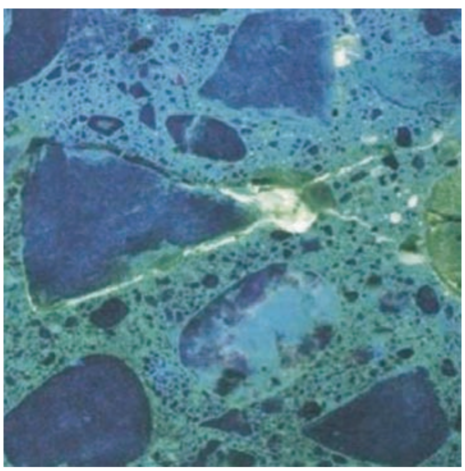
RECLAMATION

Managing Water in the West

Report DSO-05-05

Materials Properties Model of Aging Concrete



Dam Safety Technology Development Program

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14. ABSTRACT
A database model of aging concrete was developed to identify the changes in materials properties over time for Bureau of Reclamation (Reclamation) mass concrete dams. Materials properties data on mass concrete were input to the Reclamation Aging Concrete Information System (ACIS). The data were analyzed for trends in the deterioration of concretes subject to aging, including alkali aggregate reaction (AAR) and general aging of early twentieth century concrete with high water-to-cement ratios. The aging concretes were compared to dams of similar age, but not suffering from aging processes. The aging concretes were also compared to known good quality concretes that were manufactured after about 1948 to specifically resist deterioration from AAR, freezing and thawing (FT), and sulfate attack. Trends were established for comparing the compressive strength, splitting and direct tensile strength, and elastic properties of aging and non-aging dams. The strength and elastic properties of aging mass concrete differed significantly from those of comparable non-aging concretes. Both spatial variations within a structure and long-term changes in strength and elastic properties were identified. The ACIS database can be used to track the long-term materials properties behavior of dams through comprehensive concrete coring and testing programs. Laboratory core test data are included for dams ranging from about 10 to more then 83 years old. These data provide the necessary supporting documentation for the Dam Safety Office Comprehensive Facilities Review evaluation process and for dams in need of corrective action.

15. SUBJECT TERMS
Concrete deterioration timeline; dam safety; materials properties model; aging concrete database; mass concrete; alkali aggregate reaction; alkali silica reaction; freezing and thawing; concrete core tests; compressive strength; splitting tensile strength; direct tensile strength; modulus of elasticity; Poisson's ratio

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Materials Properties Model of Aging Concrete

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Mission Statements

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.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acknowledgments

The author would like to acknowledge the Science and Technology Program for providing the initial funding that led to the development of the aging concrete information system (ACIS) database and for documentation of the state of the art in Bureau of Reclamation mass concrete technology. These benefits have been invaluable in understanding those structures most in need of attention. The Dam Safety Office provided funding for the Materials Model of Aging Concrete and this final report. Dam Safety project funding was used to input much of the data on alkali-silica-affected dams and other aging dams currently under investigation. The Manuals and Standards funding allowed documentation of baseline materials properties of many of the Bureau of Reclamation's historic dams.

Several personnel from the Materials Engineering and Research Laboratory performed time-consuming, tedious data input including Erin Gleason, Veronica Madera, Jalena Maestas, and Kattie Bartojay. Lelon Lewis edited this report. Kurt von Fay began the initial work using Access programming software to develop the concept for the aggregate materials database, which provides an important resource to be coupled to the concrete properties database. He is also instrumental in the product development of concrete deterioration service life prediction software. Dr. David Harris and Dr. William Kepler provided the leadership for accomplishment of this program.

Carol Hovenden performed the Access database programming development and is largely responsible for the database organizational structure, operations and maintenance, and development of data reporting modules of the ACIS database.

Lastly, the author would like to thank the hundreds of Bureau of Reclamation field construction laboratory personnel, drill crews, and the Denver laboratory materials engineering technicians and engineers who have performed the backbreaking work to the perform concrete construction tests, and obtained and tested the hundreds of cores reported in the ACIS database.

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Research Program Summary

The objective of this research program is to model the trends of deterioration of concrete in dams to better understand the processes, the rate of change in materials properties, and ultimately, provide the necessary supporting documentation for dams in need of corrective action. The destructive behavior of concrete deterioration is both a physical and chemical phenomenon of the cement paste, the aggregate, and the paste-aggregate interface. The development and reporting for aging concrete is funded under the Reclamation Dam Safety Research Program—Materials Model for Aging Concrete (DSO Project: AGING). The basis of the materials model for aging concrete presented in this report is to (1) identify the performance of concrete from Bureau of Reclamation (Reclamation) structures without ongoing deterioration and (2) compare with documented performance in structures presently undergoing deterioration. Structures without ongoing deterioration comprise the “baseline” materials properties, that is, what the long term properties of the concrete should be. Structures with ongoing deterioration comprise the “aging” properties of affected structures. From this comparative process, the changes in materials properties can be identified on affected structures and used to develop limits of unacceptable properties and requirements for corrective action.

The most pressing need for Reclamation’s aging concrete structures is evaluating the changes in materials properties over time that affects dam safety. Current risk assessment and evaluation techniques take a “snapshot” of the dam performance under predicted loading conditions. For the most part, the condition of the concrete in the dam is assumed constant over time. However, if degradation is progressing over time, the dam condition is no longer constant. The aging structure may not be able to withstand the previously assumed loadings even if they have not changed.

This materials model is based on trends established from historic laboratory testing of Reclamation mass and structural concretes. This includes data from laboratory mixture proportioning studies, field quality control records, and core testing programs. Reclamation concretes of concern are typically from 50 to over 100 years old, constructed with much larger aggregates, and used different cements than modern-day concretes. The development of predictive modeling of concrete deterioration is an emerging technology. However, mass concrete, by virtue of its much larger aggregate sizes and different materials, does not yet fit the developing modeling technology. A materials model of aging concrete properties has been developed for dams through records of core tests entered in a comprehensive concrete database.

The benefits of development of an aging concrete materials database model include providing documentation for Reclamation Safety of Dams (SOD) and comprehensive facilities review (CFR) examinations and verification of predictive models currently under development by industry. The rate of deterioration with time is essential for accurate service life prediction. In addition, the data can be used to screen our concrete infrastructure to prioritize program funding for future rehabilitation efforts. The database has already been used to resolve outstanding Safety of Dams recommendations related to perceived decreased core strengths at Yellowtail Dam at a considerable cost savings compared to implementation of a new concrete coring and testing investigation.

Reclamation concretes are subject to wide variations in exposures and aggressive environmental degradation. Initially, Reclamation concretes were not resistant to environmental degradation processes such as sulfate attack, alkali aggregate reaction, and freezing and thawing damage. Reclamation has published more than 1,000 documents on concrete properties. Unfortunately, most of these data were published before the development of modern word processing and database technology. Extracting these data for every dam is laborious. By identifying relevant materials properties data in a relational database, trends of aging concretes in dams can be developed and compared to current structures of interest and is the focus of this research.

The aging concrete information system (ACIS) provides the necessary database of concrete materials for developing a model for concrete deterioration. Developed under the Reclamation Science and Technology (S&T) Program, ACIS is a powerful relational database of concrete materials properties from laboratory, field quality control, and hardened concrete core testing. ACIS ultimately has the capability for being linked to other existing databases currently associated with the dam safety program, such as the Dam Safety Information System (DSIS) and geographic information system technology. Data entry into ACIS has been accomplished through a variety of funded projects, including the Reclamation Science and Technology Program (primary database development), project funding (specific dam safety investigations), and the Reclamation Manuals and Standards funding (baseline of historic concrete materials properties).

Though the focus of this research program is dam safety related, similar benefits are applicable for the entire Reclamation water resources concrete infrastructure. Aging processes are affecting all Reclamation concretes but particularly those in sulfate environments and those in northern and mountain climates. Canals and associated water conveyance structures are particularly susceptible to aging-related concrete deterioration due to the lack of additional protective cover.

Conclusions and Recommendations

The properties of Reclamation dams differ significantly depending on the date of construction, geographical location and local deterioration processes, and the state of the art at the time of construction.

A comprehensive database has been developed to model the materials properties of Reclamation mass concrete. This database is capable of sorting and querying data specific to both individual dams and classes of aging concrete structures.

The materials properties of concrete incorporated into the ACIS database allow comparative modeling of the expected performance of our concrete dams with our aging structures.

Reclamation should continue to add relevant materials properties data for all concrete dam structures as these structures come up for review in the Dam Safety Office CFR program.

The strength and elastic properties of alkali-silica-reaction- (ASR) affected dams differ markedly compared to dams constructed with similar materials and mixture proportions. The ASR-affected dams have less than half the strength and elastic properties of comparable reference concretes.

The processes for ASR differ for some Reclamation dams and may be attributed to either the local materials used, the temperature environment at the dam site, or both. Parker Dam, constructed in Arizona, appears to have had early ASR reaction that has stabilized, whereas Seminoe Dam in Wyoming continues to deteriorate with time. Owyhee Dam in Idaho may have strength reduction trends similar to those at Seminoe Dam because of similar climates.

The aging concrete data should provide the necessary information to establish the ultimate or "terminal" strength parameters necessary for service life prediction models.

The concrete materials properties provide the necessary data support for analytical models used in structural analysis of our dams. This may also apply to additional dam-safety-related analysis under development.

Further research is needed to incorporate this concrete materials properties database with geographical information systems under development.

Aging Concrete Dams

Reclamation's Aging Concrete Infrastructure

More than half of Reclamation's infrastructure is more then 50 years old. The concretes used between 1902 through about 1948 in particular, were not purposely made to resist degradation from the environment. The three primary methods of concrete deterioration in our dams are (in order of specific identification and date of solution):

- *Sulfate attack*.—The chemical and physical destruction of the cement paste by aggressive, sulfate-laden waters (1937)

- *Alkali-aggregate (alkali-silica) reaction (AAR or ASR)*.—The chemical reaction between alkali compounds in cement with certain amorphous-silica-bearing aggregates, resulting in concrete "growth" by expanding silica gel (1942)

- *Freezing and thawing deterioration (FT)*.—The physical destruction of primarily cement paste by ice formation within the cement pores (1948)

A fourth mechanism specific mostly to Reclamation conveyance structures is corrosion of reinforcing steel. This is primarily related to pipelines or structures constructed accidentally with insufficient cover. However, when other mechanisms deteriorate surrounding concrete, corrosion may ultimately become the primary means of deterioration.

A Timeline for Reclamation Aging Concrete

Reclamation concrete development followed the established trends of the emerging state of the art of concrete technology in the twentieth century. Reclamation concrete is closely aligned with the development of materials properties technology for aggregates and cement, identification of and solutions for deterioration mechanisms caused by the environment and improvements in design and construction practices. These developments are summarized in figure 1. The construction of the early dams raised many questions for both designers and constructors. Concrete materials engineering developed as a means for solving problems at the materials science level. However, these materials science issues were interconnected to improvements in design and construction of major dams. Research in aggregates, cements, and materials properties were spurred on by Abrams in 1918 with his pioneering work in the design of concrete

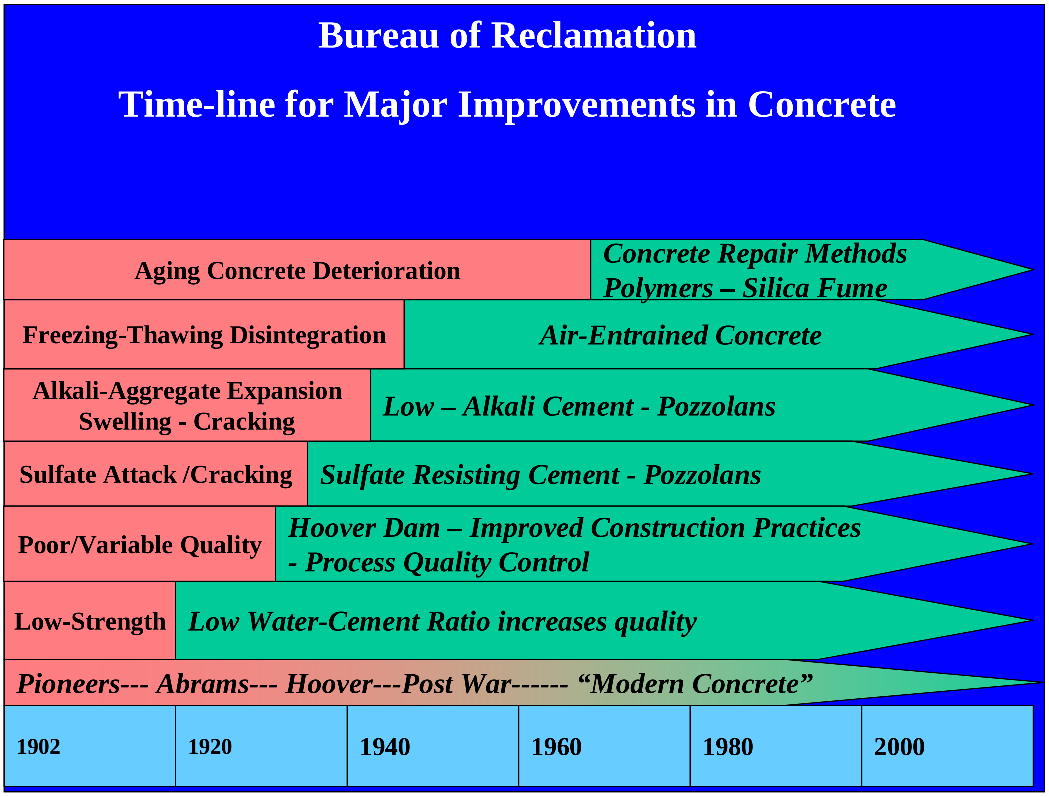

Figure 1.—Timeline for improvements in durable Reclamation concrete.

mixtures and his water-to-cement-ratio "law" (Abrams, 1918). The development of cement chemistry was spurred on in the late 1920s by the need to understand the chemical processes of hydration in order to reduce cracking from thermal heat generation for large dams and in particular Hoover Dam. The design and construction of Hoover and Grand Coulee Dams in the 1930s led to the development of concrete production on a massive scale, including improvements of concrete mixing, transporting, placing, and cooling. Close control of concrete quality led to reductions in the water and cement contents, yielding greater economy and more volumetric stability. The low-heat cements originally developed for Hoover Dam mass concrete also were found to resist deterioration in a sulfate environment. Subsequently, this materials science methodology became the foundation for the investigations in durability of concrete to resist sulfate attack, alkali-aggregate reaction, and freezing and thawing deterioration.

Trends of concrete materials properties have been developed for these different generations of concrete dam construction. Some dams have exceeded their expectations, while others have not. Comparing these concretes and their exposure conditions proved beneficial to discoveries of the necessary properties for durable concrete. For example, "sand cement" was developed by intergrading cement with finely ground sands and silts, thought to act as a pozzolan.

Unfortunately, this was later found not to be the case resulting in low strength concrete with poor durability in aggressive freezing and thawing environments. Exposed concrete at Arrowrock Dam in Idaho and Lahontan Dam in California required significant repair within 20 years and ultimately total rehabilitation of the service spillways whereas similar concrete used at Elephant Butte Dam in New Mexico was, for the most part, unaffected. The mixtures for Hoover and Grand Coulee Dams have proved superior in their respective environments compared to almost identical concretes constructed at the other locations with alkali-reactive concrete aggregates. The database of these concretes was useful for comparing the trends for ASR currently under investigation at Seminoe Dam and Parker Dam.

Concrete Deterioration and Dam Safety

The role of concrete deterioration in dam safety was documented in report No. DSO-03-05 titled *Effects of Concrete Deterioration on Safety of Dams* (Dolen, 2003). Processes of deterioration were identified specific to Reclamation concrete structures including concrete dams, embankment dams, and appurtenant works such as spillways and outlet works. Failure modes for concrete deterioration were developed for different types of Reclamation structures. One of the most difficult problems facing dam safety managers and engineers is predicting the remaining service life of structures known to be deteriorating after failure modes have been identified. If the concrete is actively deteriorating (such as in a concrete dam), the probability of failure due to the same event will gradually increase as the dam properties degrade until the risks are no longer acceptable. If there is no active deterioration, the risks essentially remain the same unless other modes of failure develop due to changes in loading conditions from flooding or seismic events.

Concrete Materials Properties Investigations and the Aging Concrete Information System

The CFR evaluation process for Reclamation concrete dams typically looks at the original design and performance under the anticipated loading conditions. As a part of this process, the materials properties of the dam are evaluated based on the original tests, if available, and any subsequent postconstruction test programs. The engineer must understand both the expected properties and the actual performance of the field mixtures used in the dam. The ACIS was developed to facilitate this process.

Construction of a major concrete structure involves a set of deliberate steps to optimize the most economical mixture for the strength under assumed loading conditions and for overall construction placement and quality. A comprehensive concrete mixture proportioning program produces perhaps thousands of data records to meet these needs. Reclamation has developed a comprehensive testing and evaluation program for mass concrete. The testing needed to optimize a mixture for construction includes the following data sets:

- *Materials source field investigations*.—Perform many evaluation tests on several sources of aggregates and cementitious materials leading to selection of candidate testing of concrete mixtures.

- *Laboratory concrete and materials investigations*.—Perform many tests from different sources of materials:

    - Aggregate quality tests (many tests from several samples)

    - Concrete workability and aggregate proportions tests (several tests on many mixtures)

    - Concrete strength optimization tests (several tests on many mixtures)

    - Select candidate mixtures for final materials properties (many tests on a few mixtures)

    - Recommendation of optimum concrete mixtures for construction

- Construction concrete mixture investigations

    - Trial batches after aggregate processing (several tests of a few mixtures)

    - Select final mixture proportions to begin construction

    - Construction quality control testing (several tests from many batches of a few mixtures)

    - Redesign of mixtures (if needed for strength and economy)

Following construction, periodic core testing is performed to confirm the assumed properties of the design are achieved, to evaluate possible construction related defects, for periodic monitoring, and if necessary, to answer specific materials properties questions. Postconstruction testing may include the following data sets:

- Postconstruction testing:

    - *Confirmation core testing*.—Materials properties (many tests from a few locations)

- ◦ *Confirmation core testing*.—Construction defects (few tests from a few specific locations)
- ◦ Periodic core testing (few or many tests from a few locations)
- ◦ Concrete deterioration core testing (few or many tests from a few or many locations)

The development of a concrete materials properties database must identify the source of the materials and associated mixtures tested. Laboratory tests establish a baseline of expected performance under standardized laboratory conditions, but may not represent the specific concrete mixtures sampled by core tests. Field quality control tests provide short term (typically 7 days to 1 year or less) strength properties of the actual field mixture and may or may not represent the full mass mixture. Core testing provides either short term or long term materials properties, and the core samples may vary with core diameter and location within the structure. The ACIS program is therefore divided into four distinct, but interconnected modules:

- Materials sources identification for either the laboratory samples or actual construction materials
- Laboratory mixture proportions and physical properties test results
- Field mixture proportions and quality control test results
- Postconstruction concrete core test results

Due to the broad scope of possible materials and mixtures, a specific dam safety investigation and data analysis most often focuses on the actual mixtures used in the dam and past test results. Laboratory materials properties used for the initial design can serve as an important historical record in the absence of construction and postconstruction records, when needed. The construction data records may be generalized, representing average test properties from the entire dam or they may track the day-to-day records for essentially different placements of the same basic mixture. ACIS has the flexibility to include both circumstances for data storage and reporting. An example of comprehensive core test records for Yellowtail and Parker Dams is included in the appendix.

ACIS and Materials Model for Aging Concrete

Concrete Deterioration Model for Dams

The goal for modeling the behavior of deteriorating concrete dams is to predict their remaining service lives. There is no deterioration model specifically developed for Reclamation mass concrete structures and particularly those structures constructed in the early twentieth century. Deterioration can be evaluated by comparative modeling coupled with predictive process modeling. This research program used comparative modeling, either by comparing good concrete to bad or by comparing accumulated data over time. Predictive service life models need verifiable performance. Typically, a model is developed, laboratory mixtures are tested under simulated (usually accelerated) conditions to calibrate the model, and finally the calibrated model is applied to the structure in question, often a new structure. This type of predictive process modeling has limited use for Reclamation concretes unless their output can be verified by historic performance. Reclamation has a unique role in modeling concrete behavior since our structures have 50 to 100 years of verifiable performance for calibration of predictive models. Reclamation also possesses a wealth of laboratory and field testing records to back up the documented performance. Reclamation was at the forefront of development of concretes to resist the aggressive environments beginning as early as 1928 when investigations were begun for the construction of Boulder/Hoover Dam. The combination of robust predictive modeling coupled to a comparative model of verifiable data and performance will provide a great leap forward in dam safety service life prediction worldwide. The materials properties trends for aging concrete are obtained by sorting and filtering relevant data from the ACIS database to compare the properties over time. The ability of ACIS to search and sort testing data records efficiently allows specific processes to be examined for many structures, or historical trends for specific structures.

Reclamation also has a good body of materials properties for structures of varying age that have not undergone deterioration with time, forming the database of “good concrete” for comparative purposes. This can be used to identify the projected “state of condition” for comparison with other structures of concern. For example, Hoover Dam, constructed from 1933 to 1936, used essentially the same state of the art from a concrete technology standpoint as Parker Dam, located about 60 river miles downstream and constructed from 1937 to 1938. Both were constructed with the same construction practices and concrete quality control programs, and used the same cement from plants located in California.

Parker Dam was constructed by one of the “seven companies” that built Hoover Dam, used the same equipment for concrete production, and likely even used some of the same personnel. Hoover has little deterioration of any kind, whereas Parker was the first dam identified in Reclamation’s inventory to suffer from alkali aggregate reaction, specifically alkali-silica reaction. The same comparison exists for Seminoe Dam, using mixtures and cements similar to those used at Grand Coulee Dam. Grand Coulee concrete has performed quite well over time, but Seminoe has been suffering from extensive deterioration from ASR combined with freezing and thawing deterioration. Once the predicted performance is identified from the good concretes, the deteriorating concretes can be evaluated for spatial and time-dependent changes.

Strength and Elastic Properties of Aging and/or ASR-Affected Dams Compared to Unaffected Dams

Averaging and Sorting of ACIS Test Data

The ACIS materials properties database is comprised of thousands of data records. These data were organized using Microsoft Access and Excel software. Querying is best performed using Access, and data analysis of the queried data was performed with Excel. The data input to ACIS allows entering both the average of several tests from one core program or individual drill holes, and individual tests. Reported average values are simply the average of the data set in question, such as core test age. Many of the data in the tables report the “weighted average” based on the actual number of tests performed. Thus, data represented by the average of 30 tests hold more weight than only one test for computing the overall, weighted average. For example, the weighted average compressive strength of mass concrete cores without aging is 5,590 lb/in^2, based on 227 tests, whereas the average without weighting is 5,160 lb/in^2. The data averages may also report the most current representative test data for dams that have had multiple test programs, where noted.

Compressive Strength and Elastic Properties Development of Aging Dams

Compressive strength and elastic properties of dams not subject to ASR were studied to determine changes in materials properties over time. The compressive strength development of the entire data set (not subject to ASR) showed possible “anomalous” trends as shown in figure 2 and table 1. Dams from early structures in the overall data set include East Park Dam, constructed in 1910. This 83-year-old concrete does not appear to have extensive deterioration. However, concretes from this era had higher water-to-cement ratios and do not have the ultimate strength potential of the later dams represented by Hoover Dam at 60 years of age. The average strength and elastic properties of the aging, pre-1920s concrete dams and post-Hoover “modern” dams are summarized in table 1. The long term compressive strength and elastic properties of the “modern” mass concrete dams—essentially the post-Hoover era dams are based on the most recent core

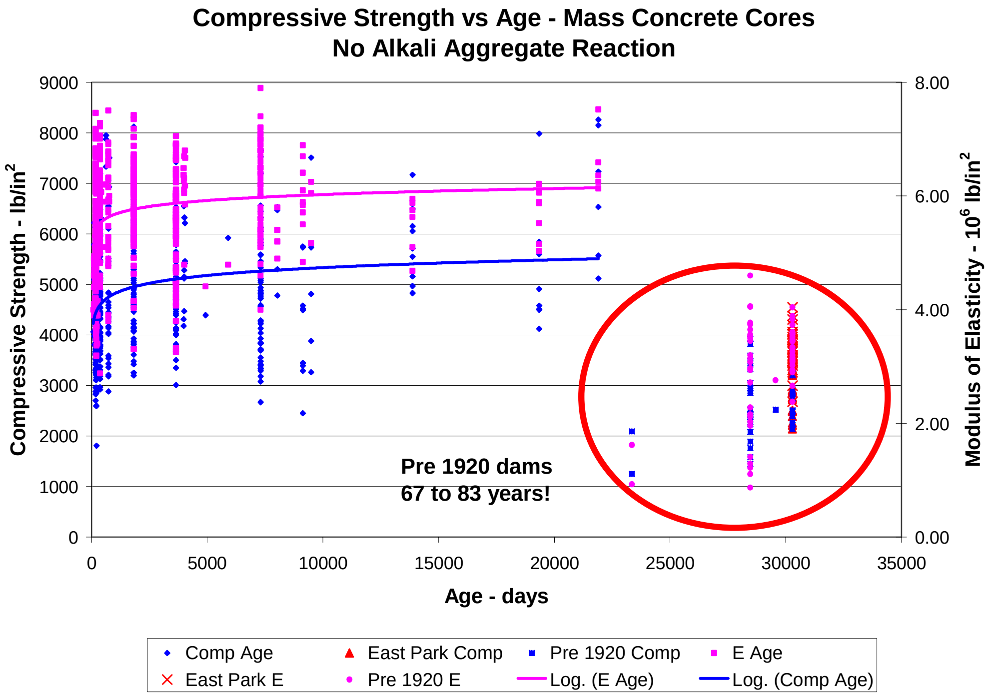

Figure 2.—Compressive strength development of concrete dams not subject to ongoing deterioration.

Table 1.—Average compressive strength and elastic properties of cores from Reclamation concrete dams not subject to aging compared to aging concretes constructed in the early twentieth century

	Average test age, days (yr)	Compressive strength, lb/in²	Modulus of elasticity, 10⁶ lb/in²	Poisson's ratio
Concrete dams (0 to 60 years old) *	10,418 (28.5)	5590	5.42	0.18
East Park Dam	30,295 (83)	2980	3.32	0.21
ACIS aging dams (1902 to 1920) *	29,100 (79.7)	2490	2.59	0.23

* Average is weighted for number of tests for a given sample set.

tests available for each structure. The old dams constructed prior to about 1920 have less than half the compressive strength and modulus of elasticity of comparable "modern dams" of the post-Hoover era. The pre-1920 dams form a separate data set for CFR evaluation purposes. These dams are the most vulnerable to concrete degradation and may require special precautions during modifications. For example, the low compressive strength of exterior mass concrete required longer reinforcing steel embedment lengths during recent outlet works structural modifications. The data then trends from the low to higher strengths in the 1920s, though some dams perform better than others. The “modern” concrete dams generally begin in the late 1920s or early 1930s, provided no other destructive mechanisms are in progress such as ASR or FT.

Compressive Strength and Elastic Properties Development of ASR-Affected Dams

Three Reclamation concrete dams have suffered from significant deterioration attributed to AAR, and in particular, ASR. Parker Dam, constructed in 1937 to1938, is located on the Colorado River about 60 river miles downstream of Hoover Dam and was the first Reclamation dam to be identified with ASR. American Falls Dam, constructed in 1927, was actually the first Reclamation structure to suffer from ASR, and it was ultimately replaced in 1977. Seminoe Dam was constructed in 1938 and has gradually experienced deterioration over time (Mohorovic, 1998). Both Parker and Seminoe dams have comparable “reference” dams constructed with similar materials and mixtures at about the same time frame with little deterioration (Dolen, 2006). The primary difference in the performance of the ASR-affected and reference dams lies in the cement alkali content, and/or aggregates used for construction. The Colorado River aggregate source used at Hoover Dam is essentially “nonreactive” and the Bill Williams River aggregate source at Parker Dam is very reactive. Evaluation of the data shows that Parker’s materials properties have not realized the same performance as Hoover Dam over time even though they used the same suppliers of type IV cement and had comparable mixtures. The concrete has about 60 percent of the compressive strength and modulus of elasticity and has shown little strength development over time.

This same comparative relationship exists between Grand Coulee Dam, constructed between 1933 and 1942, and Seminoe Dam, constructed in 1938. Due to the superior durability of the Grand Coulee materials, many laboratory test results were compared to or duplicated for other mix design investigations from that era. Modified (low heat) Type II cement, developed first for Grand Coulee Dam, was also used for the Seminoe testing program. However, ASR was unknown at the time of these tests, and possible decreases in strength and elastic properties for mixes with reactive aggregates were not investigated at the time. In retrospect, ASR may have been detected through close examination of these results or if long term tests had been performed.

Concrete dams affected by ASR are probably the most studied dams in the Reclamation dam inventory. Both Parker and Seminoe Dams have been cored and tested periodically for concrete degradation. American Falls Dam was studied extensively prior to replacement in 1977. Deterioration at Parker Dam due to ASR was identified within 2 years of construction. Damage from ASR at Seminoe Dam was not attributed primarily to ASR until the late 1990s, more then 50 years after construction. Six-inch diameter cores have been obtained and tested for strength and elastic properties and contribute to the database of ASR in mass concrete. Both the strength properties and condition of the concrete were analyzed by selective sorting in ACIS for ASR. Average strength and elastic properties of the ASR-affected and aging dams are summarized in table 2.

Table 2.—Average compressive strength and elastic properties of concrete dams subject to aging.

	Test age, days (yr)	Compressive strength, lb/in^2	Modulus of elasticity, 10^6 lb/in^2	Poisson's ratio
ASR-affected dams *	19,367 (53.1)	3695	2.28	0.20
ASR cores from the top 20 ft	17,512 (48.0)	3180	2.09	0.20
ASR cores from below 20 ft	17,888 (49.0)	4090	2.35	0.10
ACIS aging dams (1902 to 1920) *	29,095 (79.7)	2490	2.59	0.23

* Average is weighted for number of tests for a given sample set.

Strength and elastic properties were examined for ASR-affected dams compared to dams without ASR. The sorting can be performed on individual structures or for all structures by changing the querying properties. Figure 3 shows the compressive strength development of mass concrete cores with and without ASR. It is interesting to note the high compressive test results in figure 3 at 42 years (15,330 days) age, which were identified as coming from mass concrete placed in the lower portion of Parker Dam. Four different sources of cement were randomly delivered early in the construction of Parker Dam and one source of cement met the criterion for low-alkali cement. The high strength test results were from deep cores tested at the base of the dam in 1980 and may represent the unaffected concrete where the low-alkali cement was used. If so, these tests may represent the potential strength of Parker Dam if low-alkali cement had been used for all construction. Some other deep cores did not achieve the higher strengths and may represent placements that used high-alkali cement.

Data from Friant Dam provide a good comparison of the effects of ASR (Hartwell, 1990). Mass concrete was placed using both high and low alkali cements and with or without 20 percent pozzolan. The average compressive strength of ASR-affected mass concrete (high-alkali cement, no pozzolan) at 46 years age is about 3,220 lb/in^2, the modulus of elasticity is about 1.7 x 10^6 lb/in^2, and Poisson's ratio is 0.38. Tests from similar concrete with high-alkali cement and no pozzolan at 4 years age averaged about 6,760 lb/in^2, 6.0 x 10^6 lb/in^2, and 0.22, respectively. The average compressive strength decreased about 57 percent, and the average modulus of elasticity about 72 percent due to ASR. Tests performed on mass comparable concrete that used low-alkali cement plus 20 percent pozzolan showed no decrease in between 4 and 46 years age.

For some mass concrete dams, the strength and elastic properties also vary spatially with depth below the top of the dam. The tops of dams have less restraint and are more likely to expand and deteriorate. Table 2 shows average

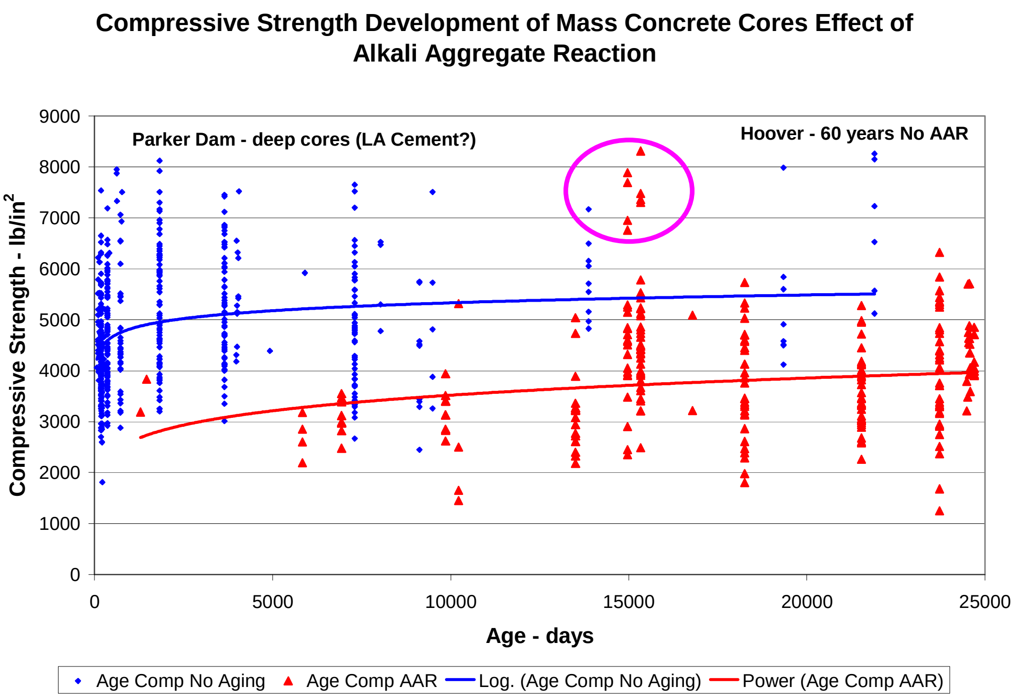

Figure 3.—Compressive strength development over time for mass concrete dams with and without ASR. The data represent tests from different dams.

compressive strength and elastic properties of ASR-affected cores sorted by depth below the top of drill holes, essentially the top 20 feet of these dams. The average compressive strength of cores from the top 20 feet of these drill holes is about 3,180 lb/in^2, compared to 4,090 lb/in^2 for cores tested more than 20 feet below the top of the drill holes, and 5,590 lb/in^2 for non-ASR-affected mass concrete. The average modulus of elasticity changed from 2.09 x 10^6 lb/in^2 to 2.35 x 10^6 lb/in^2, for cores tested above and below the 20-foot depth. These data compare with the non-ASR-affected concrete modulus of about 5.4 x 10^6 lb/in^2.

The decrease in modulus of elasticity is more apparent than compressive strength in ASR-affected dams for both early and long term ages. This can lead to apparent "low stresses" using conventional linear elastic structural analysis. However, these analyses should be used with caution as the behavior may be best represented using nonlinear analysis.

Figure 4 shows the relationship between compressive strength and modulus of elasticity for all concrete cores with and without ASR. Although the correlation coefficient for the equations is poor, the trend lines are added to show the demarcation between the two classes of concretes. Individual correlations between compressive strength and modulus of elasticity are normally much better for individual dams using the same aggregate types. The trends show that the strength to modulus of elasticity relationship is a good indicator of ASR and may be used in developing failure criteria for predictive models.

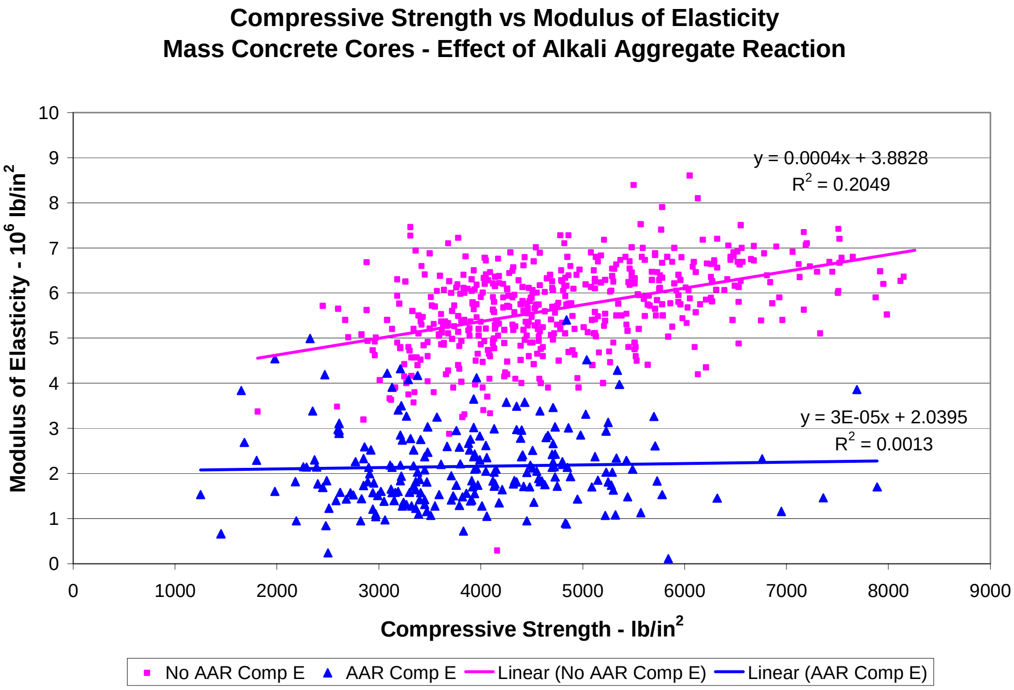

Figure 4.—Comparison of strength to modulus of elasticity in compression for mass concrete dams with and without ASR.

Tensile Strength Properties of Aging/ASR and Non-ASR-Affected Dams

Tensile strength is becoming more critical in the structural analysis of concrete dams, particularly for dynamic analysis due to earthquakes. Tensile strength tests were normally not performed until the 1970s, and the tensile strength development for dams constructed prior to this era is unknown. The results of direct and splitting tensile strength of good quality concrete and aging/ASR-affected concrete and are shown in table 3 and figure 5. The tensile strength data are entered in the database as average values for normally only a few tests for each mixture. The aging data also include some tests of old dams not subject to ASR. However, it is clear that the tensile strength of aging/ASR-affected dams averages about 50 percent of the direct tensile strength and 30 percent less in splitting tensile strength compared to dams without ASR degradation or aging. Also, the aging concrete data are often based only on "testable" concrete and do not represent the condition of the deteriorated concrete that could not be tested. Lift line ratios may not be directly comparable since the aging dams often have more disbonded lift lines. This input parameter is being added to more recent test programs and is a factor for some older and newer dams. Shear bond properties are not shown for this data set and have not yet been analyzed due to insufficient records.

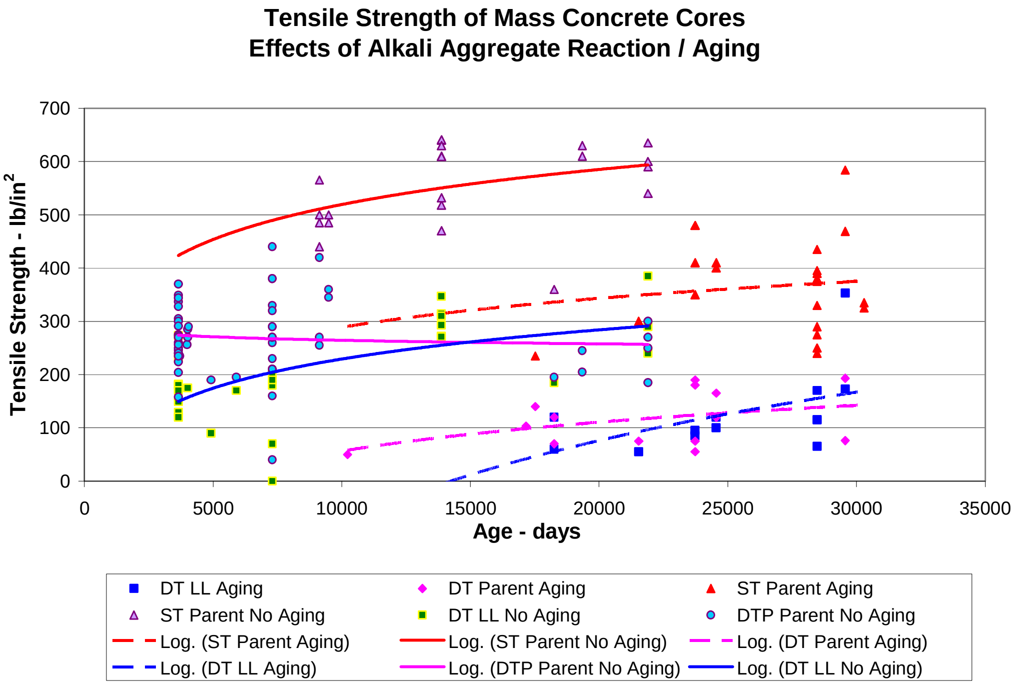

Figure 5.—Comparison of the effects of aging and ASR on tensile strength of mass concrete dams.

Table 3.—Effect of aging on tensile strength of mass concrete cores expressed as a percentage of average compressive strength,[1] based on data from the ACIS concrete materials database

	Tensile strength, lb/in^2 (%)[2]	
	No aging[3]	With aging[3]
Direct tensile strength (parent concrete)	245 (4.4)	105 (3.1)
Direct tensile strength (lift lines)	185 (3.3)	115 (3.4)
Splitting tensile strength (static)	520 (9.3)	365 (10.9)
Splitting tensile strength (dynamic)	745 (13.3)	420 (12.6)

[1] Average is weighted for number of tests for a given sample set.
[2] (%) Tensile strength expressed as a percent of comparable compressive strength.
[3] Average core test age for no aging dams is 10862 days (30 years); average age for aging dams is 25931 days (71 years).

Applications of Materials Properties Modeling

Strength Trends at Parker and Seminoe Dams

The strength trends at both Parker and Seminoe Dams have been studied extensively for the effects of ASR. Cracking in Parker Dam was identified as ASR after examinations confirmed the process first identified in 1942 (Stanton, 1942). Extensive concrete coring and testing have been performed since 1940, and the strength trends are well documented. Seminoe Dam suffered from early freezing and thawing near the dam crest, but ASR was not identified as a significant contributing factor to degradation until more then 60 years after construction. The deterioration at Seminoe Dam seems more alarming because the mass concrete appears to have nearly reached its projected ultimate strength potential before the onset of ASR. The slow rate of reaction may be due to the nature of the aggregates and the cold temperatures at the site. Another northern climate dam with the potential for similar behavior is Owyhee Dam, in Idaho. Tests near the crest of Owyhee Dam are revealing behavior similar to that at Seminoe Dam, and potentially reactive aggregates are prevalent in the vicinity of the dam.

From a comparative standpoint, Parker Dam concrete mixtures, cements, and construction methods are almost identical to those for Hoover Dam, the primary difference being that Hoover Dam used primarily non-reactive aggregates from the Colorado River, and Parker Dam used reactive aggregates from the Bill Williams River. The Type IV cement developed for use in Hoover Dam was also used for Parker Dam. In fact, some of the concrete manufacturing equipment used for Hoover Dam was transported directly to Parker Dam. Many of the Reclamation field staff and contractor personnel likely came from Boulder City. One key piece of equipment not used at Parker Dam was the cement blending plant. Several different sources of cement were used in the dam, resulting in spatially varying strength and elastic properties due to individual shipments with differing alkali contents. The performance of both dams has been reported extensively, and thus, comparison of these dams shows the change in materials properties attributed to ASR. Looking more closely at Parker Dam, concrete core results reveal spatial relationships, with high strength concrete in some sections in the bottom of the dam similar to Hoover Dam concrete, and poorly performing concrete in the upper portion of the dam. As previously mentioned, it is suspected that these tests represent unaffected concrete where the low-alkali cement was supplied to the dam. Some Type IV cement was used early in construction of Grand Coulee Dam, for which core tests at 1 to 3 years were available. The mass concrete core tests show exceptional compressive strength exceeding 7,000 lb/in^2.

Both laboratory and field data were compared for these three dams. Figure 6 shows results of compressive strength tests over time and the difference in strength gain expected (Hoover and Grand Coulee Dams) compared to the actual results at Parker Dam. The Parker data at 1 through 90 days of age are the average results of construction quality control cylinders, and the rate of strength gain compares favorably to laboratory trends. The core test results are shown only at 67 years of age to compare to the Hoover 60-year tests. Also interesting to note are the laboratory compressive strength results from 1935 using the Parker cement (supplied by the Metropolitan Water District)for both Bill Williams aggregate and Brett Pit aggregate shown in figure 7. This comparative testing was often done during the early mixture design studies conducted in the 1930s.

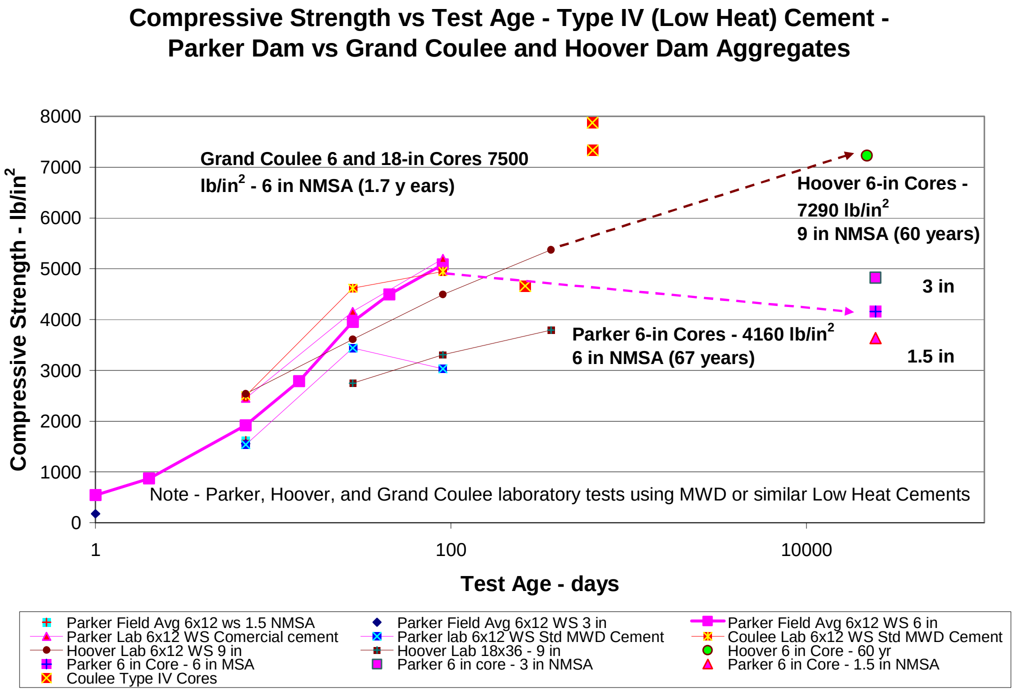

Figure 6.—Compressive strength development of mass concretes with Type IV cement for Parker Dam, Hoover Dam, and Grand Coulee Dam.

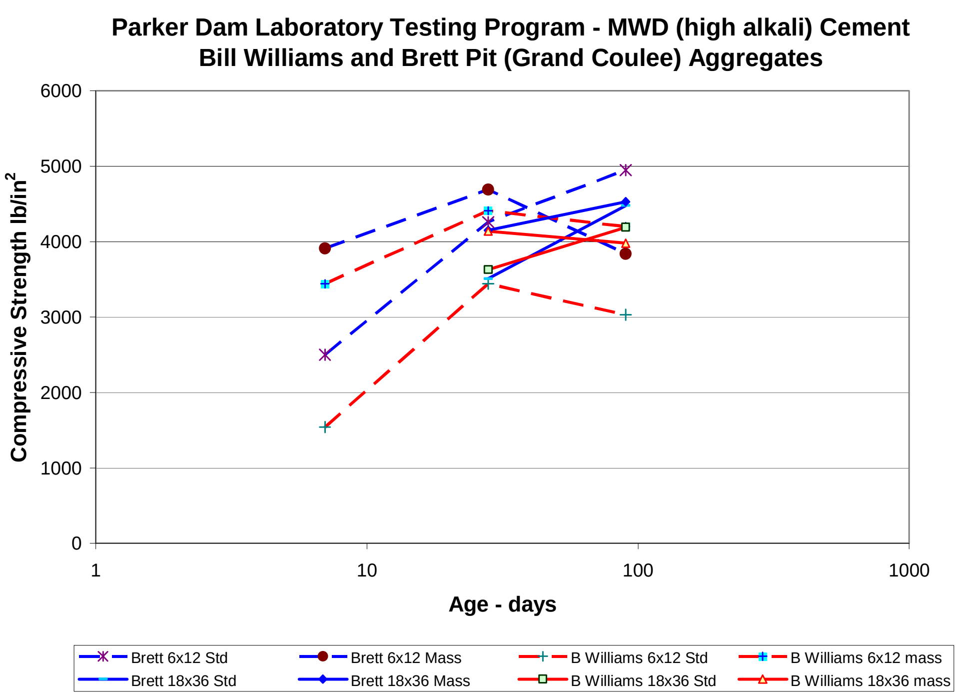

Figure 7.—Comparison of compressive strength development of laboratory concrete mixtures using Parker Dam cement with Parker (Bill Williams) and Grand Coulee (Brett Pit) aggregates.

Three of the four curing conditions with the Parker aggregates decreased in strength between 28 and 90 days. Only one of the four conditions for the Brett aggregate had a decrease in compressive strength between 28 and 90 days. Tests were not conducted beyond 90 days in the Parker mixture design studies because it is an arch dam. These laboratory tests may have been an unidentified precursor of the ASR that would attack the dam once it was constructed.

The compressive strength trends in figure 8 from the two ASR-affected dams show a relatively constant state for Parker Dam and a decreasing strength trend with Seminoe Dam. Some of the data scatter is due to the overall sampling not sorted by elevation and includes tests of concrete not significantly affected by ASR either due to the cement alkali content of individual block placements or location in the dam. When sorted by elevation, the rate of change can also be observed for the two dams as shown in figures 9 and 10. The compressive strength trends do not show an overall change with time for Parker Dam, even though some spatial trends may be present. For Seminoe Dam, it is readily apparent that the overall compressive strength is decreasing over time and that the compressive strength has significant spatial deterioration near the top of the dam as shown in figure 10. The deterioration is extending more deeply into the dam over time. The modulus of elasticity also shows the same trends as shown in figure 12. If ASR is suspected in dams, the compressive strength to modulus of elasticity ratios and spatial orientation may provide the best supporting documentation for CFR evaluation purposes.

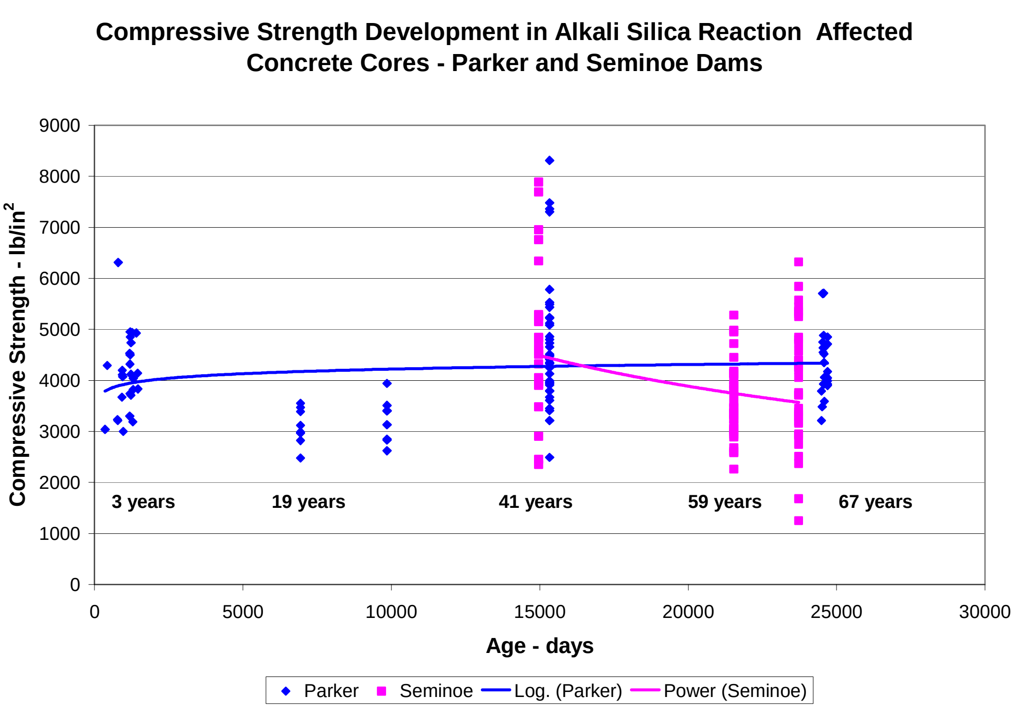

Figure 8.—Compressive strength trends for mass concrete cores at Parker and Seminoe Dams.

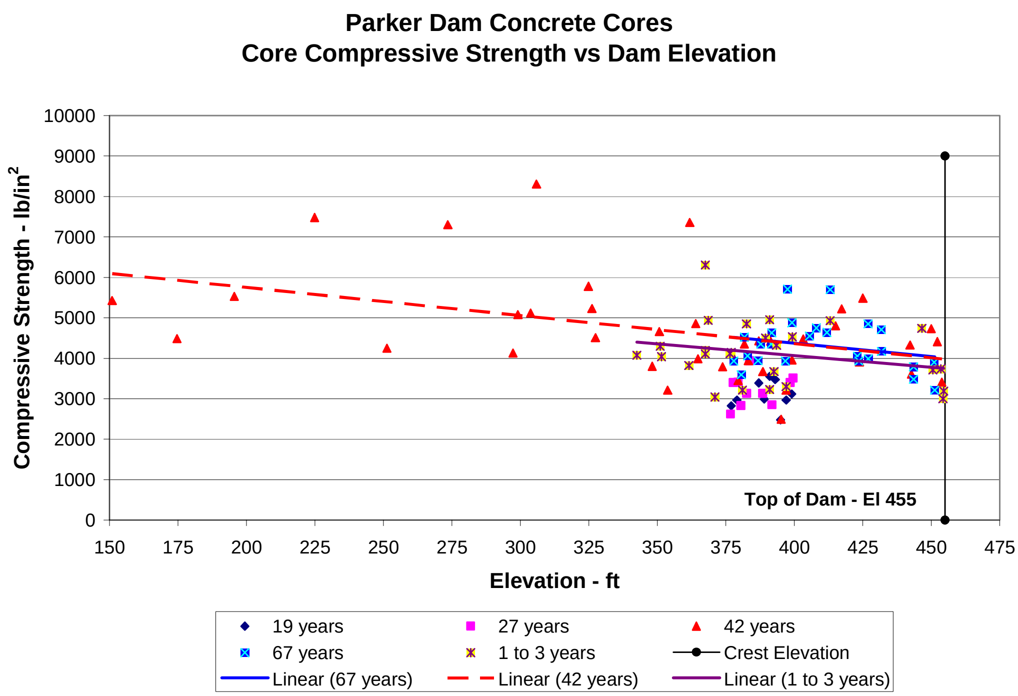

Figure 9.—Compressive strength of mass concrete at Parker Dam, Arizona sorted by elevation within the structure. The top of the dam is at elevation 455.

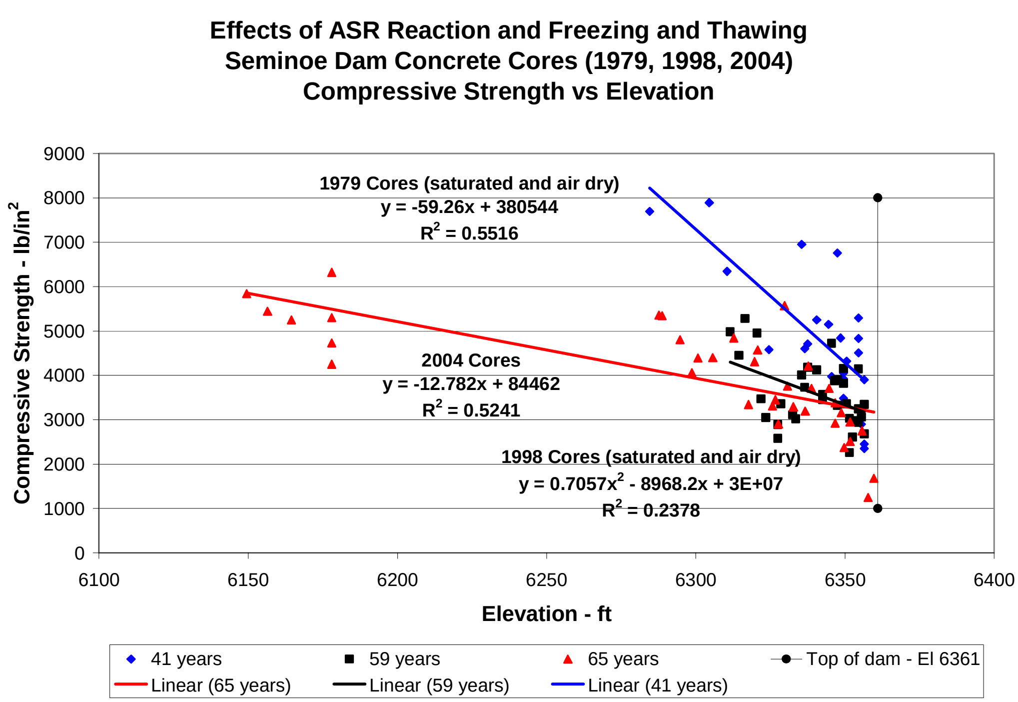

Figure 10.—Compressive strength trends of mass concrete at Seminoe Dam, Wyoming, sorted by elevation showing changes in strength over time.

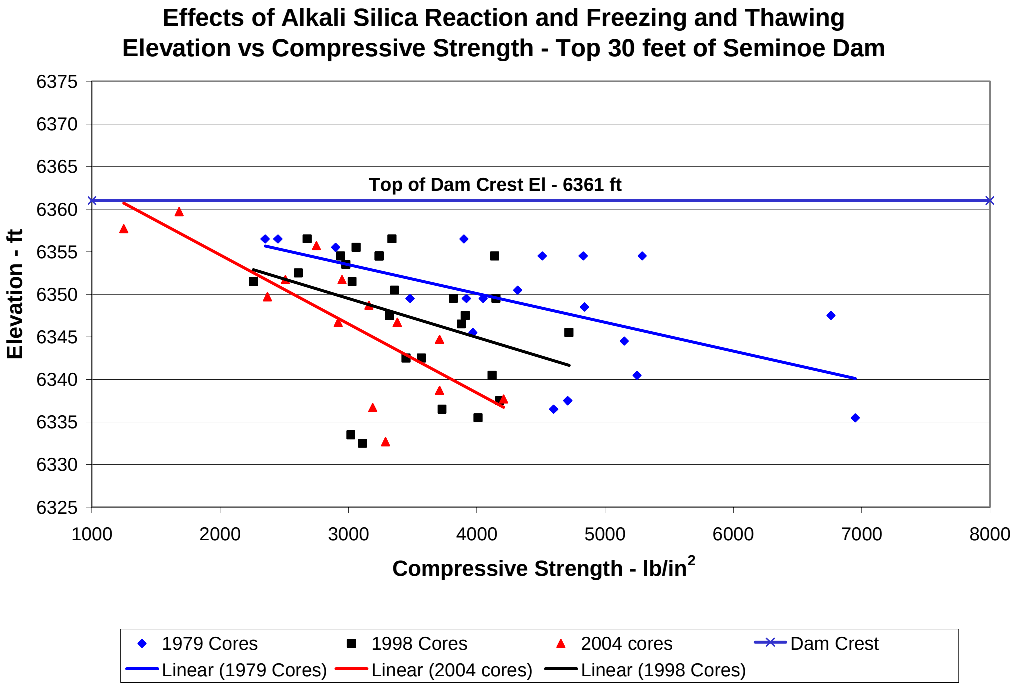

Figure 11.—Compressive strength development in mass concrete at the top of Seminoe Dam, Wyoming, sorted by elevation showing decreasing strength over time.

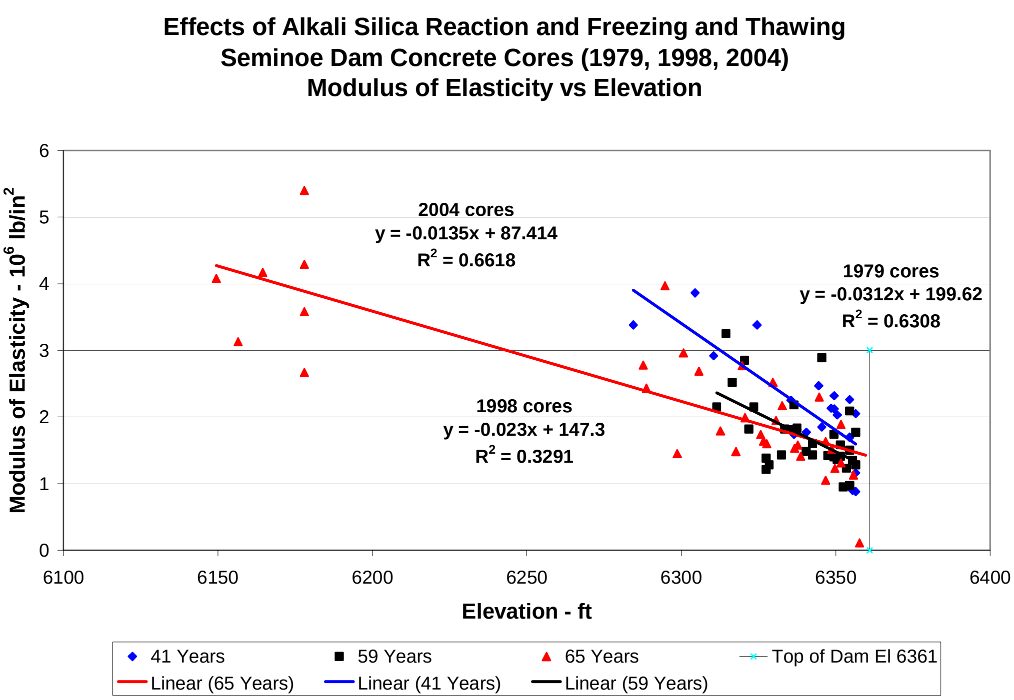

Figure 12.—Modulus of elasticity in compression trends of mass concrete at Seminoe Dam, Wyoming, sorted by elevation showing changes in modulus over time.

Yellowtail Dam Issue Evaluation

The Yellowtail Dam issue evaluation presented a unique opportunity to use the ACIS database to examine strength trends to resolve an outstanding dam safety recommendation. Yellowtail Dam is a concrete thick arch structure approximately 525 feet high located about 45 miles southwest of Hardin, Montana. Mass concrete in the dam was placed in 1963, 1964, and 1965. Four mass concrete mixtures with 6-inch nominal maximum size aggregate (NMSA) were used in the dam. This included “interior concrete” (the primary mass mixture) and “exterior concrete” with a higher cementitious materials content for increased durability. The cementitious materials content was decreased in July 1963 after high compressive strengths were recorded from control cylinders cast early during construction. The remaining concrete construction was completed with revised mixtures and purposely lower ultimate compressive strengths. Thus, four potential mixtures could be sampled, each with differing materials properties. Ten-inch diameter concrete cores were extracted from the dam from the control cable gallery (elevations 3185 and 3207) and the filling line gallery (elevation 3462) for periodic testing at 6 months, 1 year, 5 years, 10 years, and 25 years of age (Graham, 1969). During the 2001 Comprehensive Facility Review, a cursory summary of the results from previous core programs showed apparent anomalous behavior in properties between 10 and 25 years after construction. Specifically, compressive strength, modulus of elasticity, and Poisson’s ratio showed a relatively high variability, and an apparent decrease in strength was recorded between 10 and 25 years, resulting in the following SOD recommendation.

> 2001-SOD-B—Sample and test the concrete at Yellowtail Dam to determine the strength properties and compare to past tests.

A detailed examination of the results of all core tests was performed using ACIS. Individual tests were entered to determine strength trends related to the core tests spatially by core location, test age, and depth (Dolen, 2005). The results of compressive strength and elastic properties from this analysis are summarized in table 4. Although the overall behavior showed decreasing strength, the results of a detailed examination revealed spatial variability between the different mixtures placed in the dam and additional variability due to different (vertical) lifts placed within individual blocks for the same mixtures placed on different dates. The apparent decrease in compressive strength was likely attributed to variability of tests performed at different locations (and with different mixtures) and to the different moisture conditioning of cores tested at 10 years of age. Spatial variability was identified for the same concrete mixtures within individual blocks sampled from lift to lift. This may be due to concrete mixture variability during construction, core test variability, or within lift variability for the 7½-foot deep lifts. When “apples and apples” core tests were compared, the lower strength tests were identified in concrete not previously tested, and some of the confusion of test evaluation was due to comparing concrete mixtures before to those after the cementitious materials were decreased.

Table 4.—Compressive strength of 25-year cores compared to reference core tests by spatial orientation—Yellowtail Dam issue evaluation—Yellowtail Dam, Montana

			Compressive strength, lb/in^2					
Mix	Drill hole	Elevation	6 mo	1 yr	5 yr	10 yr[1]	25 yr	Percent 1 yr
INT9/1963	18-13-V	3179.8	4460	6310	6660	7520	7510	119
INT/9B1963	18-13-V	3176.6	*No comparable data for this lift*				4810	
INT6/1963R	10-9-V	3204.5	4100	4400	5810	6550	5730	130
INT6B/1963R	10-9-V	3198.5	*No comparable data for this lift*				3880	
INT6B/1963R	10-9-V	3194.7	*No comparable data for this lift*				3260	
INT2/1964	5-9-V	3459.6	3300	3250			3390	104
INT2B/1964	5-9-V	3450.1	*No comparable data for this lift*				3450	
INT8/1964	24-10-V	3459.6		3400			3440	101
INT8B/1964	24-10-V	3453.6	*No comparable data for this lift*				4520	
INT8C/1964	24-10-V	3447.9	*No comparable data for this lift*				3290	
EXT3/1964	5-10-V	3459.5	4410	5090			4580	90
EXT3B/1964	5-10-V	3453.7	*No comparable data for this lift*				5730	
EXT3B/1964	5-10-V	3449.7	*No comparable data for this lift*				5750	
EXT5/1964	24-11-V	3459.5	3440	3900			4490	115
EXT5B/1964	24-11-V	3452.5	*No comparable data for this lift*				2450	
Average[2]			4280	5360	6240	7040	6620	
Average (all tests)							4420	
Average[3]			3940	4390			4860[3]	110[3]
Standard deviation (25 years—all tests)							1283	

[1] 10-year cores tested dry (may test about 10-20% higher than saturated test specimens).
[2] Average based on two comparable tests each at 6 mo, 1, 5, 10, and 25 yr.
[3] Average of comparable tests at 25 yr. 25-yr tests as a percent of 1-yr tests only where comparable data exists from the same lift as previous core programs (6 tests). Insufficient comparable data available for 5- and 10-yr tests.

This analysis resulted in a recommendation that the strength properties were not decreasing in the dam, and a comprehensive coring program related to this issue was not necessary. The estimated cost savings for performing a concrete coring and testing investigation at this dam was about $250,000.

Concluding Remarks and Recommendations

The concrete materials properties model developed for mass concrete provides a valuable resource for Reclamation and the Dam Safety Program. Compressive strength, elastic properties, and tensile properties can be identified for three different types of mass concrete; the pre-1920s dams, the post-Hoover dams, and the ASR-affected dams. Verifiable data are needed to document a dam's current condition for dam safety reviews. Knowledge of the expected materials properties for concrete dams is a resource for designers performing initial examinations and comparison to the current condition. Analysis of possible changes in materials properties over time must be noted in structural analysis for long term stability. If the properties are decreasing due to aggressive deterioration, the potential for a dam safety modification exists, and program funding will be needed for design and construction. Verifiable data will be needed to present the case to program managers and the public.

Significant effort has been expended to identify the changes in materials properties due to alkali-silica reaction due in part to current investigations at Seminoe and Parker Dams. Freezing and thawing properties have been entered for mass concrete at Warm Springs and Black Canyon Dams and some structural concretes for aging embankment dam spillways and outlets. This database can be expanded with additional records. These materials properties are important for developing predictive models of concrete deterioration. Freezing and thawing predictive modules under development could be verified from this testing database.

The ACIS concrete materials database is only as good as the data input. Early age concrete properties are difficult to locate and verify due to the lack of a central depository of concrete testing before the creation of the Reclamation Concrete Laboratory in the early 1930s. These early 1900s structures are also the dams most likely to require attention in the next decade. Several early designs require particular attention. The early thin arch dams such as Gerber and Warm Springs Dams are located in aggressive environments and subject to deterioration from freezing and thawing. Early multiple thin arch or slab and buttress dams constructed between 1910 and 1930 may also be in need of investigation. These dams lack the inherent strength and durability to resist the long term effects of aging, and they often have thinner cross sections and thus, less mass to loose before lowering the factors of safety.

Analysis of verifiable materials properties is also necessary for security issues in dam safety. Models developed for nonlinear analysis in seismic or high energy applications normally require input parameters of concrete materials properties. Mass concrete materials properties differ from typical structural concretes due to their varying strengths, elastic properties, materials, and mixture proportions.

Reclamation's database of mass concrete properties is likely the most comprehensive in the world. Aging concrete durability was most recently a featured topic in the 2003 International Committee on Large Dams (ICOLD) Congress in Montreal, Canada. Both the U.S. Society on Dams and ICOLD expressed interest in publishing the results of aging properties and processes of mass concrete dams.

The incorporation of the concrete materials properties with geographical information systems will provide data for decision makers in real time. This trend is necessary as Reclamation becomes more dependent on the Internet for its information. A major need is the transfer of hundreds of documents of materials properties into modern information technology systems. Reclamation's early entry into the development of mass concrete technology is also a handicap as the data becomes unavailable unless transferred from hard copies to modern data storage. Lastly, Reclamation's technical staff itself is aging with the potential for an accompanying loss of institutional knowledge. Documentation of materials properties is necessary to transfer this information to the next generation of dam and dam safety engineers.

References

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

Dolen, Timothy P., Gregg Scott, Kurt von Fay, and Robert Hamilton, *The Effects of Concrete Deterioration on Safety of Dams*, Dam Safety Research Report No. DSO-03-05, December, 2003.

Stanton, T.E., "Expansion of Concrete through Reaction between Cement and Aggregates," *Transactions of ASCE,* Vol. 66, December, 1940, pp. 1781-1811.

Dolen, T.P., *2005 Concrete Coring—Laboratory Testing Program—Seminoe Dam, Kendrick Project, Wyoming*, Technical Memorandum No. MERL-2005-3, Bureau of Reclamation Technical Service Center, Denver, CO, 2003.

Dolen, T.P., *Parker Dam 2005 Concrete Coring – Laboratory Testing Program, Parker-Davis Project, California-Arizona, Lower Colorado Region*, Technical Memorandum No. MERL-2005-20, March 2006.

Hartwell, J.N., *Alkali-Aggregate Reaction Investigations at Friant Dam, California*, Report No. R-90-05, U.S. Department of the Interior, Bureau of Reclamation, March 1990.

Graham, James R., *Concrete Performance in Yellowtail Dam, Montana—5-Year Core Report*, Report No. C-1321, U.S. Department of the Interior, Bureau of Reclamation, Concrete and Structural Branch, Denver, Colorado, October 30, 1969.

Dolen, T.P., *Yellowtail Dam Issue Evaluation, Mass Concrete Materials Properties Summary, Pick-Sloan Missouri Basin Project, Montana, Great Plains Region*, Technical Memorandum No. YEL-D8180-IE-2005-1 / MERL-2005-7, May 2005.

Aging Concrete Information System Database References—U.S. Department of the Interior, Bureau of Reclamation, Materials Engineering and Research Laboratory, Technical Service Center, Denver, Colorado

Tests of Concrete Cores Extracted from Grand Coulee Dam, Columbia Basin Project, Washington, Laboratory Report No. C-138, June 13, 1941.

Long, J.F., *Tests of Concrete Cores from Mass Concrete Test Blocks—Shasta and Friant Dams—Central Valley Project (Results to 5 Years' Age)*, Materials Laboratories Report No. C-346, November 1950.

Laboratory and Field Investigations of Concrete, Hungry Horse Dam, Hungry Horse Project, Concrete Laboratory Report No. C-699, December 4, 1953.

Harboe, E.M., *Properties of Mass Concrete in Bureau of Reclamation Dams*, Concrete Laboratory Report No. C-1009, December 6, 1961.

Memorandum from Chief, Concrete and Structural Branch, *Santa Cruz Dam Concrete Cores*, New Mexico, September 10, 1976.

Kepler, W.F., *Owyhee Dam—1982 Concrete Core Investigation*, Report No. GR-82-11, August 1982.

Harboe, E.M. *Properties of Concrete in Glen Canyon Dam—25-Year Report*, Report No. GR-85-12, April 1986.

Riffle, H.C. and F.L. Smith, *Strength and Elastic Properties of Concrete in Flaming Dam—10-Year Core Report*, CRSP, Wyoming, Report No. GR-13-76. February 1976.

Kepler, W.F., *Evaluation of Concrete Cores—Arrowrock Dam, Idaho,* Boise Project, Pacific Northwest Region, Report No. R-89-03, May 1989.

Kepler, W.F., *Concrete Performance at Pueblo Dam, Colorado, 15-Year Core Report*, Fryingpan-Arkansas Project, Colorado, Report No. R-89-13, December 1989.

Kepler, W.F., *Concrete Performance at Crystal Dam, Colorado—10-Year Report*, Report No. R-90-09, April 1990.

Kepler, W.F., *Checked Data, Hoover Dam Concrete Core Tests*, Boulder Canyon Project, Arizona-Nevada.

Memorandum, *Concrete Core Test*, East Park Dam, 1993.

Harris, D.W., *Summary of Material Characteristics Monticello Dam Core Testing Program*, Solano Project, California, June 1998.

Snorteland, N.J., *Concrete Performance at Elephant Butte Dam, New Mexico*, February 1999.

Dolen, T.P. and C. Mohorovic, *1996/1997 Concrete Coring-Laboratory Testing Program, Warm Springs Dam Corrective Action Study, Safety of Dams Program, Vale Project, Oregon*, May 15, 2000.

Dolen, T.P. and P.A. Mitchell, *2001-2002 Concrete Coring—Laboratory Testing Program, Folsom Dam Modifications*, Report No. MERL-2002-01, Contract for U.S. Army Corps of Engineers, Sacramento District, California, April 3, 2002.

Madera, Veronica, *East Canyon Dam 2004 Concrete Coring—Laboratory Testing Program*, Weber Basin Project, Utah, Upper Colorado Region, Technical Memorandum No. MERL-2005-01, March 2005.

Madera, Veronica, *Hungry Horse Dam 2005 Concrete Coring—Laboratory Testing Program*, Hungry Horse Project, Montana, Pacific Northwest Region, Technical Memorandum No. MERL-2006-1, April 2006.

Appendix

Data Reports for Mass Concrete Cores—Yellowtail and Parker Dams

Core - Compressive Strength / Elasticity Report

Filter: Feature = YELLOWTAIL

Project: PSMBP-YELLOWTAIL

YELLOWTAIL

DAM

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age Yrs	Test Age Days	Depth From	Depth To	Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
DH-63-10-1															
	11/20/1963	10	7+43												
				0	180	0	2	INT-5	1	3450					152
				0	180	4	6	INT-5	1	3780	1	5.49	0.23		151
DH-63-10-2															
	11/21/1963	10	7+45												
				0	180	0	2	INT-6	1	4310	1	5.3	0.23		150
				0	180	2	4	INT-6	1	3890	1	5.05	0.18		154
DH-63-18-1H															
	11/14/1963	18	12+22												
				0	210	0	2	INT-10	1	4740					154
				0	210	4	6	INT-10	1	3570	1	6.04	0.27		153
				0	210	6	8	INT-10	1	4540	1	5.71	0.22		151
DH-63-18-1V															
	8/7/1963	18	12+20												
				0	180	0	2	INT-11	1	4570	1	5.03	0.08		150
				0	180	2	4	INT-11	1	2880	1	5.62	0.14		154
				0	180	4	6	INT-11	1	5430	1	5.54	0.24		154
DH-63-18-2															
	11/15/1963	18	11+80												
				0	225	2	4	INT-9	1	4460	1	5.66	0.26		152
				1	0	0	2	INT-9	1	5120	1	6.1	0.26		151
				1	0	2	4	INT-9	1	4530	1	5.28	0.29		153
				1	0	4	6	INT-9	1	5220	1	5.38	0.22		154
DH-63-18-3															
	11/18/1963	18	12+00												
				0	180	0	2	EXT-1	1	4500	1	5.47	0.26		153
				0	180	2	4	EXT-1	1	5900	1	6.21	0.24		154
DH-63-5-5															
	6/25/1965	5	4+90												

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				1	0	0	2	INT-1	1	2970	1	5.01	0.2		153
				1	0	2	4	INT-1	1	3520	1	5.72	0.3		152
DH-64-14-2															
	11/24/1964	14	9+92												
				0	180	0	2	INT-13	1	4070	1	4.74	0.21		148
				0	180	2	4	INT-13	1	3720	1	4.98	0.2		153
DH-64-18-4A															
	5/3/1963	18	12+23												
				1	0	0	2	INT-11	1	5940	1	5.8	0.21		151
DH-64-18-4B															
	6/5/1964	18	12+23												
				1	50	0	2	INT-9	1	6310	1	6.07	0.23		152
DH-64-18-6															
	6/8/1964	18	12+88												
				1	0	0	2	EXT-1	1	4470	1	5.36	0.22		153
				1	0	2	4	EXT-1	1	3810	1	5.38	0.25		150
DH-64-20-2															
	11/17/1964	20	13+20												
				0	180	0	2	INT-12	1	5120	1	5.58	0.27		146
				0	180	2	4	INT-12	1	4430	1	4.96	0.19		151
DH-64-24-1															
	11/9/1964	24	15+52												
				0	180	0	2	EXT-4	1	4390	1	5.75	0.21		153
				0	180	2	4	EXT-4	1	3980	1	5.05	0.19		152
DH-64-24-2															
	11/9/1964	24	15+48												
				0	180	0	2	EXT-5	1	4180	1	5.32	0.2		151
				0	180	2	4	EXT-5	1	2700	1	5.02	0.18		149
DH-64-5-1															
	12/1/1964	5	4+85												
				0	180	0	2	EXT-2	1	3610	1	5.37	0.22		150
				0	180	2	4	EXT-2	1	3610	1	5.53	0.25		152
DH-64-5-2															
	12/1/1964	5	4+80												
				0	180	0	2	EXT 3	1	4120	5	4.95	0.24		152
				0	180	2	4	EXT 3	1	4690	1	5.07	0.21		152
DH-64-5-3															
	11/30/1964	5	4+90												
				0	180	0	2	INT-1	1	4000	1	5.36	0.21		152

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				0	180	2	4	INT-1	1	2830	1	5.08	0.21		150
DH-64-5-4															
	12/1/1964	5	4+85												
				0	180	0	2	INT-2	1	3640	1	4.89	0.24		146
				0	180	2	4	INT-2	1	2960	1	4.62	0.21		153
DH-64-9-1															
	11/30/1964	9	7+04												
				0	180	0	2	INT-3	1	4570	1	5.74	0.19		154
				0	180	2	4	INT-3	1	3680	1	5.33	0.24		154
DH-64-9-2															
	11/30/1964	9	7+05												
				0	180	0	2	INT-4	1	3250	1	4.42	0.2		
				0	180	2	4	INT-4	1	3300	1	4.72	0.23		150
DH-65-10-3															
	6/4/1964	10	7+45												
				1	0	1	3	INT-6	1	4390	1	4.83	0.24		151
				1	0	3	5	INT-6	1	4410	1	5.82	0.24		156
DH-65-10-4															
	6/5/1964	10	7+44												
				1	0	0	2	INT-5	1	4310	1	5.9	0.22		154
				1	0	2	4	INT-5	1	4150	1	5.3	0.26		150
	6/29/1965	20	13+25												
				1	0	0	2	INT-12	1	5640	1	5.74	0.21		152
				1	0	2	4	INT-12	1	5480	1	6.32	0.25		156
DH-65-14-4															
	6/28/1965	14	9+90												
				1	0	0	2	INT-13	1	3890	1	5.22	0.23		150
				1	0	2	4	INT-13	1	3790	1	4.82	0.2		153
DH-65-18-10															
	6/29/1965	18	12+15												
				1	0	0	2	INT-7	1	5710	1	5.65	0.22		150
				1	0	2	4	INT-7	1	4420	1	5.18	0.21		154
DH-65-18-9															
	9/14/1968	18	12+00												
				5	0	0	2	EXT-1	1	4630	1	6.02	0.19		154
				5	0	2	4	EXT-1	1	5610	1	5.49	0.26		153
DH-65-24-7															
	6/30/1965	24	15+30												
				1	0	0.3	2	INT-8	1	3620	1	5.12	0.23		152

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				1	0	2	4	INT-8	1	3180	1	5.94	0.3		152
DH-65-24-8															
	7/1/1965	24	15+48												
				1	0	0	2	EXT-4	1	4440	1	5.36	0.22		153
				1	0	2	4	EXT-4	1	4160	5	0.29			154
DH-65-24-9															
	7/1/1965	24	15+48												
				1	0	0.5	2	EXT-5	1	4130	1	4.99	0.21		150
				1	0	2	4	EXT-5	1	3970					149
				1	0	4	5.5	EXT-5	1	3870					151
				1	0	5.5	7	EXT-5	1	3630	1	5.27	0.25	154	
DH-65-5-6															
	6/25/1965	5	4+86												
				1	0	0	2	INT-2	1	3370	1	4.57			147
				1	0	2	4	INT-2	1	3130	1	5.2	0.24		153
DH-65-5-7															
	6/24/1965	5	4+75												
				1	0	0	2	EXT-2	1	4900	1	5.49	0.25		152
				1	0	2	4	EXT-2	1	3910	1	6.04	0.23		154
DH-65-5-8															
	6/24/1965	5	4+80												
				1	0	0	2	EXT 3	1	5130	1	5.04	0.2		151
				1	0	3	4	EXT 3	1	5050	1	5.13	0.2		156
DH-65-9-3															
	6/26/1965	9	7+02												
				1	0	0	2	INT-3	1	4030	1	6.33	0.25		156
				1	0	2	4	INT-3	1	4150	1	5.39	0.25		154
DH-65-9-4															
	6/25/1965	9	7+06												
				1	0	0	2	INT-4	1	2920					146
				1	0	2	4	INT-4	1	3500	1	5.21	0.23		148
				1	0	4	6	INT-4	1	4050	1	5.21	0.23		153
DH-68-10-5															
	10/3/1968	10	7+45												
				5	0	0	2	INT-6	1	5860	1	5.77	0.24		151
				5	0	2	4	INT-6	1	5760	1	6.11	0.21		153
DH-68-10-6															
	10/3/1968	10	7+44												
				5	0	0	2	INT-5	1	4890	1	5.77	0.24		154

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				5	0	2	4	INT-5	1	4230	1	5.18	0.21		151
DH-68-18-7															
	7/31/1968	18	12+25												
				5	0	2	4	INT-9	1	6350	1				150
				5	0	4	6	INT-9	1	6960	1	5.4	0.2		152
DH-68-18-8															
	8/3/1968	18	12+10												
				5	0	0	2	INT-10	1	5350	1	5.76	0.23		154
				5	0	2	4	INT-10	1	4690	1	5.41	0.21		152
DH-74-10-7															
	3/22/1974	10	7+46												
				10	330	0	2	INT-5	1	4180	1	6.37	0.26		152
				10	330	2	4	INT-5	1	4310	1	6.49	0.29		155
DH-74-10-8															
	3/22/1974	10	7+45												
				10	335	0	2	INT-6	1	6550	1	6.27	0.27		151
DH-74-18-10															
	3/9/1974	18	12+34												
				11	37	4	6	INT-9	1	7520	1	6.67	0.25		157
DH-74-18-11															
	3/16/1974	18	12+04												
				10	350	0	2	EXT-1	1	5120	1	6.31	0.22		
				10	355	2	4	EXT-1	1	5150	1	6.7	0.26		
DH-74-18-12															
	3/19/1974	18	12+04												
				10	350	0	2	EXT-1	1	5280	1	6.05	0.23		154
				10	350	2	4	EXT-1	1	4470	1	6.11	0.24		152
DH-74-18-9															
	3/11/1974	18	12+32												
				11	22	0	2	INT-10	1	5420	1	6.8	0.25		153
				11	22	2	4	INT-10	1	5460	1	6.18	0.28		151
				11	22	4	6	INT-10	1	6210	1	5.85	0.19		152
DH-88-10-9															
	7/7/1988	10	7+45												
				26	0	2	4	INT-6	1	5730					
				26	0	8	10	INT-6	1	3880	1	5.17	0.25		155
				26	0	12	13	INT-6	1	3260	1	6.25	0.26		156
DH-88-18-13															
	6/28/1988	18	12+31												

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				26	0	4	6	INT-9	1	7510	1	6.04	0.25		154
	12/1/1988	18	12+30												
				26	0	8	10	INT-9B	1	4810	1	6.05	0.25		152
DH-88-24-10															
	7/10/1988	24	15+30												
				25	0	2	4	INT-8	1	3440	1	4.84	0.22		151
				25	0	8	10	INT-8	1	4520	1	6.7	0.29		155
				25	0	14	16	INT-8	1	3290					155
DH-88-24-11															
	7/24/1988	24	15+45												
				25	0	2	4	EXT-5	1	4490	1	5.89			154
				25	0	9	11	EXT-5	1	2450	1	5.71	0.21		154
DH-88-5-10															
	8/3/1988	5	4+80												
				25	0	2	4	EXT 3	1	4580	1	6.89	0.28		152
				25	0	8	10	EXT 3	1	5730	1	5.84	0.26		155
				25	0	12	13	EXT 3	1	5750	1	6.1	0.25		154
DH-88-5-9															
	7/19/1988	5	4+87												
				25	0	2	4	INT-2	1	3390	1	5.5	0.26		152
				25	0	12	13	INT-2	1	3450	1	6.41	0.28		156

Core - Compressive Strength / Elasticity Report

Filter: Feature = PARKER DAM AND POWERPLANT

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age Yrs	Test Age Days	Depth From	Depth To	Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density

Project: PARKER-DAVIS

PARKER DAM AND POWERPLANT

DAM

Drillhole Number	Core Date	Dam Block	Drillhole Station	Yrs	Days	From	To	Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
DH-1938-2,2A															
	11/1/1938	D	1+95												
				2	68	0	10	M6AZNOV1937	3	6310	1	3.8	0.17		148
				2	208	0	10	M6AZNOV1937	5	4195	3	3.8	0.17		146
DH-1938-6-1															
	11/1/1937	E	2+06												
				2	218	0	10	M6AZNOV1937	5	4075	1	3.7	0.18		
DH-1938-6-3															
	11/1/1938	D	1+80												
				2	209	0	10	M6AZNOV1937	4	4110	3	4	0.13		148
DH-1938-6-4															
	12/1/1938	D	1+56												
				2	193	0	10	M6AZDEC1937	6	3670	4	3.43	0.13		147
DH-1938-6-5															
	11/1/1938	Q	8+41												
				1	63	0	10	M6CANov1937	6	4295	1	3.4	0.14		147
DH-1938-6-6															
	11/27/1938	Q	8+44												
				0	357	0	10	M6CANov1937	3	3040	3	3.17	0.12		149
DH-1938-6-7															
	12/2/1938	R	8+60												
				2	51	0	10	M6CADEC1937	6	3210	3	3.07	0.15		147
DH-1938-8,8A															
	12/1/1938	R	8+69												
				2	47	0	10	M6CADEC1937	8	3230	4	3.13	0.17		146
DH-1940-10-27															
	10/7/1940	E	2+25												
				3	234	0	2	MASS 1.5MSA	1	4080					149
DH-1940-6-11															
	1/1/1940	F	2+60												

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				3	194	0	1	MASS 1.5MSA	1	3190					150
DH-1940-6-47_50															
	11/7/1940	E	2+25												
				3	315	0	1	M6 JAN38	1	4930	1	2.08	0.15		152
DH-1940-6-51_54															
	11/12/1940	E	2+25												
				3	360	0	1	M6 DEC37	1	4140	1	3.2	0.17		152
DH-1940-6-7															
	9/7/1940	E	2+45												
				2	235	0	1.5	M6 SEPT37	1	3000	1	2.35	0.13		147
DH-1941 ALL6															
	1/1/1941	VARIES													
				4	0	0	10	M6 AVG	3	3830	3	3.4	0.2		
DH-1941-10-64															
	2/20/1941	J	4+91.7												
				3	90	0	1.5	M6 AVG	1	4530	1	3.79	0.22		153
				3	90	2.5	3.5	M6 AVG	1	3300	1	2.48	0.28		
				3	100	6	7	M6 AVG	1	4320	1	2.72	0.19		152
				3	107	8.5	9.5	M6 AVG	1	4950	1	3.83	0.22		152
				3	107	10	11	M6 AVG	1	4500	1	2.76	0.19		
				3	112	17	18	M6 AVG	1	4850	1	3.85	0.19		151
				3	135	23	24	M6 AVG	1	4120	1	3.51	0.22		154
				3	171	31	32	M6 AVG	1	4940	1	3.79	0.15		154
				3	203	38	39	M6 AVG	1	3820	1	2.62	0.14		154
				3	210	48	49	M6 AVG	1	4040	1	3.58	0.25		154
DH-1941-10-86															
	5/23/1941	E	2+40												
				3	100	1	2	MASS 1.5MSA	1	3740	1	1.42	0.17		150
				3	127	4	5	MASS 1.5MSA	1	3710	1	1.86	0.15		151
				3	136	8	9	MASS 1.5MSA	1	4740					154
DH-1945-6-1															
	5/19/1945	J	4+94												
				7	240	0	1	M6 AVG	1	4980	1	2.73	0.14		153
				7	240	1	2	M6 AVG	1	4670	1	2.11	0.12		152
				7	240	2	3	M6 AVG	1	4630	1	3.21	0.16		152
				7	240	3	4	M6 AVG	1	4330	1	2.52	0.16		153
				7	240	5.5	6.5	M6 AVG	1	4200	1	2.02	0.04		154
				7	240	7	8	M6 AVG	1	4920	1	3.25	0.15		152
				7	240	8	9	M6 AVG	1	4600	1	2.41	0.14		152

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				7	240	10.5	11.5	M6 AVG	1	4340	1	2.8	0.13		151
DH-1945-6-2															
	5/20/1945	E	2+22												
				7	150	0	1	MASS 1.5MSA	1	3030	1	1.79	0.11		151
				7	150	1	2	MASS 1.5MSA	1	2390	1	1.77	0.13		150
				7	150	3.5	4.5	MASS 1.5MSA	1	3020	1	2.09	0.16		152
				7	150	5.5	6.5	MASS 1.5MSA	1	3650	1	2.09	0.13		151
				7	150	7	8	MASS 1.5MSA	1	4180	1	2.82	0.15		151
				7	150	9.5	10.5	MASS 1.5MSA	1	5520	1	2.58	0.15		153
DH-1949-10-1A															
	4/27/1949	E	2+30												
				11	180	0.9	2.3	MASS 1.5MSA	1	2940					153
DH-1949-10-1B															
	4/27/1949	E	2+30												
				11	180	3.2	5	M6 AVG	1	2980	1	3.27	0.28		155
DH-1949-10-2A															
	4/27/1949	Q	8+08												
				11	180	3.8	5.5	MASS 1.5MSA	1	3810	1	2.38	0.2		155
DH-1949-10-2B															
	4/27/1949	Q	8+08												
				11	180	0.2	1.8	M6 AVG	1	3225	1	1.64	0.11		153
DH-1956-10-1A-1															
	8/24/1956	E	2+30												
				18	215	2	3.6	MASS 1.5MSA	1	3020	1	2.01	0.13		151
				18	215	4	5.6	MASS 1.5MSA	1	3620	1	1.48	0.11		151
DH-1956-10-1A-2															
	8/24/1956	E	2+30												
				18	300	2.4	4	M6 AVG	1	4230					153
				18	300	4.9	6.5	M6 AVG	1	3700	1	1.74	0.1		152
				18	300	8	9.6	M6 AVG	1	3990	1	1.51	0.08		153
				18	300	13	14.6	M6 AVG	1	4260	1	3.43	0.17		13
DH-1956-10-2A1															
	8/24/1956	Q	8+08.5												
				18	215	1.4	3	MASS 1.5MSA	1	3200	1	1.25	0.13		153
				18	215	3	4.6	MASS 1.5MSA	1	2890	1	1.45	0.14		151
DH-1956-10-2A-1															
	8/24/1956	Q	8+08												
				18	215	0	1.6	MASS 1.5MSA	1	3450	1	2.49	0.16		151
				18	215	2.2	3.8	MASS 1.5MSA	1	3500	1	1.19	0.11		151

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
DH-1956-10-2A-2															
	8/24/1956	Q	8+08												
				18	300	0	1.5	M6 AVG	1	3590					153
				18	300	1.6	3.1	M6 AVG	1	3480					153
				18	300	4.5	6.1	M6 AVG	1	4290					152
				18	300	7.5	9.1	M6 AVG	1	4310	1	3.68	0.2		153
				18	300	10.4	12	M6 AVG	1	4800	1	1.32	0.08		151
				18	300	13.4	15	M6 AVG	1	5120	1	3.05	0.17		151
				18	300	17.4	19	M6 AVG	1	4270	1	1.78	0.07		153
DH-1956-10-3															
	1/1/1956	K	5+07												
				19	0	0	2	M6 AVG	1	3120	1	0.95	0.18		
				19	0	2	4	M6 AVG	1	2970	1	0.84	0.12		151
				19	0	4	6	M6 AVG	1	2480	1	0.95	0.13		152
				19	0	6	8	M6 AVG	1	3470	1	1.1	0.12		151
				19	0	8	10	M6 AVG	1	3550	1	1.16	0.15		152
				19	0	10	12	M6 AVG	1	2990	1	1.28	0.16		151
				19	0	12	14	M6 AVG	1	3390	1	1.51	0.14		153
				19	0	20	22	M6 AVG	1	2970	1	1.1	0.1		153
				19	0	22	24	M6 AVG	1	2820	1	1.04	0.17		152
DH-1964-6-3															
	1/1/1964	K	5+14												
				27	0	0	1	M6 AVG	1	3510	1	1.57	0.08		152
				27	0	1	2	M6 AVG	1	3400	1	1.57	0.16		151
				27	0	7.7	8.7	M6 AVG	1	2850	1	1.07	0.17		153
				27	0	11.1	12.1	M6 AVG	1	3130	1	1.65	0.06		
				27	0	15.9	16.9	M6 AVG	1	3940	1	1.58	0.12		152
				27	0	16.9	17.9	M6 AVG	1	3130	1	1.55	0.09		152
				27	0	19	20	M6 AVG	1	2830	1	2.13	0.12		152
				27	0	20	21	M6 AVG	1	3410	1	1.44	0.14		155
				27	0	21.8	22.8	M6 AVG	1	3400	1	1.87	0.28		153
				27	0	22.8	23.8	M6 AVG	1	2620	1	1.73	0.18		158
DH-1980-6-1															
	6/1/1980	D	1+80												
				42	0	4.5	5.5	M6 AVG	1	4730	1	1.7	0.1		153
				42	0	11.8	12.8	M6 AVG	1	3610	1	1.07	0.03		155
				42	0	37.3	38.3	M6 AVG	1	5220	1	2.26	0.12		152
				42	0	39.5	40.5	M6 AVG	1	4800	1	2.43	0.15		157
				42	0	71.3	72.3	M6 AVG	1	3940	1	2.37	0.33		154

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				42	0	75	76	M6 AVG	1	3450	1	1.46	0.13		153
				42	0	92.7	93.7	M6 AVG	1	7360	1	2.75	0.19		155
DH-1980-6-2															
	6/1/1980	Q	8+25												
				42	0	1.1	1.2	M6 AVG	1	3410	1	2.41	0.13		154
				42	0	2.4	3.4	M6 AVG	1	4410	1	1.84	0.15		151
				42	0	12.3	13.3	M6 AVG	1	4330	1	1.84	0.15		155
				42	0	29.5	30.5	M6 AVG	1	5490	1	2.6	0.18		155
				42	0	30.8	31.8	M6 AVG	1	3910	1	2.29	0.14		154
				42	0	51.3	52.3	M6 AVG	1	4480	1	3.58	0.17		156
				42	0	72.8	73.8	M6 AVG	1	4350	1	3.01	0.14		152
				42	0	90.5	91.5	M6 AVG	1	4860	1	2.03	0.1		154
DH-1980-6-3															
	1/1/1980	F	2+80												
				42	0	0.4	1.4	M6 AVG	1	3960	1	2.3	0.14		152
				42	0	2.5	3.5	M6 AVG	1	3210	1	1.53	0.8		151
				42	0	8.2	9.2	M6 AVG	1	4420	1	1.92	0.07		153
				42	0	12.5	13.5	M6 AVG	1	4430	1	2.2	0.11		152
				42	0	34.7	35.7	M6 AVG	1	3990	1	1.71	0.13		153
				42	0	45.7	46.7	M6 AVG	1	3210	1	2.11	0.13		154
				42	0	48.8	49.8	M6 AVG	1	4660	1	2.37	0.11		153
				42	0	72.1	73.1	M6 AVG	1	4510	1	2.84	0.18		153
				42	0	74.7	75.7	M6 AVG	1	5780	1	2.51	0.07		152
				42	0	95.8	96.8	M6 AVG	1	5120	1	2.18	0.1		153
				42	0	100.4	101.4	M6 AVG	1	5080	1	2.85	0.05		153
DH-1980-6-4															
	1/1/1980	K	5+20												
				42	0	4.3	5.3	M6 AVG	1	2490	1	2.18	0.1		153
				42	0	11	12	M6 AVG	1	3670	1	1.72	0.2		154
				42	0	25.7	26.7	M6 AVG	1	3790	1	2.21	0.2		154
				42	0	51.4	52.4	M6 AVG	1	3800	1	1.7	0.04		153
				42	0	73.4	74.4	M6 AVG	1	5230	1	2.09	0.14		154
				42	0	93.6	94.6	M6 AVG	1	8310	1	5.04	0.18		153
				42	0	102.2	103.2	M6 AVG	1	4130	1	1.84	0.05		154
				42	0	126	127	M6 AVG	1	7300	1	5.03	0.23		154
				42	0	148.2	149.2	M6 AVG	1	4250	1	2.94	0.13		152
				42	0	174.6	175.6	M6 AVG	1	7480	1	3.7	0.14		151
				42	0	203.9	204.9	M6 AVG	1	5530	1	2.59	0.1		152
				42	0	224.8	225.8	M6 AVG	1	4485	1	2.58	0.26		152

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				42	0	248.5	249.5	M6 AVG	1	5430	1	3.49	0.15		154
DH-2005-6-1-1.5															
	1/12/2005	F	2+52.5												
				67	36	3.3	4.3	MASS 1.5MSA	1	3210		1.29	0.49	2310	148
				67	60	11	12	MASS 1.5MSA	1	3480		1.84	0.28	1360	149
				67	242	22.7	23.7	MASS 1.5MSA	1	4170		2.76	0.21	2000	150
				67	242	27.5	28.5	MASS 1.5MSA	1	3990		2.37	0.28	1720	149
				67	242	31	32	MASS 1.5MSA	1	3930		2.66	0.27	1780	150
DH-2005-6-1-3															
	1/12/2005	F	2+52.5												
				67	80	8.6	9.5	MASS 3MSA							153
				67	90	7.7	8.6	MASS 3MSA	1	4640		2.05	0.18	1670	152
				67	106	20.4	21.4	MASS 3MSA	1	4880		2.79	0.26	1910	154
				67	106	22.8	23.8	MASS 3MSA	1	3930		1.93	0.12	1780	152
				67	110	27.3	28.2	MASS 3MSA	1	4630		2.61	0.2	1640	151
DH-2005-6-1-6															
	1/12/2005	F	2+52.5												
				67	116	1.9	2.8	M6 AVG	1	4350		1.75	0.17	1760	156
				67	123	7.8	8.8	M6 AVG	1	4420		1.81	0.16	2000	152
				67	129	6.9	7.6	M6 AVG							154
DH-2005-6-2-1.															
	1/26/2005	L	5+52.5												
				67	36	11	12	MASS 1.5MSA	1	3790		2.2	0.27	2240	149
				67	60	42.6	43.6	MASS 1.5MSA							151
				67	72	41.4	42.4	MASS 1.5MSA	1	5700		3.03	0.25	2790	151
				67	242	3.5	4.5	MASS 1.5MSA	1	3900		2.83	0.24	1560	150
				67	242	22.8	23.8	MASS 1.5MSA	1	4710	1	2.13	0.17	2540	150
				67	242	27.6	28.6	MASS 1.5MSA	1	4850	1	2.62	0.26	2150	149
				67	242	31.5	32.5	MASS 1.5MSA	1	4050		3.02	0.19	2020	150
DH-2005-6-2-3															
	1/26/2005	L	5+52.5												
				67	80	0.5	1.5	MASS 3MSA							151
				67	80	1.5	2.5	MASS 3MSA	1	4750		3.26	0.16	2040	152
				67	85	4	5	MASS 3MSA	1	4550		1.72	0.29	1920	151
				67	110	12	12.9	MASS 3MSA	1	5710		3.65	0.28	1920	153
				67	119	18	19	MASS 3MSA	1	4350		2.97	0.17	2420	151
DH-2005-6-2-6															
	1/26/2005	I	5+52.5												
				67	126	2.8	3.8	M6 AVG	1	3940	1	1.36	0.31	2670	156

Drillhole Number	Core Date	Dam Block	Drillhole Station	Test Age		Depth		Related Field Mix	No. of Comp. Strength Tests	Average Compressive Strength	No. of Mod. of Elasticity Tests	Average Modulus of Elasticity	Average Poissons Ratio	Average Failure Strain	Average Density
				Yrs	Days	From	To								
				67	130	5.6	6.6	M6 AVG							152
				67	130	6.6	7.5	M6 AVG	1	4060	1	2.09	0.09	1210	155
				67	130	8.9	9.8	M6 AVG	1	3590		2.35	0.5	1700	153
				67	133	11.7	12.6	M6 AVG	1	3930		1.53	0.1	2350	155