 1984; Central Arizona Project, Central Utah project, Columbia Basin Project
1940s to present	Reclamation standard practice to identify potentially reactive aggregates through petrographic examination, use of low-alkali cement, and Class F or N pozzolans essentially eliminates ASR in Reclamation new concrete construction.	Bureau of Reclamation
Early 1990	Lithium investigations, Bartlett Dam. Investigations showed that lithium effective in stopping ASR expansion of Pyrex glass mortar bars. Tested source aggregate latter determined to be not very reactive.	Bureau of Reclamation
1995	1995 USCOLD Special Conference on AAR in Dams and Powerplants, Hosted by TVA. Centerpiece of conference was the work they have done w/ wide-slot cutting at several of their dams affected by AAR.	Bureau of Reclamation, Tennessee Valley Authority
Mid-1990s	Acres, International established a website to collect/share information (internationally) on AAR. Reclamation contributed to this in the early to mid-90s.	Bureau of Reclamation, Acres, International
Late-1990s	Research started to find methods to determine amount of ASR expansion remaining in ASR affected hardened concrete.	Bureau of Reclamation
1996	Spillway gates modified at Friant Dam because of ASR induced expansion.	Bureau of Reclamation
1999	Seismic tomography of Seminoe Dam indicates locations of apparent concrete deterioration correlated with results of the concrete core testing and cracks observed on the downstream face of the dam.	Bureau of Reclamation
2001	Results of the structural evaluations performed by Acres, International on Seminoe Dam indicate that in-situ stress measurements are needed to calibrate the structural analysis models and confirm anticipated dam performance.	Acres, International
2001	Reports from Hydro-Quebec provided to Reclamation show that lithium compounds can reduce expansion caused by ASR.	Hydro-Quebec
1970s to present	Concrete deterioration at Seminoe Dam confirmed as a slow reacting form of ASR caused by strained quartz combined with surficial F/T action (high alkali cement used during construction in 1939).	Hurcomb, 1999

Table A-4.—Timeline for F/T Resistance of Concrete

Date	Event	Author/Project
1902 to 1920	Early Reclamation projects experience general durability related problems including F/T deterioration and sulfate attack; concrete mixtures proportioned using volumetric batching with little control of water.	
1918	Identification of W/C ratio for improved quality concretes.	Abrams, Duff
1923	"Some Doubts About Concrete" Poor durability of "outdoor concrete."	Editorial, *Engineering News Record*[45]
mid 1920s	Reclamation begins proportioning concrete mixtures using Abrams' methods Quality control of concrete is limited by methods and equipment for placement.	Black Canyon Dam
1926 and 1934	Use of soaps as waterproofing agent for concrete. Reports of concrete containing foaming air. Cements causing this "problem" were discontinued.	White and Bateman
1934 to 1937	Development of F/T testing apparatus. "Good" concrete would withstand 150 to 200 cycles of F/T.	Burnett and Porter, Bureau of Reclamation
1939	Durable concrete pavements in New York identified as using cement that entrained air.	Lawton, New York State
1938 to 1942	Durability of concrete pavements in Northeastern United States improved using various "grinding aids" from cement manufacturing.	New York State; Carlson, R.A., Portland Cement Association, Bureau of Reclamation
1939 to 1942	Numerous trials of concrete pavements using air-entrained cement and admixtures.	Wuerpel
1941	Laboratory and field studies using air-entrainment in concrete for military facilities.	Wuerpel, U.S. Army Corps of Engineers
1942	Fourth edition of *Concrete Manual* published without discussion of air-entrainment in concrete. World War II delays further updates of *Concrete Manual* until 1949.	Bureau of Reclamation, Concrete Manual 4th edition
Nov. 1943 to Jan. 1945	Field correspondence and laboratory studies on use of T.D.A., Darex, and Vinsol Resin admixtures for F/T resistance in concrete.	Bureau of Reclamation [46]
August 1944	Last Reclamation concrete mixture proportioning test programs without AEAs for F/T Resistance.	Bureau of Reclamation [47]

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[45] Editorial, *Engineering News Record*, February 1, 1923, v. 90.

[46] Bureau of Reclamation, *Effect of Admixtures T.D.A., Darex, And Vinsol Resin on the Properties of Concrete Made With Buffalo Rapids Aggregate and Cement*, Buffalo Rapids Project, Laboratory Report No. C 272, Concrete and Metals Laboratory, Engineering and Geological Control and Research Division, Denver, Colorado, February 27, 1945.

[47] Bureau of Reclamation, *Trial concrete mixes, west portion of Alva B. Adams tunnel and Shadow Mountain Dam*, Colorado-Big Thompson Project, Laboratory Report No. C-253, Concrete and Metals Laboratory, Engineering and Geological Control and Research Division, Denver, Colorado, October 17, 1944.

Table A-4.—Timeline for F/T Resistance of Concrete

Date	Event	Author/Project
June 1945	First notation of entrained-air in concrete in *ACI Recommended Practice for the Design of Concrete Mixes*.	ACI Committee 613
1945	Air-entraining admixtures used in concrete at Anderson Dam, Idaho.	Bureau of Reclamation
February 1946	ACI Symposium on *Entrained Air in Concrete*.	42 nd Annual Convention of ACI
March 1946	New laboratory procedures for proportioning concrete mixtures with entrained air.	Bureau of Reclamation[48]
September 1949	Fifth edition of *Concrete Manua*l requires entrained air for all Reclamation concrete.	Bureau of Reclamation, *Concrete Manual.* 5th edition

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[48] Bureau of Reclamation, *Entrained Air–A Factor in the Design of Concrete Mixes*, Materials Laboratories, Report No. C-310, March 15, 1946.

Mission Statement

The mission of the Department of the Interior is to protect and provide access to our Nation’s natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.