U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Study of the Properties of Aged Concretes Containing Various Cements Parapet Wall, Green Mountain Dam

DSO-98-03

Materials Engineering and Research Laboratory

March 1998

DSO
DAM SAFETY OFFICE

Study of the Properties of Aged Concretes Containing Various Cements
Parapet Wall, Green Mountain Dam
DSO-98-03

by
Caroline E. Mohorovic
David W. Harris, PE, PhD

U.S. Department of Interior
Bureau of Reclamation
Dam Safety Office

March 1998

Contents

Tables

Figures

Introduction

In 1940, the Portland Cement Association (PCA) and the Bureau of Reclamation (Reclamation) Materials Testing Lab, Denver, Colorado, formed a partnership to study the long-term behavior of 27 different types of cement in concrete under service conditions. A parapet wall containing three or four test panels of each cement was constructed along the upstream bank at Green Mountain Dam, Big Thompson Project, Colorado (Douglass et al. 1947). A detail and photographs of the wall are provided in figures 1 and 13 (all figures are located at the back of this document).

Green Mountain Dam served as one location for a nationwide study conducted by PCA to investigate the durability of various cements in different climactic conditions. The 27 cements represented the range of physical and chemical properties of commercial cements used across the United States in the 1940s. Six of these cements were used with and without entrained air in the cement. At each test location, the concrete mix design is the same for all specimens—only the cement composition and the source of aggregate varied. Test sections comprised of several specimens of each of the twenty-seven cements were placed in New York, Massachusetts, South Carolina, Missouri, Colorado, Florida, California, and Georgia (McMillan and Tyler 1948).

All five categories of Portland cements, as designated by the American Society for Testing Materials (ASTM) standards, are represented in the Green Mountain parapet wall (ASTM 1997). These are described in table A. According to the original 1940 agreement between PCA and Reclamation, long-term differences among cement mix designs under service conditions were to be compared through periodic testing of concrete samples. Tests on cast cylinders were conducted in the Denver laboratory as the wall was constructed in 1943. The study was intended to span several decades, yet project records of testing cease approximately 38 months after the wall was constructed. C.T. Douglas and R.F. Blanks published the results for the Reclamation in Report No. C-345—*Long-time Study of Cement Performance in Concrete Tests on 28 Cements Used in the Parapet Wall of Green Mountain Dam* (March 1947). The cement chemistry, along with the fresh and hardened properties of these mixes, are provided in tables 1 and 2 (numbered tables are at the back of this document).

This project resumed the study of the durability of various concrete mix designs after 50 years of environmental exposure. After completion of a visual inspection and nondestructive testing of all panels, 14 cements were selected for coring and laboratory testing. Cored samples were tested for static compressive strength, dynamic compressive strength, splitting tensile strength, cyclic (nonlinear) compressive strength, modulus of elasticity, sonic modulus, Poisson's ratio, and unit weight. The selected panels are described in table 3.

This report emphasizes the results of material properties tests conducted in Reclamation's Materials Engineering and Research Laboratory. Additional papers concerning other aspects of this study were written by University of Colorado at Denver contributors and were submitted to the American Society of Civil Engineers Journals. Osama Mohamed, a graduate student of civil engineering at the University of Colorado at Denver, is preparing a thesis based on this study. All data and publications resulting from this project reflect the combined intellectual, material, and financial resources of both parties.

Description of Study

Concrete Mix Design

The concrete for the panels was batched and cured onsite at Green Mountain Dam, Colorado, in April and May 1943. The dam is located on the Blue River in the Rocky Mountains, south of Kremmling, Colorado. The concrete mix design and ingredient sources were the same for all panels. The type of cement varied, but the proportion added to the mix remained constant. The mix designs, fresh properties, and hardened properties are presented in table 2 (Douglass et al. 1947).

All cement was furnished by the Portland Cement Association. The aggregate was obtained locally and limited to a maximum nominal size of 1-1/2 inches. Water was supplied from Green Mountain Reservoir and a nearby mountain spring. Initial studies indicated that the sand and course aggregate, which jointly comprise 84 percent of the mix weight, were reactive with high-alkali cements (Bureau of Reclamation 1942).

The water-to-cement ratio ranged from 0.48 to 0.55. The slump ranged from 2.0 in. (5.1 cm) to 3.75 in. (9.5 cm), and the fresh unit weight ranged from 143.6 lb/ft^3 (2,300 Kg/m^3) to 150.4 lb/ft^3 (2,409 Kg/m^3) among mix designs (table 2) (Douglass et al. 1947).

Sample Population

The parapet wall contains panels representing all five categories of Portland cement, as cited in ASTM C 150, *Standard Specification for Portland Cement* (ASTM 1997). The cement types and the number of representative concrete mixes are provided in table A.

Table A.—Distribution of Portland cement types placed in the parapet wall at Green Mountain Dam, Big Thompson Project, Colorado (Douglass et al. 1947)

Cement type	Cement characteristics	Number of cements (no air entrainment)	No. of cements (air-entrained)
Type I	No special requirements for mix	8	3
Type II	Moderate sulfate resistance Moderate heat of hydration	6	1
Type III	High early strength	3	1
Type IV	Low heat of hydration	4	1
Type V	High sulfate resistance	1	0

Concrete mixes are identified by a two-digit number. The first digit (1-5) represents the mix type. Six of the mixes contain an air entrainment admixture, Vinsol Resin. For three of these mixes, the Vinsol Resin was interground with the cement at the mixer. Their identification number is followed by the letter "T." For the remaining three mixes, Vinsol Resin was added during mixing of the concrete, and these are denoted with the letter "B."

Sample Selection for Laboratory Testing

Project appropriations required that the coring and destructive testing portion of the study be limited to 14 representative mix designs. The cores represent the range of cement mixes and the anticipated durability problems, with an emphasis on mixes similar to those found in Reclamation's mass concrete structures. The following selection criteria were employed to decide the cored sample population:

Selection Criteria

1. Represent at least one panel of each cement type.
2. Emphasize mixes similar to those used for Reclamation mass concrete structures.

3. Provide Good versus Bad comparison based upon visual inspection.
4. Provide High versus Low comparison based upon alkali activity.
5. Provide AEA versus No AEA comparison.
6. Emphasize samples visually similar and chemically different.
7. Emphasize samples visually different and chemically similar.
8. Emphasize mixes applicable to current designs.

Samples chosen for laboratory testing are listed and described in table 3.

Low heat of hydration concrete mix designs, similar to those derived with Type II and Type IV cements, have been often used for Reclamation mass structures (Bureau of Reclamation 1988). Concrete mixes containing Type I cements are most often used by Reclamation to predict durability and aging problems. Consequently, the test results from these cements are compared.

According to the 1943 study, the coarse aggregate and the sand used in the concrete were found to be highly reactive with high alkali cement. Thus, the equivalent alkalies (Na equivalent) of each cement, as described in ASTM C 150, *Standard Specification for Portland Cement*, were used as an indicator of the potential for alkali aggregate reaction. Cements with equivalent alkalies greater than 0.6 are more susceptible to alkali-aggregate reaction (AAR) than those with equivalent alkalies below 0.6. The equivalent alkalis are noted in bold print in table 1.

Sulfates were not found in the water; thus, sulfate attack was not a concern. Due to the location and aggregate composition, long-term damage due to freeze-thaw and alkali-aggregate reaction were also emphasized in this study.

Sample Procurement

Six by 12-inch cores were extracted from the wall and brought to the laboratory for testing. Cores were drilled from the top of the panels to an average depth of approximately 15 inches using a Bantam 600 drill with an 18-inch-long core barrel. Each drill hole produced one laboratory specimen.

Concrete cylinders were dry upon procurement, once water from the drill slurry evaporated. Prior to drilling, the parapet wall had been exposed to summer sun and mostly dry weather. Cores were sealed in plastic as they were obtained for transport to the Denver laboratory to preserve their in-situ moisture content.

The top few inches of every core was removed at the laboratory to eliminate the effects of surface damage and bleed water in test specimens.

Testing

The current test program was designed to compare the present condition of different mixes, as well as determine changes in durability by comparing current results to past findings. Accordingly, similar tests were conducted on all panels. All of the current tests, excluding the nonlinear tests, were included in the 1943 investigation. A summary of the test schedule is provided:

Table B.—Test schedule for cored specimens, parapet wall at Green Mountain Dam, Colorado

Test/procedure	Number of samples tested	Purpose
Visual inspection	All panels	General durability observations, crack pattern determination
Nondestructive testing (field and laboratory)	One panel of each selected test panel, every core in laboratory	Determine structural integrity and location of crack propagation Compare static moduli, field sonic moduli, and laboratory sonic moduli
Static compression	2-3 cores from each selected test panel	Determine compressive strength, static modulus of elasticity, Poisson’s ratio
Split tension	0-1 core from each selected panel	Determine tensile strength
Dynamic compression	4 cores—1 per selected panel	Determine dynamic compressive strength
Nonlinear-cyclic compression test	1 core from each selected test panel	Determine and compare nonlinear and linear test parameters

Test results were grouped and analyzed according to cement type to emphasize general durability characteristics of mixes containing the same cement type. Air-entrained and nonair-entrained mixes were compared. Results of current tests are reported in tables 4 through 10 and figures 2 and 6 through 12. Long-term trends comparing strength and age were provided in figures 3, 4, and 5.

The exposed faces of every panel were visually inspected and photographed. Photographs of the test panels are provided in figure 13.

Unit weights were calculated using gravimetric methods for each mix cored. Uniaxial static compression and split tension tests were conducted following ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* and ASTM C 496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* (ASTM 1997). Compressive stresses are recorded from initial loading to failure by the laboratory data acquisition system. Ultimate strengths are recorded for the split tension tests.

The initial chord moduli and Poisson's ratio were calculated for static compression tests according to ASTM C 469, *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. The laboratory data acquisition system continually recorded load, axial strain and lateral strain through the load cell and strain gages attached to each cylinder as tests were performed. These values were used to compute the initial chord moduli according to the ASTM specifications.

Dynamic compression tests were performed according to procedures established at the Reclamation laboratory. Specimens were prepared and strain gaged according to methods provided for static compression tests and then loaded at strain rates of approximately 10^{-3} to 10^{-4} micro strain. Stresses and strains were recorded by the laboratory data acquisition system. Initial dynamic chord moduli were calculated according to ASTM C 469 specifications for static compression.

The unload-reload compression tests were performed according to procedures developed at the Denver laboratory. Cores are prepared, strain gaged, and initially loaded as defined for a static compression test. To perform the cyclic (nonlinear) load cycles, cores were unloaded and reloaded at strain intervals of 100, 250, 500, and 1000 micro strain. Once a strain interval is reached, cores are unloaded until the stress decreases to the "baseline stress." This is the stress previously noted that corresponds to a strain of 50 micro strain. Specimens are then reloaded from the baseline stress until the next strain interval value is reached.

Current laboratory capabilities limit the unload-reload tests to a maximum stress value of 4,000 lb/in^2 (27.6 MPa). Since the specimens did not fail before 4,000 lb/in^2 (27.6 MPa), they were cyclically loaded to this limit and then failed according to the ASTM C 469 static compression test procedures. Plots of the unload-reload test cease at the 4,000-lb/in^2 (27.6-MPa) limit.

The laboratory data acquisition system continually recorded stress and strain to plot the unload-reload cycles. A line was estimated that best fit the slope of each unload-reload cycle. Since the slopes of these lines varied little, they were averaged to provide the unload - reload moduli for each test.

Nondestructive sonic tests were performed on intact panels onsite as well as on cored specimens at the laboratory. An ultrasonic velocity meter manufactured by James Instruments, Inc., was used to measure the travel time of compression waves (P-waves) through the cores and panels.

Pulse velocities were measured on panels in the field prior to coring (table 9). Five measurements were taken horizontally 6 inches and 14 inches from the top of the wall. The thickness of the wall was measured at each reading location with calipers. This provided the path length. Velocity was computed by dividing the path length by the travel time (James Instruments, Inc.)

Pulse velocities were measured on cores at the Reclamation laboratory according to the method previously described.

The sonic moduli were computed from the laboratory and field pulse velocities according to a formula provided in the equipment manual, provided in table 9 (James Instruments, Inc.). The sonic modulus is dependent on the wave velocity, density of the specimen, and Poisson's ratio. Densities and Poisson's ratios for each mix were measured in the laboratory.

Results

Visual Inspection

The visual condition of the panels varied significantly among concrete mix designs. Panels containing Type V cement continuously maintained the best appearance. Panels containing Types I through IV cement all included some damaged panels.

Most of the panels appeared to be in good condition for 50-year-old concrete. These panels displayed light surface cracks and slight delamination, spalling, and d-cracking at surface edges. Such cracks are most likely due to age and freeze-thaw damage.

Panels in poor condition were covered with efflorescence, excessively cracked, and deteriorated, possibly deterioration due to AAR. Petrographic analysis is necessary to determine the causes and extent of decay.

Compressive Strength and Elastic Properties

The compressive strength, initial chord moduli, and Poisson's ratio for each sample tested are provided in table 4.

The average static compressive strengths, arranged by cement type, were 6,500 lb/in^2 (44.8 MPa) for Type I, 6,100 lb/in^2 (42.1 MPa) for Type II, 5,230 lb/in^2 (36.1 MPa) for Type III, 5,810 lb/in^2 (40.1 MPa) for Type IV, and 6340 lb/in^2 (43.7 MPa) for Type V cement. The coefficients of variation for these averages were 8, 28, 19, 27, and 1 percent, respectively.

Only one mix design containing a Type V cement was used in the parapet wall to make four panels. Accordingly, negligible variation was expected for this mix.

The average initial chord moduli from the static compression tests was 3.34 x 10^6 lb/in^2 (23.0 GPa), with a coefficient of variation of 85 percent. The values ranged from 1.05 x 10^6 lb/in^2 (7.2 GPa) for mix 31 to 4.71 x 10^6 lb/in^2 (32.5 GPa) for mix 41.

The average Poisson's ratio for the specimens subjected to static compressive loads was 0.22 with a coefficient of variation of 26 percent. Values ranged from 0.13 (Type III) to 0.34 (Type IV).

Dynamic Compressive Strength and Properties

The average dynamic strength of the core specimens was 7,580 lb/in^2 (52.2 MPa) with a coefficient of variation of 11 percent, as illustrated in table 4. Because the number of procured cylinders was limited, only four cylinders, two mixes with and without entrained air (mixes 16, 16B, 42, 42B) were tested. The ratio of average dynamic to average static compressive strength for these mixes is 1.06.

The average dynamic modulus of elasticity, measured from cores of mix 16 and 42, was 3.93 x 10^6 lb/in^2. The ratio of average dynamic to static modulus for these two mixes was 1.10 for mix 16 and 1.23 for mix 42.

Nonlinear (Cyclic Compressive) Properties

The average ultimate nonlineal strength of all specimens was 6,550 lb/in^2 (45.2 MPa), with a coefficient of variation of 12 percent (table 4). Cyclic (nonlinear) compressive strengths of the cored cylinders ranged from 4,920 lb/in^2 (33.9 MPa) for a Type III mix to 8,170 lb/in^2 (56.3 MPa) for a Type IV mix.

The average unload-reload chord moduli for all samples was 3.84 x 10^6 lb/in^2 (26.5 GPa), with a coefficient of variation of 18 percent. These values ranged from 2.26 x 10^6 lb/in^2 (15.6 GPa) for mix 34 to 4.50 x 10^6 lb/in^2 (31.0 GPa) for mix 51.

Splitting Tensile Strength

The average splitting tensile strength of all core specimens was 505 lb/in^2 (3,480 KPa), with a coefficient of variation of 20 percent. Average splitting tensile strengths, according to cement type, ranged from 375 lb/in^2 (2,585 KPa) for the Type I mixes to 610 lb/in^2 (4,205 KPa) for the Type II mixes. Little variation was found among test values (table 6).

Unit Weight

The unit weights for the cored specimens ranged from 142.4 lb/ft^3 (2,280 Kg/m^3) for mix 16B to 148.1 lb/ft^3 (2370 Kg/m^3) for mix 43A (table 7).

Sonic Testing

The average laboratory sonic velocity and sonic modulus were 13,690 ft/s (4,170 m/s), with a coefficient of variation of 17 percent, and 5.05 x 10^6 lb/in^2 (34.8 GPa), with a coefficient of variation of 29 percent (table 9). The field laboratory sonic velocities measured at 6 inches and 14 inches from the top of the panels were slightly lower. The respective values are 12,230 ft/s (3,730 m/s) and 12,710 ft/s (3,870 m/s), with coefficients of variation of 25 and 17 percent. The average sonic moduli at these locations were 4.44 x 10^6 lb/in^2 (30.6 GPa) and 4.61 x 10^6 lb/in^2 (31.8 GPa), with coefficients of variation of 34 and 26 percent.

Discussion

Visual Inspection

In general, poor visual condition correlated to lower test strengths. Panels 24, 31, and 43 exhibit the greatest visual deterioration and, consequently, provided the lowest compressive strengths of the cored samples. These results are summarized in figure 7.

Approximately 15 percent of the panels displayed significant visual degradation associated with AAR. Map and pattern cracking, extrusion of a white gel-like substance, and discoloration were noted in concentrated surface areas of several panels containing Types I through IV cement. Alkali-aggregate attack continuously cracks and weakens concrete and may ultimately result in the failure of a structure.

According to ASTM guidelines, cements with chemical compositions that include a sodium (Na) equivalent greater than 0.6 are more likely to react with alkalis in the aggregate.[10] Most of visually damaged panels contain sodium equivalents greater than the 0.6 ASTM guideline, as indicated in figure 6. Petrographic analysis is necessary to determine if AAR has reduced the durability of these concrete mixes. Two out of three of the most damaged panels, panels 24 and 43, had high sodium equivalents of 0.906 and 1.143, respectively.

Approximately 25 percent of the panels containing Types I, II, III, and IV cement exhibited a white, chalky discharge known as efflorescence, which is most likely due to intermittent cycles of wetting and drying. This indicates that salts in the cement may be leached out of the concrete as the panels dry. Although efflorescence in itself is merely an esthetic concern, it often indicates increased porosity and a loss of strength in the cement. A petrographic examination is required to confirm this theory.

Panels containing air entrainment appeared to be in better condition than their counterparts without entrained air. Surfaces of air-entrained mixes looked smoother and displayed less deterioration from freeze-thaw damage than do panels containing the same mix without air entrainment.

Static Compressive Strength and Elastic Properties

As indicated by the coefficients of variation, mixes containing Types II, III, and IV cements provided significantly more variation than did the mixes containing Type I cement. Much of the variation for Types II, III, and IV was attributed to specific panels that did not achieve the strength gain characteristic of the cement type.

The strengths of mix 24 (Type II), mix 31 (Type III), and mix 43 (Type IV) were 4,140 lb/in^2 (28.5 MPa), 3,750 lb/in^2 (25.9 MPa), and 3,270 lb/in^2 (22.5 MPa). These values were well below the average for each type, and lower than the 1-year strengths (figure 4), indicating deterioration. Panels containing these mixes exhibited more surface damage than their counterparts.

It appears that the cements used in mixes 24, 31, and 43 attributed to the loss of strength and durability of the panels. Two of the mixes, mixes 24 and 43, contained sodium equivalents that greatly exceeded the ASTM recommended limit. However, the reasons for these low test values cannot be determined with certainty without further testing and petrographic analysis. It can be concluded that aged structures containing a Types II, III, or IV mix should be examined on a case-by-case basis.

The ratio of 50-year to 28-day average compressive strength for each cement type is as follows: 1.34 for Type I, 1.54 for Type II, 1.19 for Type III, 1.38 for Type IV, and 1.90 for Type V. In general, these strength increases seem reasonable. However, the ratio for Type IV cements was lower than expected. Typically, Type IV cements display the largest long-term to 28-day strength ratios, which are approximately 2.0.[13]

The variation in values of the initial chord moduli reflects the variation in the compressive strengths. Higher moduli corresponded to higher compressive strengths, which is expected.

Dynamic Compressive Strength and Properties

The ratios of dynamic to static compressive strength and dynamic to static initial moduli are 1.06 and 1.18, respectively, for the cores tested. These values are reasonable for mass concrete. Air-entrained specimens produce lower strengths than their counterparts without entrained air under dynamic loading conditions.

Nonlinear (Cyclic Compressive) Properties

The cyclic loading process did not, in general, affect the ultimate static compressive strength of the samples. The ultimate static strengths of the cores were not affected by the successive removal and reapplication of load prior to failure. Thus, both linear, elastic and nonlinear, plastic results may be obtained from one sample. Excluding the results of mix 24, the ratio of average nonlineal to average static compressive strength was 1.03 (table 5). The nonlineal and static compressive strengths for this mix were 6,970 lb/in^2 (48.1 MPa) and 4,140 lb/in^2 (28.5 MPa), respectively.

Concrete mixes containing Type III cements expended significantly more energy in the unload-reload process than did the concretes containing other types of cement. Therefore, more energy was used to absorb load in these mixes. The quantity of energy expended is expressed as the area contained within each unload and reload loop. The area of the loops created by these unload-reload cycles was two to four times larger than those created by mixes that did not contain Type III cement.

All cement types demonstrate moduli that are higher than the modulus of elasticity in the first unload-reload cycle, which is generated at 100 micro strains. The steeper slopes indicate that the samples can absorb more stress with less strain under stresses previously experienced. This implies that the mixes are stiffer having undergone a small load increment. From this initial load cycle, the moduli of following unload-reload cycles stay nearly the same or slightly decrease for mixes with cement Types I, II, and V, and generally increase for cement Types III and IV (figure 9).

The cyclic (nonlinear) compression tests provided ratios of plastic strain to elastic strain that ranged from 5 to 25 percent (table 8). The ratios of plastic strain to total strain (plastic + elastic) ranged from 5 to 20 percent. When subject to three or four repetitive loads well within the load capacity of the material, 5 to 20 percent of the concrete was permanently strained. Specimen 34B exhibited more plasticity than all other specimens, with a plastic strain to elastic strain ratio of 25 percent. The concrete experienced fatigue from small, successive loads, indicating plastic properties and a need for nonlinear testing.

Splitting Tensile Strength

The average splitting tensile strength was 8.44 percent of the average static compressive strength, which is typical.

One specimen from mix 16 provided an extremely low tensile strength of 290 lb/in^2 (2,000 KPa), which resulted in the low average split tensile strength for the Type I cement mixes. Additional tests of this mix are necessary to determine if the low test measurement is a misrepresentation that may be removed from the average.

Unit Weight

The unit weights measured in the current test program are 0.7 to 4.2 percent less than the unit weights measured from the fresh concrete in 1943 (table 7). Specimens containing air entrainment provided the lowest percentage losses of unit weight for each cement type. Thus, air entrainment seems to preserve the mass of aged concrete, whereas nonair-entrained concrete may experience a significant loss of mass with time.

Air Entrainment

Mixes with air-entrained cements (noted with the letter B) exhibited compressive strengths similar to cores of the same mix without air entrainment. The average static compressive strength of air-entrained cores was 103 percent of their counterparts without air entrainment, and the average cyclic compressive strength was 104 percent of their counterparts without air entrainment. The average dynamic compressive strength of air-entrained cores was 88 percent of their counterparts without air entrainment. Variation among strength due to entrained air was not expected since the quantity of water varied slightly and the quantity of cement was constant for all mixes.

Sonic Testing

Field data obtained at the 14-inch depth consistently provided higher velocities and sonic moduli than data taken at a 6-inch depth. The 6-inch depth, which is closer to the top surface of the wall, may reflect either long-term deterioration near the surface edges or settling of heavier materials to lower depths as the concrete was consolidated (table 9).

Sonic moduli of the laboratory cores were consistently higher than those from the field, which is the result of the higher velocities measured from the laboratory cores. The higher velocities may be due to the different orientation of the measurement, since cores were obtained vertically from the top of the panels.

The average ratio of sonic modulus to static modulus of elasticity for the core samples was 1.71, with a coefficient of variation of 21 percent. The static, dynamic, and sonic moduli are compared in table 10.

Conclusions

1. The average static compressive strength of all cored cylinders was 5,980 lb/in^2 (41.2 MPa). Static compressive strengths of the core specimens ranged from 3,240 lb/in^2 (22.3 MPa) for a Type IV mix to 7,870 lb/in^2 (54.3 MPa) for a different Type IV mix.

2. The average static compressive strengths of each cement type varied as follows:

	Number of cores tested	Average static compressive strength	Coefficient of variation
Type I	8	6,500 lb/in^2 (44.8 MPa)	0.08
Type II	3	6,100 lb/in^2 (42.1 MPa)	0.28
Type III	5	5,230 lb/in^2 (36.1 MPa)	0.19
Type IV	9	5,810 lb/in^2 (40.1 MPa)	0.27
Type V	2	6,340 lb/in^2 (43.7 MPa)	[1] 0.01

[1] One mix type used.

3. Types II and IV cements, which were commonly used in Reclamation dams, provided the greatest variability with respect to long-term material properties (figure 2). Aged properties of these concrete mixes should not be estimated according to properties of the cement type. They need to be determined on a case-by-case basis.

4. Some concrete mixes containing Types II, III, and IV cements did not gain the strength expected of the cement type over time (figures 3 through 5). The average compressive strengths of mix 24 from Type II, mix 31 from Type III, and mix 43 from Type IV were 4,140 lb/in^2 (28.5 MPa), 3,750 (25.9 MPa) lb/in^2, and 3,270 lb/in^2 (22.5 MPa), respectively. These were well below the average for each cement type and lower than their 1-year strengths. The low strengths of mixes 24 and 43 are most likely attributed to alkali-aggregate reactions as described in conclusion 14.

5. The cyclic (nonlinear) loading process did not, in general, affect the ultimate static compressive strengths of the samples. Therefore, both linear, elastic and nonlinear, plastic results could be obtained from one sample. The average cyclic (nonlinear) compressive strength of all cylinders was 6,550 lb/in^2 (45.2 MPa), with a coefficient of variation of 0.12 . Cyclic strengths ranged from 4,920 lb/in^2 (33.9 MPa) for a Type III mix to 8,170 lb/in^2 (56.3 MPa) for a Type IV mix. Excluding one outlying result, the average ultimate strength from cyclic loading to average static compressive strength ratio was 1.0. Variations among ultimate compressive strengths for samples that did and did not undergo cyclic loading reflect material, not procedural, variation.

6. All cement types demonstrate moduli that are higher than the modulus of elasticity in the first unload-reload cycle, which is generated at 100 micro strains. This implies that the mixes are stiffer, having undergone a small load increment. From this initial load cycle, the moduli of following unload-reload cycles stay nearly the same or slightly decrease for mixes with cement Types I, II, and V, and generally increase for cement Types III and IV (figures 8 and 9).

7. Concrete mixes containing Type III cements expended significantly more energy in the unload-reload process than did the concretes containing other types of cement. The area of the loops created by these unload-reload cycles was two to four times larger than corresponding loops created by mixes that did not contain Type III cement (figure 10).

8. The concrete experienced permanent fatigue from small, successive loads and warrants a need for nonlinear modeling. The cyclic (nonlinear) compression tests provided ratios of plastic strain to elastic strain that range from 5 percent (Type V) to 25 percent (Type III) and ratios of plastic strain to total strain that range from 5 percent (Type V) to 20 percent (Type III) when cylinders were unloaded (table 8).

9. The average dynamic strength of the core specimens was 7,580 lb/in^2 (52.3 MPa), with a coefficient of variation of 0.03. Dynamic compressive strengths of the cylinders ranged from 6,950 lb/in^2 (47.9 MPa) to 8,810 lb/in^2 (60.7 MPa). Both were Type I mixes. The ratio of average dynamic to average static compressive strength for cores subject to both tests is 1.06.

10. All compressive failure strains occurred at approximately 2,000 micro strains. This includes samples tested under cyclic loading and uniaxial compression. Regardless of the mix design, concrete tends to fail once a strain of 2,000 micro strains is obtained (table 4).

11. Increases in pulse velocity and sonic moduli measured from sonic testing correlated to higher static compressive strengths (table 9). Velocities and sonic moduli for cement Types II, III, and IV provided significantly more variation than did the velocities and sonic moduli for Type I mixes. Mixes 24, 31, and 43, which exhibited the lowest compressive strengths, had velocities and sonic moduli that measured less than 50 percent of the overall averages of these parameters.

12. The average ratio of sonic modulus to static modulus of elasticity (Young's modulus) for the cores was 1.71, with a coefficient of variation of 0.36. This ratio was inversely proportional to strength. As strength increased, values of sonic and static moduli tended to converge.

13. Visual degradation indicated some correlation to compressive strength and no correlation to cement type. The most severely damaged panels (24, 31, and 43) provided the lowest compressive strengths (figure 7). Approximately 20 percent of the panels containing Types I, II, III, and IV cements exhibited damage that is indicative of either freeze-thaw deterioration or alkali-aggregate reaction (figure 11). These panels were marred by excessive spalling, map and pattern cracking, discoloration, and efflorescence. Petrographic analysis is necessary to determine the nature of the deterioration.

14. Chemical composition indicated correlation with visual condition and compressive strength. According to ASTM 150 guidelines, cements with chemical compositions that include a sodium (Na) equivalent greater than 0.6 are more likely to react with alkalies in the aggregate (ASTM 1997). Most of the visually damaged panels contain sodium equivalents that exceed 0.6. In general, compressive strengths of cores increased as the sodium equivalent decreased (figure 6). Petrographic analysis is necessary to determine if alkali-aggregate reaction has decreased the durability of these mixes.

15. Air entrainment provided consistency and durability that was lacking in the nonair-entrained mix designs. Nonair-entrained mixes should be studied on a case-by-case basis due to their variability. The visual condition of panels containing air entrainment exhibited less variation among similar panels and significantly less overall deterioration than the panels that did not contain the admixture. Air-entrained mixes experienced the least loss of unit weight for each mix type, yet did not significantly affect compressive strength.

References

American Society for Testing Materials. *1997 Annual Book of ASTM Standards*. Concrete and Mineral Aggregates Vol. 4.02. American Society of Testing and Materials. Philadelphia, Pennsylvania. 1997.

Bureau of Reclamation. *Long Time Cements Studies - Construction of Parapet Wall on Green Mountain Dam with 28 Cement*. Materials Laboratory report No. C-224. U.S. Bureau of Reclamation. Denver, Colorado. October 1942.

———. *Concrete Manual, 8th ed. revised*. A Water Resources Technical Publication. Department of the Interior. 1988.

Douglass, C.T., et al. *Long Time Study of Cement Performance in Concrete-Tests on 28 Cements used in the Parapet Wall of Green Mountain Dam, Colorado Big-Thompson Project, Colorado*. Materials Laboratory Report No. C-345. Bureau of Reclamation. Denver, Colorado. March 1947.

James Instruments, Inc. *V-Meter Construction Manual, Mark II*. Chicago, Illinois. [no date].

McMillan, F.R., and I.L. Tyler. *Long-time Study of Cement Performance in Concrete*. Bulletin 26, Research Laboratories of the Portland Cement Association. Chicago, Illinois. August 1948.

Mindess, Sidney, and J. Francis Young. *Concrete*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 1991.

Acknowledgments

This project was formulated and completed as a joint venture between the University of Colorado at Denver, Undergraduate Department of Civil Engineering, with financial support from the National Science Foundation, and the Bureau of Reclamation Materials Engineering and Testing Laboratory and the Dam Safety Office, Denver.

Special thanks to William Kepler, Timothy Dolen, Kurt Mitchell, Kurt Von Fay, Gregg Day, Nathan Snorteland, and William DePuy for sharing their time, resources, and expertise during this study. Thanks to all employees of the Materials Engineering and Testing Laboratory and members of the University of Colorado who contributed to the completion of this project.

Cement Type														
P.C.A. Name	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**0**	**21**	**22**	**23**	**24**	**25**
USBR Name	4476	4477	4479	4480	4481	4482	4484	4485	4500	4486	4488	4489	4490	4491
Chemistry														
SiO_2	20.55	21.53	22.17	21.87	20.29	21.14	21.27	21.17	21.65	23.61	22.09	21.41	20.69	22.51
Al_2O_3	5.91	6.27	5.11	5.07	6.09	5.27	5.90	6.42	5.12	4.67	5.18	4.92	5.24	4.94
Fe_2O_3	2.32	2.29	2.14	2.99	2.39	3.32	3.08	2.12	5.05	3.08	3.66	5.28	4.60	4.67
CaO	63.93	63.72	65.68	62.65	67.09	64.59	64.9	64.15	64.24	64.43	62.56	64.46	61.04	62.12
MgO	3.79	3.29	1.50	2.86	0.89	2.31	1.46	2.57	0.75	1.34	3.58	1.07	3.22	2.41
SO_3	1.60	1.59	1.55	1.68	1.99	1.92	1.72	1.90	1.96	1.26	1.44	1.52	1.69	2.00
Loss	1.08	0.71	1.57	1.45	0.88	0.85	0.95	1.01	0.76	0.94	0.90	0.75	2.35	0.54
Insoluble	0.07	0.09	0.10	0.10	0.16	0.12	0.11	0.18	0.09	0.13	0.08	0.11	0.09	0.09
Free CaO*	0.43	0.11	1.61	0.19	0.44	0.73	0.42	0.33	0.58	0.65	0.05	0.43	0.88	0.21
Na_2O	0.23	0.35	0.04	0.03	0.07	0.27	0.06	0.16	0.13	0.26	0.26	0.61	0.07	0.25
K_2O	0.61	0.50	0.26	1.36	0.24	0.46	0.57	0.18	0.50	0.48	0.37	0.16	1.27	0.59
$CHCl_3$ - sol.	0.001	0.003	0.001	0.001	0.003	0.001	0.000	0.003	0.001	0.003	0.001	0.003	0.002	0.002
Na equiv.	**0.631**	**0.679**	**0.211**	**0.925**	**0.228**	**0.573**	**0.435**	**0.278**	**0.459**	**0.576**	**0.503**	**0.715**	**0.906**	**0.638**
Na eq. SD							**I:**	**0.252**					**II:**	**0.154**
CaO SD							**I:**	**0.473**					**II:**	**0.333**
TiO_2	0.23	0.23	0.32	0.21	0.29	0.25	0.30	0.25	0.22	0.23	0.30	0.26	0.22	0.29
P_2O_5	0.24	0.23	0.14	0.09	0.41	0.14	0.19	0.04	0.15	0.19	0.11	0.26	0.11	0.07
Mn_2O_3	0.07	0.09	0.08	0.13	0.05	0.12	0.16	0.48	0.17	0.07	0.05	0.06	0.27	0.04
C_3S	54.5	45.2	50.3	44.7	67.0	53.5	51.8	47.1	47.3	40.6	42.2	52.9	40.9	37.1
C_2S	17.9	27.7	25.7	29.1	7.7	20.3	22.0	25.2	26.5	37.1	31.6	21.5	28.5	36.6
C_3A	11.7	12.7	9.9	8.4	12.1	8.3	10.4	13.4	5.0	7.2	7.5	4.1	6.1	4.5
C_4AF	7.1	7.0	6.5	9.1	7.3	10.1	9.4	6.4	15.4	9.4	11.1	16.1	14.0	14.2
$CaSO_4$	2.7	2.7	2.6	2.9	3.4	3.3	2.9	3.2	3.3	2.1	2.4	2.6	2.9	3.4

* values provided by P.C.A.

Table 1. - Chemical analysis of cements used in the parapet wall at Green Mountain Dam, Colorado.
Original data provided in USBR Materials Laboratory Report No. C-345.

Cement Type

P.C.A. Name	**31**	**33**	**34**	**41**	**42**	**43**	**43A**	**51**	**12T**	**16T**	**21T**
USBR Name	4492	4493	4494	4495	4496	4497	4498	4499	4478	4483	4487
Chemistry											
SiO_2	20.43	20.05	20.46	22.92	26.36	23.34	25.13	24.44	21.5	21.29	23.84
Al_2O_3	5.49	5.66	4.34	1.89	3.28	5.04	3.85	3.54	6.21	5.28	4.55
Fe_2O_3	2.08	2.57	3.21	4.92	2.65	4.43	3.03	3.12	2.18	3.36	3.15
CaO	63.78	65.13	65.8	59.4	62.81	61.17	62.92	64.27	63.78	64.41	64.25
MgO	3.49	1.71	2.59	3.19	2.15	1.72	1.43	1.77	3.29	2.10	1.55
SO_3	2.26	2.29	1.71	1.93	1.50	2.07	1.82	1.56	1.55	1.94	1.25
Loss	1.79	1.74	1.49	1.41	0.77	1.27	1.56	1.15	0.72	0.96	0.99
Insoluble	0.13	0.11	0.10	0.07	0.11	0.08	0.07	0.13	0.09	0.07	0.08
Free CaO*	1.45	1.83	2.27	0.44	0.21	0.12	0.35	0.54	0.12	0.75	0.60
Na_2O	0.29	0.27	0.34	0.13	0.18	1.09	0.44	0.08	0.36	0.26	0.23
K_2O	0.34	0.50	0.27	1.17	0.30	0.08	0.00	0.26	0.46	0.50	0.44
$CHCl_3$ - sol.	0.002	0.001	0.003	0.008	0.001	0.002	0.003	0.004	0.032	0.033	0.022
Na equiv.	**0.514**	**0.599**	**0.518**	**0.900**	**0.377**	**1.143**	**0.440**	**0.251**	**0.663**	**0.589**	**0.520**
Na eq. SD		**III**	**0.048**			**IV**	**0.368**				
CaO SD		**III**	**0.410**			**IV**	**0.143**				
TiO_2	0.20	0.26	0.22	0.23	0.17	0.27	0.18	0.19	0.23	0.26	0.25
P_2O_5	0.17	0.10	0.11	0.14	0.07	0.10	0.11	0.20	0.24	0.13	0.19
Mn_2O_3	0.07	0.05	0.20	0.27	0.15	0.09	0.10	0.08	0.09	0.12	0.06
C_3S	52.0	56.9	64.3	20.3	24.2	24.9	28.2	40.8	46.3	51.4	39.1
C_2S	19.4	14.6	10.2	50.5	57.4	48.2	50.8	39.4	26.8	22.3	38.9
C_3A	11.0	10.7	6.1	4.6	4.2	5.8	5.1	4.1	12.7	8.3	6.7
C_4AF	6.3	7.8	9.8	15.0	8.1	13.5	9.2	9.5	6.7	10.2	9.6
$CaSO_4$	3.8	3.9	2.9	3.3	2.6	3.5	3.1	2.7	2.6	3.3	2.1

Table 1. - Chemical analysis of cements used in the parapet wall at Green Mountain Dam, Colorado. Original data provided in USBR Materials Laboratory Report No. C-345.

			Mix Proportions					Fresh Properties				Hardened Properties	
Cement Type	Panel No.	Total Unit Weight	Water	Cement	Aggregate	Sand	Coarse Aggregate	Temp.	Slump	Unit Weight	w/c ratio	f'c 28 day	E 28 day
		(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(deg. F)	(in.)	(lb/ft^3)		(lb/ft^2)	(x10^6)
Type I:	11	4047.3	293	563.5	3190.8	1308.2	1882.6	51	2.75	149.9	0.52	5140	4.73
Normal	12	4036.5	295	556.6	3184.9	1305.8	1879.1	51	2.75	149.5	0.53	4850	4.63
	13	4020.3	307	558.2	3155.1	1293.6	1861.5	51	2.75	148.9	0.55	4090	4.49
	14	4039.2	295	556.6	3187.6	1306.9	1880.7	50	3.25	149.6	0.53	4830	4.42
	15	4020.3	304	552.7	3163.6	1297.1	1866.5	49	2.75	148.9	0.55	5150	4.74
	16	4041.9	299	553.7	3189.2	1307.6	1881.6	50	3.25	149.7	0.54	4600	4.68
	17	4033.8	302	559.3	3172.5	1300.7	1871.8	48	2.25	149.4	0.54	4750	4.55
	18	4031.1	309	561.8	3160.3	1295.7	1864.6	47	3.00	149.3	0.55	4560	4.55
Type II:	0	4041.9	299	564.2	3178.7	1303.3	1875.5	50	3.00	149.7	0.53	4240	4.79
Modified	21	4039.2	302	559.3	3177.9	1303.0	1875.0	50	3.00	149.6	0.54	3750	4.42
	22	4055.4	300	566.0	3189.4	1307.6	1881.7	48	3.25	150.2	0.53	4170	4.39
	23	4050	299	564.2	3186.8	1306.6	1880.2	50	3.00	150	0.53	4450	4.74
	24	4039.2	288	564.7	3186.5	1306.5	1880.0	47	3.25	149.6	0.51	4820	4.73
	25	4060.8	299	564.2	3197.6	1311.0	1886.6	50	2.00	150.4	0.53	4030	4.47
Type III:	31	4009.5	322	555.2	3132.3	1284.3	1848.1	50	2.75	148.5	0.58	4660	4.72
High early	33	4006.8	315	552.6	3139.2	1287.1	1852.1	50	3.00	148.4	0.57	4550	4.74
strength	34	4017.6	318	557.9	3141.7	1288.1	1853.6	50	2.25	148.8	0.57	4540	4.76
Type IV:	41	4044.6	294	565.4	3185.2	1305.9	1879.3	49	3.50	149.8	0.52	3350	4.26
Low heat	42	4060.8	307	558.2	3195.6	1310.2	1885.4	50	3.25	150.4	0.55	2530	3.89
	43	4036.5	294	565.4	3177.1	1302.6	1874.5	50	3.00	149.5	0.52	3250	3.94
	43A	4036.5	297	571.2	3168.3	1299.0	1869.3	49	3.25	149.5	0.52	3320	4.10
Type V:	51	4036.5	297	560.4	3179.1	1303.4	1875.7	49	3.25	149.5	0.53	3880	4.51
Sulfate-resistant													
AEA mixes:	12T	3985.2	291	559.6	3134.6	1235.0	1899.6	52	3.00	147.6	0.52	4530	4.58
	16T	3971.7	289	566.7	3116.0	1224.6	1891.4	50	3.75	147.1	0.51	4460	4.68
	21T	3966.3	280	571.4	3114.9	1224.1	1890.7	51	3.00	146.9	0.49	3740	4.26
	16B	3906.9	280	560.0	3066.9	1196.1	1870.8	51	3.75	144.7	0.50	4180	4.50
	34B	3877.2	287	551.9	3038.3	1184.9	1853.3	54	2.50	143.6	0.52	4290	4.33
	42B	3904.2	269	560.4	3074.8	1199.2	1875.6	53	3.50	144.6	0.48	2630	4.63

T: AEA (Vinsol Resin) was intergrinded.

B: AEA (Vinsol Resin) was added at the mixer.

Table 2. - Mix designs, fresh properties, and hardened properties of the concretes as provided by USBR Report No. C-345 (1947), Big Thompson Project, Green Mountain Dam, CO.

Entry No.	Cement No.	Visual examination	Chemical	Na eq. Limit =0.6	Other comments
1	14	Extremely poor condition Orangy tint Spalling on edges Map & pattern cracking 6" horiz. crack at bottom	Highest Alkali Activity for Type I Highest Na equiv. (T I) Highest K2O content (T I)	over 0.925	Test due to visual, alkali data
2	16	Good condition, slight discoloration along crack lines	Average chemical composition. Only variation is addition of air entrainment in 16B	under 0.573	Compare 16 with 16B to examine effects of air-entrainment
3	16B	Very good condition, little to no discoloration			
4	18	2 panels very bad, 1 ok Gold-orangy tint throughout Lots of spalling, deterioration Some cracking	Low Alkali Activity for Type 1 Lowest K2O content (T I)	under 0.278	Compare reasons for damage, alkali effect with sample 14
5	21	Good visual condition Spalling, limited area cracking Orangy tint 6" horiz. crack at bottom	Average chemical composition	under 0.576	Compare to 24
6	24	Worst visual condition Orangy Tint Map, area cracking Effervescence thru cracks 6" horiz. crack at bottom	Highest Alkali Activity for Type II Highest Na equiv. (T II) Highest free lime, Mg (T II) Lowest K2O content (T II)	over 0.906	Compare to 21
7	31	Differential cracking within 1 panel Differential discoloration within 1 panel Gold-Orangy tint Map cracking/more horizontal cracks Much effervescence 6" horiz. crack at bottom	Highest Mg (T III) High calcium sulfate	under 0.514	Compare conditions within panel to find reason for difference
8	34	Good condition Little spalling cracking Grey color	High free lime	under 0.518	Use good sample to compare to 34B (AEA in good condition)
9	34B	Good condition Little spalling cracking Grey color	Same as 34B	under 0.518	Compare to 34
10	41	Avg.- good condition Some cracking	High Alkali Activity Highest K2O content (T IV)	over 0.9	Compare effect of hi AA to 43
11	42	Good condition, slight whitish surface discoloration	Low Alkali-Activity Low free lime	under 0.377	Compare 42 with 42B to examine effects of air-entrainment
12	42B	Very good condition, concentrated dark cracks at panel sides			
13	43	Poor condition Orangy Tint Map, area cracking Lots of effervescence at sides. 6" horiz. crack at bottom	Highest Alkali Activity - all panels Lowest free lime	over 1.143	Compare to 41 Study extreme AA content
14	51	Great condition Grey, unaffected color	Low Alkali Activity Only Type V specimen	under 0.251	use for full sweep

Table 3. - Parapet panels selected for coring and laboratory testing, Green Mountain Dam, CO.

Compression Tests

Cement Mix No.	Core No.	Test	L/D factor	Compressive Strength (lb/in^2)	ASTM Chord Modulus (E) (lb/in^2 x10E^6)		Poisson's Ratio	Average Strength by Type: (lb/in^2)		Average Moduli by Type: (lb/in^2 x10E^6)		Strains at Ultimate Strength (ue)	Strains at Failure (ue)
14	1	C	0.97	5980	2.84		0.30					1675	1675
14	3	C	0.98	6690	3.99		0.23					1860	1860
16	2	C	0.98	7040	3.81		0.16					2025	2025
16	4	C	1.00	6780	3.64		0.21					2000	2000
16B	1	C	1.00	5930	3.58		0.21					1900	1900
16B	3	C	0.99	6250	3.88			Type I		Type I		1650	1650
18	2	C	1.00	6000	3.57		0.18	Avg:	6500	Avg:	3.56	1900	1900
18	4	C	0.97	7290	3.18		0.20	SD:	526	SD:	0.38	2600	2600
21	1	C	1.00	7240	4.55		0.23	Type II		Type II		1875	1875
21	3	C	1.00	6930	4.30		0.19	Avg:	6100	Avg:	4.43	1625	1625
24	2	C	0.89	4140	N/A		0.19	SD:	1707	SD:	0.18		
31	1	C	1.00	3750	1.05		0.22					3050	3050
34	4	C	0.99	5150	2.71		0.17					2250	2250
34	5	C	1.00	5200	2.74			Type III		Type III		2500	2500
34B	4	C	1.00	5500	2.83		0.13	Avg:	5230	Avg:	2.44	1700	1700
34B	5	C	1.00	6550	2.89		0.15	SD:	1002	SD:	0.78	2225	2225
41	1	C	1.00	6530	1.95		0.28					2550	2550
41	3	C	1.00	7870	4.71		0.28					1550	1550
42	3	C	0.97	6590	3.42							1825	1825
42	4	C	0.98	5400	2.72		0.33					1720	1720
42B	1	C	1.00	6430	3.24		0.34					2050	2050
42B	2	C	0.98		N/A								
43	2	C	0.90	3240	N/A							1500	1500
43	3	C	0.89	3300	N/A			Type IV:		Type IV:			
43A	1	C	0.99	6720	N/A		0.17	Avg:	5810	Avg:	3.21		
43A	3	C	1.00	6190	N/A			SD:	1573	SD:	1.02		
								Type V:		Type V:			
51	3	C	1.00	6310	3.98		0.25	Avg:	6340	Avg:	3.98	1750	1750
51	4	C	1.00	6360	3.98		0.27	SD:	35	SD:	0.00	1950	1950
Avg. Static Compression (all types):				**5980**	**3.34**		**0.22**					**1988**	**1988**
Standard Deviation (all types):				**1190**	**0.85**		**0.06**					**385**	**385**
Coefficient of Variation (all types):				**20%**	**26%**		**26%**					**19%**	**19%**
								Type I:					
16	4	Dyn C	0.98	8810	4.09			Avg:	7880			2200	2200
16B	3	Dyn C	0.98	6950	N/A			SD:	1315				
								Type IV:					
42	2	Dyn C	0.97	7360	3.77			Avg:	7280			1725	1725
42B	4	Dyn C	0.98	7200	N/A			SD:	113				
Avg. Dynamic Compression (all types):				**7580**	**3.93**							**1963**	**1963**
Standard Deviation (all types):				**840**	**0.23**							**336**	**336**
Coefficient of Variation (all types):				**11%**	**6%**							**17%**	**17%**
					Avg. U-R E (x10^6)	ASTM Chord E (x10^6)					Avg. U-R E (x10^6)		
14	2	NL	0.99	6180	3.67	3.06						2225	2225
16	1	NL	0.97					Type I:		Type I:			
16B	2	NL	0.99	6710	3.62	3.12		Avg:	6523	Avg:	3.88	2070	2070
18	5	NL	1.00	6335	4.36	3.72		SD:	265	SD:	0.41		
								Type II:		Type II:			
21	2	NL	1.00	6460	3.89	4.71		Avg:	6715	Avg:	3.58	1775	1775
24	1	NL	0.97	6970	3.27	3.04		SD:	361	SD:	0.44	2450	2450
								Type III:		Type III:			
34	3	NL	1.00	4920	2.26	2.06		Avg:	5495	Avg:	2.90	2250	2250
34B	2	NL	1.00	6070	3.53	2.80		SD:	813	SD:	0.90	2100	2100
41	5	NL	1.00	8170	4.49	3.92						2300	2525
42	1	NL	0.98	6950	N/A	3.96		Type IV:		Type IV:			
42B	3	NL	0.98	6310	4.35			Avg:	6945	Avg:	4.39	1800	1950
43A	2	NL	1.00	6350	4.33	3.92		SD:	868	SD:	0.09	1800	1800
								Type V:		Type V:			
51	1	NL	1.00	7160	4.50	3.80		Avg:	7160	Avg:		2100	2100
Avg Non-linear Compression (all types):				6550	3.84	3.46						**2087**	**2125**
Standard Deviation (all types):				770	0.68	0.73						**232**	**248**
Coefficient of Variation (all types):				12%	18%	21%						**11%**	**12%**

C = static compression
Dyn C = dynamic compression
NL = nonlinear (unload-reload)

Table 4. - Compressive strengths and elastic properties of cores, parapet wall, Green Mountain Dam, CO.

Cement no.	Static Compressive Strength (lb/in^2)	Ave. Static Compressive Strength/Mix (lb/in^2)	Unload-Reload Strength (lb/in^2)	Ratio U-R/Static Strength
14	5980			
14	6690	6335	6180	0.98
16B	5930			
16B	6250	6090	6710	1.10
18	6000			
18	7290	6645	6340	0.95
21	7240			
21	6930	7085	6460	0.91
24	4140	4140	6970	1.68
34	5150			
34	5200	5175	4920	0.95
34B	5500			
34B	6550	6025	6070	1.01
41	6530			
41	7870	7200	8170	1.13
42	6590			
42	5400	5995	6950	1.16
42B	6430	6430	6310	0.98
43A	6720			
43A	6190	6455	6350	0.98
51	6310			
51	6360	6335	7160	1.13
			Average ratio (all mixes):	**1.08**
			Average ratio (excluding mix 24):	**1.03**

Table 5. - Comparison of ultimate static and non-linear compressive strengths of cores, Green Mountain Dam, CO.

Cement No.	No.	Core No.	**Test**	Tensile Strength (lb/in^2)	Avg. Strength by Cement Type (lb/in^2)
16	4	4	**ST**	460	Type I
		5	**ST**	290	Avg: 375
21	1	4	**ST**	660	Type II
		5	**ST**	560	Avg: 610
34	4	1	**ST**	385	
		2	**ST**	505	
34B	4	1	**ST**	495	Type III
		3	**ST**	380	Avg: 440
41	1	2	**ST**	615	Type IV
		4	**ST**	525	Avg: 570
51	4	2	**ST**	530	Type V
		5	**ST**	635	Avg: 585
			Average split tensile strength:	**505**	
			Standard deviation:	**110**	
			Coefficient of variation:	**22%**	

ST = splitting tension

Table 6. - Splitting tensile strengths of cores, Green Mountain Dam, CO.

Average Unit Weights of Concrete Mixes

Cement No.	Unit Weight 1943 (Table 2) (lb/ft^3)	Unit Weight 1997 (lb/ft^3)	% Loss (1943-97) %	Avg. By Cement Type 1997 (lb/ft^3)
14	149.6	144.0	3.7%	
16	149.7	147.0	1.8%	
16B	144.7	142.4	1.6%	Type I
18	149.3	144.5	3.2%	Avg: 144.5
21	149.6	146.0	2.4%	Type II
24	149.6	144.0	3.7%	Avg: 145.0
31	148.5	147.4	0.7%	
34	148.8	143.1	3.8%	Type III
34B	143.6	142.7	0.6%	Avg: 144.4
41	149.8	146.7	2.1%	
42	150.4	144.1	4.2%	
42B	144.6	143.6	0.7%	
43	149.5	143.9	3.7%	Type IV
43A	149.5	148.1	0.9%	Avg: 145.3
				Type V
51	149.5	146.5	2.0%	Avg: 146.5

Table 7. - Unit weight comparison of cores, Green Mountain Dam, CO.

	STRAIN INTERVAL									
	100					**250**				
Mix	Plastic Strain	Elastic Strain	**Ratio Plastic/Elastic**	Total Strain	**Ratio Plastic/Total**	Plastic Strain	Elastic Strain	**Ratio Plastic/Elastic**	Total Strain	**Ratio Plastic/Total**
(#)	(ue)	(ue)	**(%)**	(ue)	**(%)**	(ue)	(ue)	**(%)**	(ue)	**(%)**
14	25	107	**23%**	132	**19%**	40	270	**15%**	310	**13%**
16B	25	183	**14%**	208	**12%**	50	328	**15%**	378	**13%**
18	10	110	**9%**	120	**8%**	25	270	**9%**	295	**8%**
21	20	106	**19%**	126	**16%**	40	277	**14%**	317	**13%**
24	10	115	**9%**	125	**8%**	25	291	**9%**	316	**8%**
34	20	106	**19%**	126	**16%**	30	254	**12%**	284	**11%**
34B	25	108	**23%**	133	**19%**	45	257	**18%**	302	**15%**
41	20	106	**19%**	126	**16%**	40	259	**15%**	299	**13%**
42b	10	107	**9%**	117	**9%**	30	262	**11%**	292	**10%**
43a	20	104	**19%**	124	**16%**	50	275	**18%**	325	**15%**
51	5	106	**5%**	111	**5%**	15	259	**6%**	274	**5%**

	STRAIN INTERVAL									
	500					**1000**				
Mix	Plastic Strain	Elastic Strain	**Ratio Plastic/Elastic**	Total Strain	**Ratio Plastic/Total**	Plastic Strain	Elastic Strain	**Ratio Plastic/Elastic**	Total Strain	**Ratio Plastic/Total**
(#)	(ue)	(ue)	**(%)**	(ue)	**(%)**	(ue)	(ue)	**(%)**	(ue)	**(%)**
14	65	495	**13%**	560	**12%**	120	988	**12%**	1108	**11%**
16B	75	503	**15%**	578	**13%**	150	1000	**15%**	1150	**13%**
18	65	493	**13%**	558	**12%**	165	989	**2%**	1154	**14%**
21	60	500	**12%**	560	**11%**	100	1000	**10%**	1100	**9%**
24	40	524	**8%**	564	**7%**	75	991	**8%**	1066	**7%**
34	45	491	**9%**	536	**8%**	75	988	**8%**	1063	**7%**
34B	75	496	**15%**	571	**13%**	225	988	**23%**	1213	**19%**
41	60	497	**12%**	557	**11%**	100	990	**10%**	1090	**9%**
42b	45	505	**9%**	550	**8%**	70	995	**7%**	1065	**7%**
43a	65	504	**13%**	569	**11%**					
51	50	509	**10%**	559	**9%**	120	1000	**12%**	1120	**11%**

	STRAIN INTERVAL				
	1500				
Mix	Plastic Strain	Elastic Strain	**Ratio Plastic/Elastic**	Total Strain	**Ratio Plastic/Total**
(#)	(ue)	(ue)	**(%)**	(ue)	**(%)**
34	120	1500	**8%**	1620	**7%**
34B	375	1500	**25%**	1875	**20%**

	Average Plastic/Elastic		Average Plastic/Total	
Mix	Ratio per Mix	Std. Dev.	Ratio per Mix	Std. Dev.
(#)	**(%)**	**(%)**	**(%)**	**(%)**
14	16%	5%	14%	4%
16B	15%	1%	13%	1%
18	8%	5%	11%	3%
21	14%	4%	12%	3%
24	8%	1%	8%	1%
34	11%	5%	10%	4%
34B	21%	4%	17%	3%
41	14%	4%	12%	3%
42b	9%	2%	8%	2%
43a	17%	3%	14%	3%
51	8%	3%	7%	3%

Plastic/Elastic Strain Ratio:	
Max Strain Ratio (Mix 34B):	25%
Min. Strain Ratio (Mix 51):	5%
Plastic/Total Strain Ratio:	
Max Strain Ratio (Mix 34B):	5%
Min. Strain Ratio (Mix 51):	20%

Table 8. - Ratios of plastic and elastic strains and plastic to total (elastic +plastic) strains at the end of each unload portion of the unload-reload cycles for the cyclic loading/ non-linear tests. Plastic strain represents permanent strain induced in the specimen from loading; elastic strain dissipates once the load is removed.

Cement No.	Panel No.	Poisson's Ratio	Density	Laboratory values*		Field Values**			
						6" from top		14" from top	
				Velocity	Sonic Modulus	Velocity	Sonic Modulus	Velocity	Sonic Modulus
			(lb/in^3)	(ft/s)	($x 10^6 lb/in^2$)	(ft/s)	($x 10^6 lb/in^2$)	(ft/s)	($x 10^6 lb/in^2$)
14	1	0.265	144.9	14440	5.27	13310	4.48	13560	4.65
16	4	0.185	147.1	15020	6.56	14330	5.97	14160	5.83
16B	4	0.21	140.3	14580	5.71	13830	5.14	13760	5.09
18	1	0.19	145.3	14920	6.35	13860	5.48	14260	5.80
Type I Average:				**14740**	**5.97**	**13830**	**5.27**	**13940**	**5.34**
Standard Deviation:				**280**	**0.59**	**420**	**0.63**	**330**	**0.58**
Coeff. Of Variation:				**2%**	**10%**	**3%**	**12%**	**2%**	**11%**
21	1	0.21	146.0	14560	5.93	13960	5.45	14180	5.63
24	4	0.19	143.8	7760	1.70	6380	1.15	9480	2.54
Type II Average:				**11160**	**3.82**	**10170**	**3.30**	**11830**	**4.08**
Standard Deviation:				**4810**	**2.99**	**5360**	**3.04**	**3320**	**2.18**
Coeff. Of Variation:				**43%**	**78%**	**53%**	**92%**	**28%**	**53%**
31	1	0.22	147.5	9480	2.50	6870	1.31	8470	2.00
34	4	0.17	143.1	14210	5.80	13310	5.09	13280	5.06
34B	4	0.14	143.0	14590	6.26	13450	5.32	13390	5.28
Type III Average:				**12760**	**4.86**	**11210**	**3.91**	**11710**	**4.11**
Standard Deviation:				**2850**	**2.05**	**3760**	**2.25**	**2810**	**1.83**
Coeff. Of Variation:				**22%**	**42%**	**34%**	**58%**	**24%**	**45%**
41	1	0.28	146.9	14100	4.93	14070	4.91	13330	4.40
42	4	0.33	144.1	14020	4.12	12980	3.53	13280	3.70
42B	4	0.34	143.7	15270	4.69	13940	3.91	13820	3.85
43	1	N/A	145.0			5820	N/A	7840	N/A
43A	1	0.17	148.8			13100	5.12	13420	5.38
Type IV Average:				**14460**	**4.58**	**11980**	**4.37**	**12340**	**4.33**
Standard Deviation:				**700**	**0.41**	**3480**	**0.77**	**2520**	**0.76**
Coeff. Of Variation:				**5%**	**9%**	**29%**	**18%**	**20%**	**18%**
51	4	0.26	146.5	14990	5.80	14220	5.22	14350	5.32
Total Average:				**13690**	**5.05**	**12230**	**4.44**	**12710**	**4.61**
Standard Deviation:				**2306**	**1.49**	**3071**	**1.50**	**2180**	**1.19**
Coefficient of Variation:				**17%**	**29%**	**25%**	**34%**	**17%**	**26%**

* Laboratory velocities are based on the average of 2-5 core readings from the vertical cross-section of the wall.

** Field velocities and moduli are based on the average of 4-5 readings taken horizontally from the wall.

<u>Formulas (James Instruments, Inc.)</u>:

1. Pulse velocity = l/t
2. Sonic Modulus of Elasticity = $(v^2 d\,(1+u)(1-2u))/144a(1-u)$

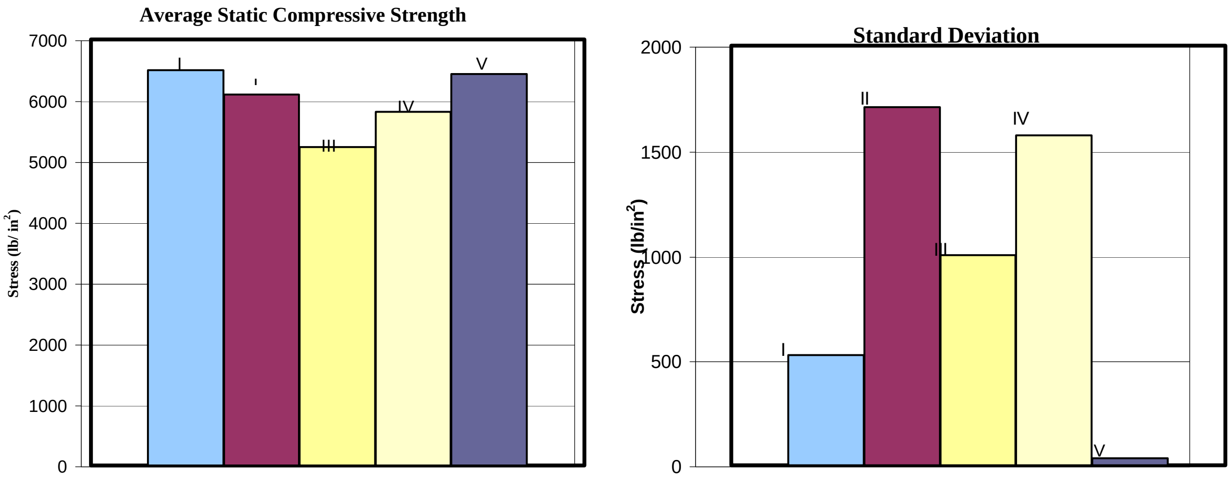
l = path length
t = travel time
v = veloctiy of wave
d = density of samples
u = Poisson's ratio of sample
a = acceleration of gravity (32.2 ft/s2)

Table 9.- Field and laboratory velocities and sonic moduli resulting from sonic tests, Green Mountain Dam, CO.

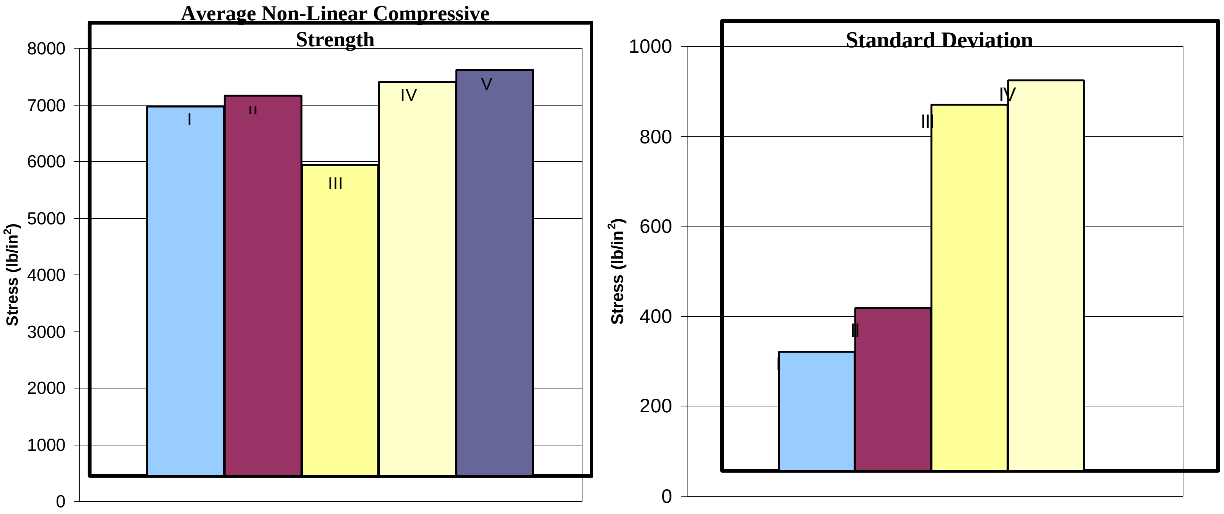
Cement No.	Panel No.	Ave. Static Modulus of Elasticity	Dynamic Modulus of Elasticity	Field Sonic Modulus 6" from top	Field Sonic Modulus 14" from top	Laboratory Core Sonic Modulus	Ratio of core sonic /core static Modulus
		(x 10^6 lb/in^2)	(x 10^6 lb/in^2)	(x 10^6 lb/in^2)	(x 10^6 lb/in^2)	(x 10^6 lb/in^2)	(x 10^6 lb/in^2)
14	1	3.42		4.48	4.65	5.27	1.54
16	4	3.73	4.09	5.97	5.83	6.56	1.76
16B	4	3.73		5.14	5.09	5.71	1.53
18	1	3.38		5.48	5.8	6.35	1.88
21	1	4.43		5.45	5.63	5.93	1.34
24	4	N/A		1.15	2.54	1.70	N/A
31	1	1.05		1.31	2	2.50	2.38
34	4	2.73		5.09	5.06	5.80	2.12
34B	4	2.86		5.32	5.28	6.26	2.19
41	1	3.33		4.91	4.4	4.93	1.48
42	4	3.07	3.77	3.53	3.7	4.12	1.34
42B	4	3.24		3.91	3.85	4.69	1.45
43	1	N/A		N/A	N/A	N/A	N/A
43A	1	N/A		5.12	5.38	N/A	N/A
51	4	3.98		5.22	5.32	5.80	1.46
Total Average:		**3.25**		**4.43**	**4.61**	**5.05**	**1.71**
Standard Deviation:		**0.84**		**1.50**	**1.19**	**1.49**	**0.36**
Coeff. of Variation:		**26%**		**34%**	**26%**	**29%**	**21%**

Table 10. - Comparison of elastic, dynamic and sonic moduli for cored panels, Green Mountain Dam, CO.

1. Static Compressive Strength



2. Unload-Reload (NL) Compressive Strength



3. Static Modulus of Elasticity

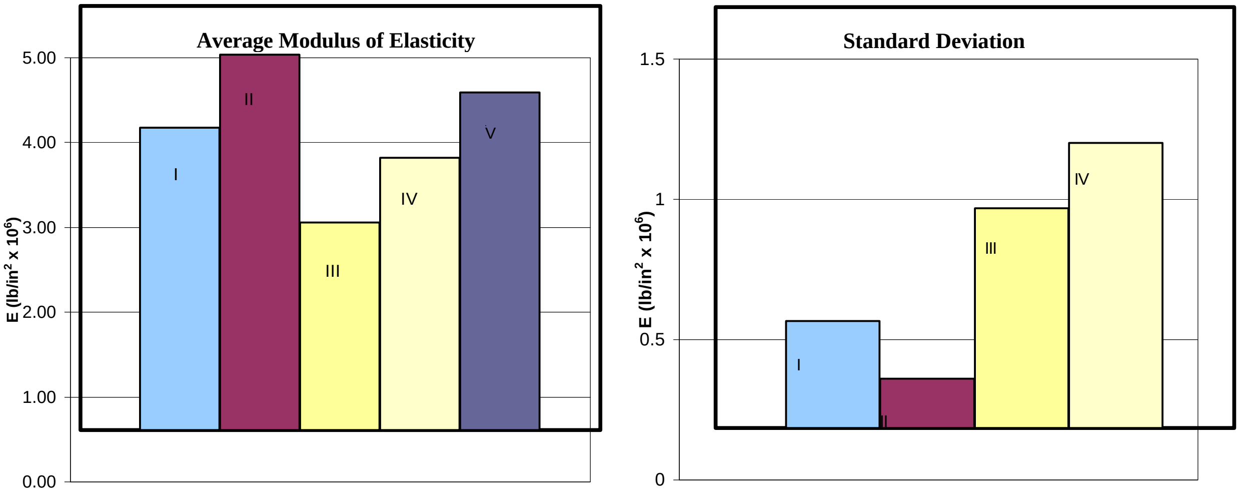


Figure 2. - Comparison of strengths and static moduli by cement type, Green Mountain Dam, CO.

Figure 2. - Comparison of strengths and static moduli by cement type, Green Mountain Dam, CO.

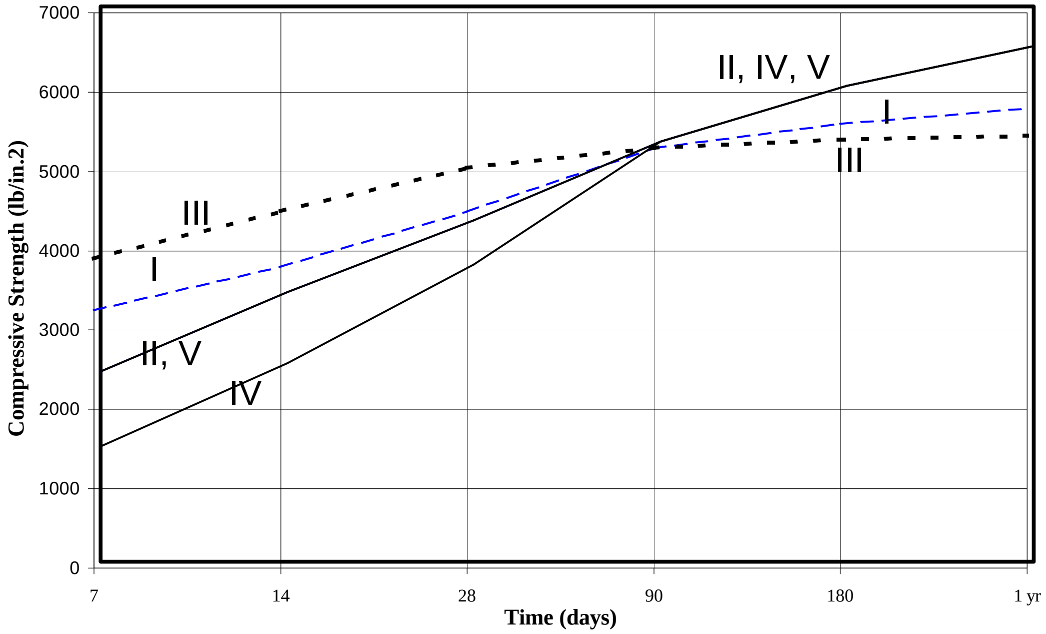


Figure 3. - Strength of 6 x 12 in. cylinders made with the same aggregates, but different cement types (Adapted from *Concrete Manual*, 8th ed., USBR, Denver, CO 1975.)

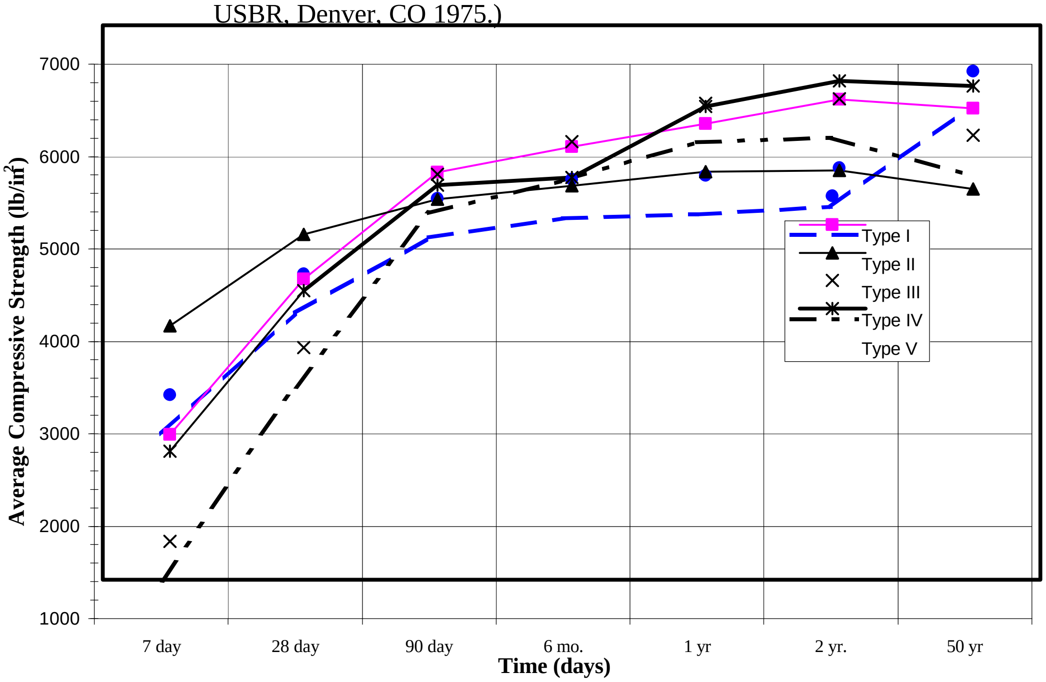


Figure 4. - Average Strength of the 16 cored, field (6 x 12 in) samples of cements by ASTM type, Green Mountain Dam, CO.

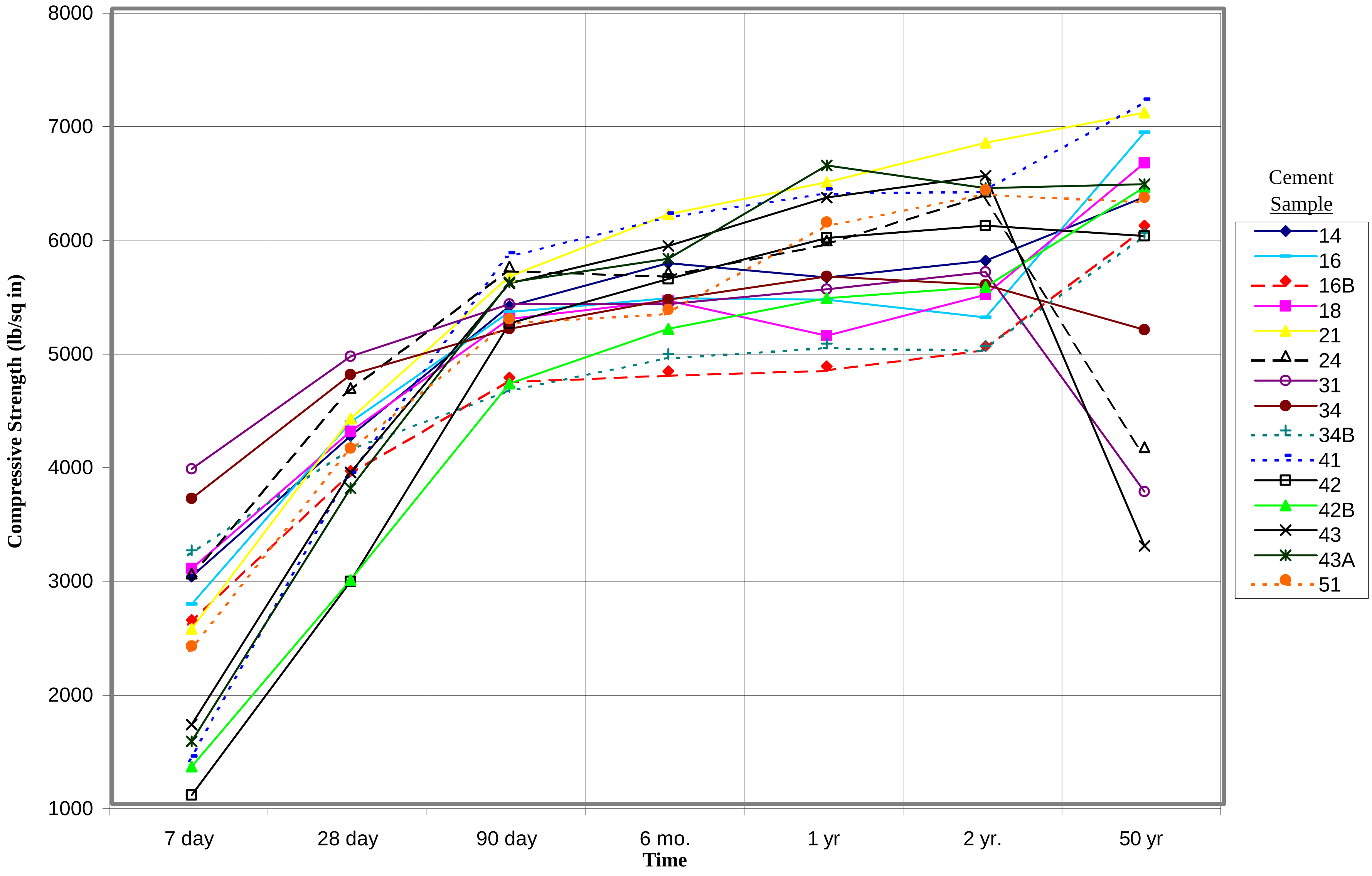


Figure 5. - Comparison of the compressive strengths of test samples over time, Green Mountain Dam, CO.

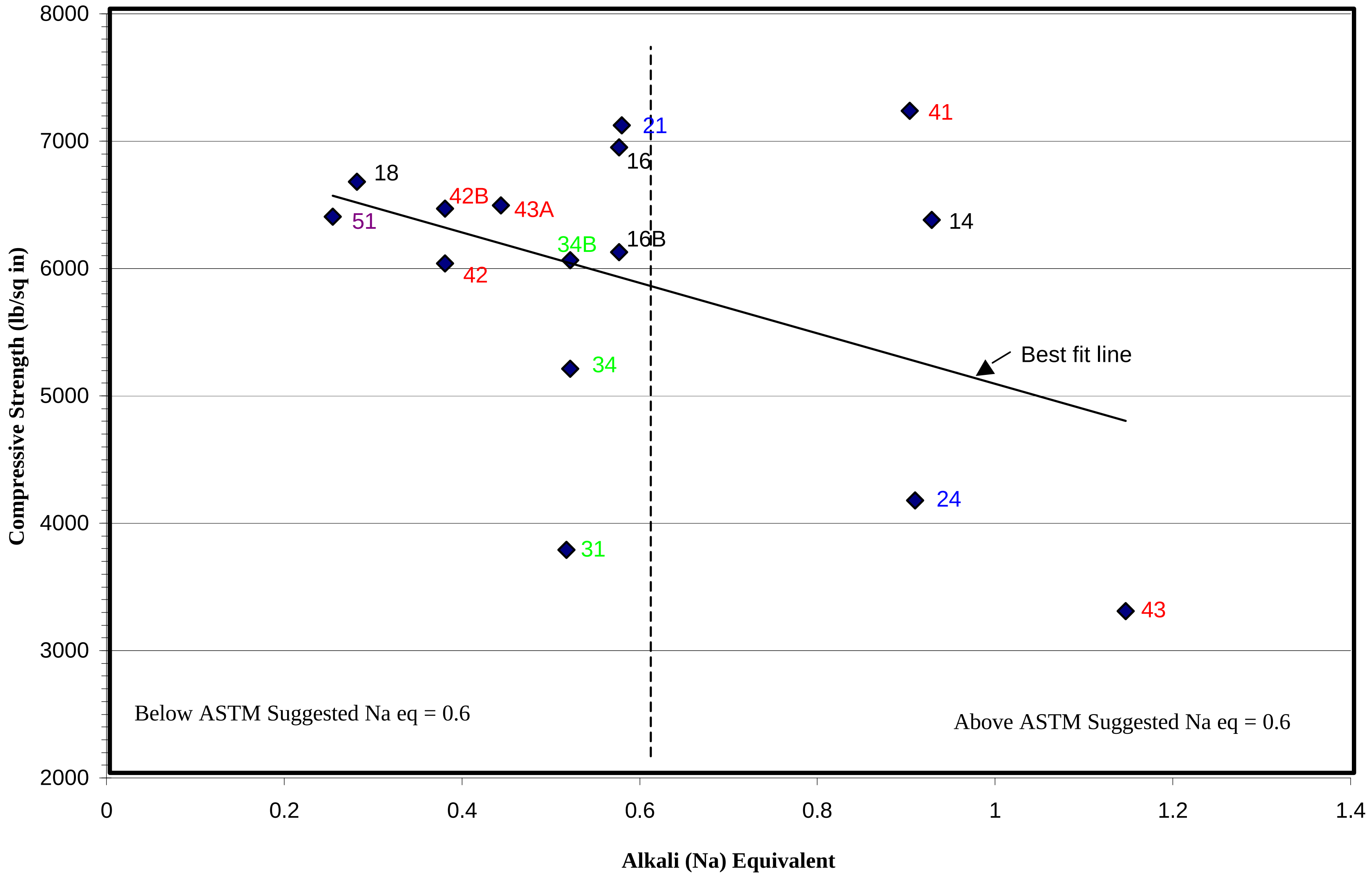
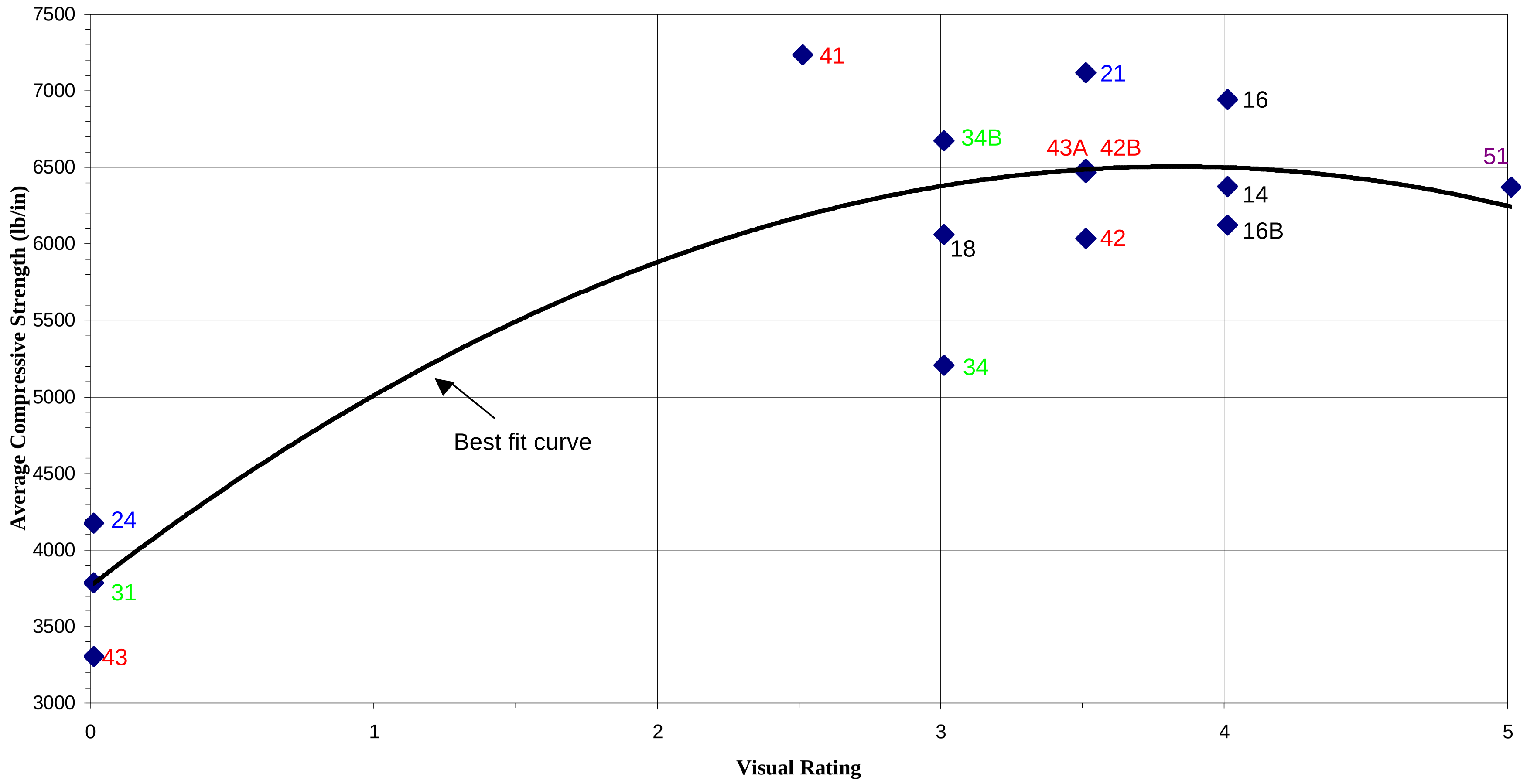


Figure 6. - Compressive strength versus the alkali activity of the cement in tested concrete cores, Green Mountain Dam, CO.



Visual Rating Scale (relative ratings):
5: Excellent Condition
0: Poorest Condition

Figure 7. - Visual Rating versus compressive strength, Green Mountain Dam, CO.

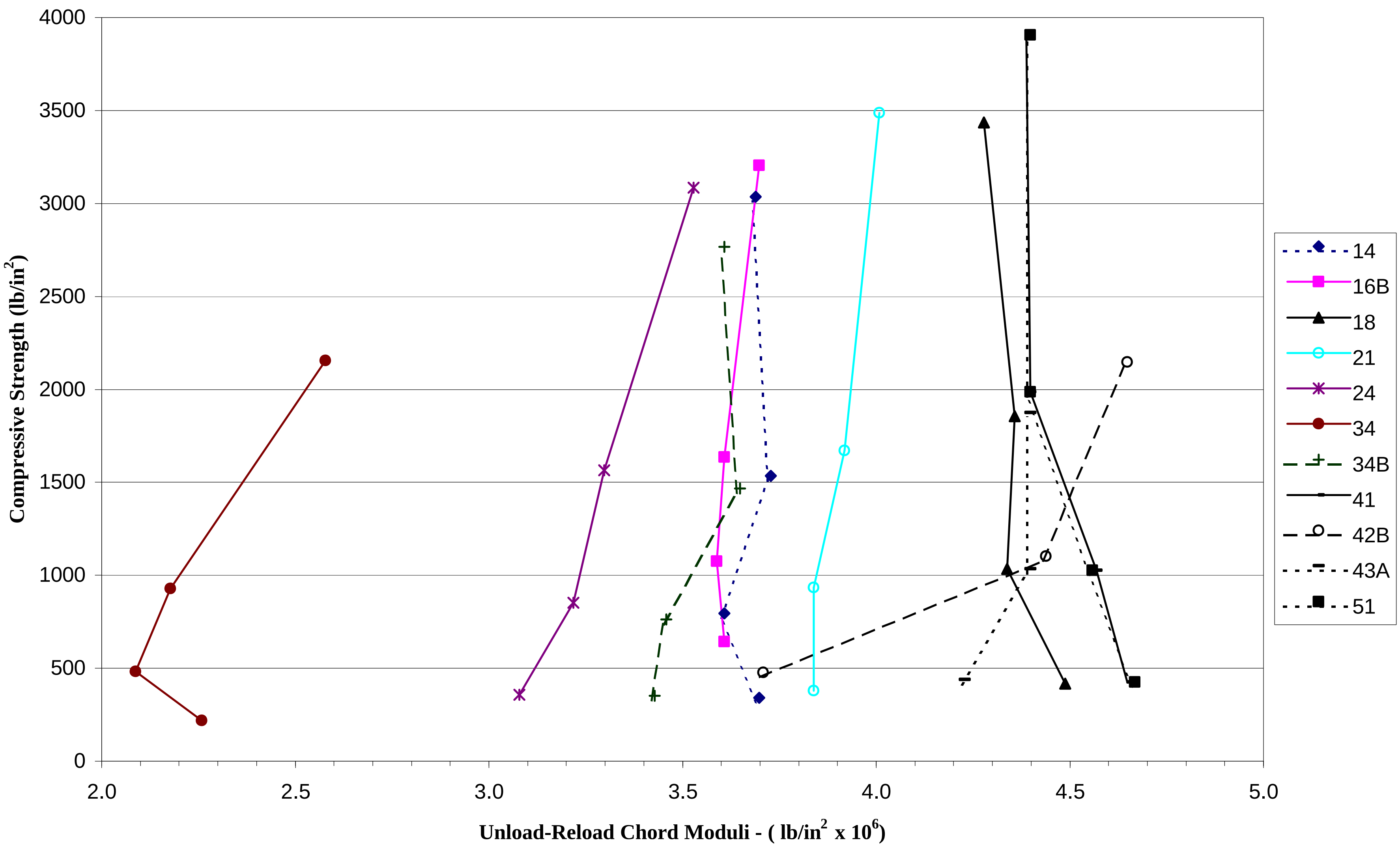


Figure 8. - Compressive Stress versus average unload-reload chord moduli, Green Mountain Dam, CO.

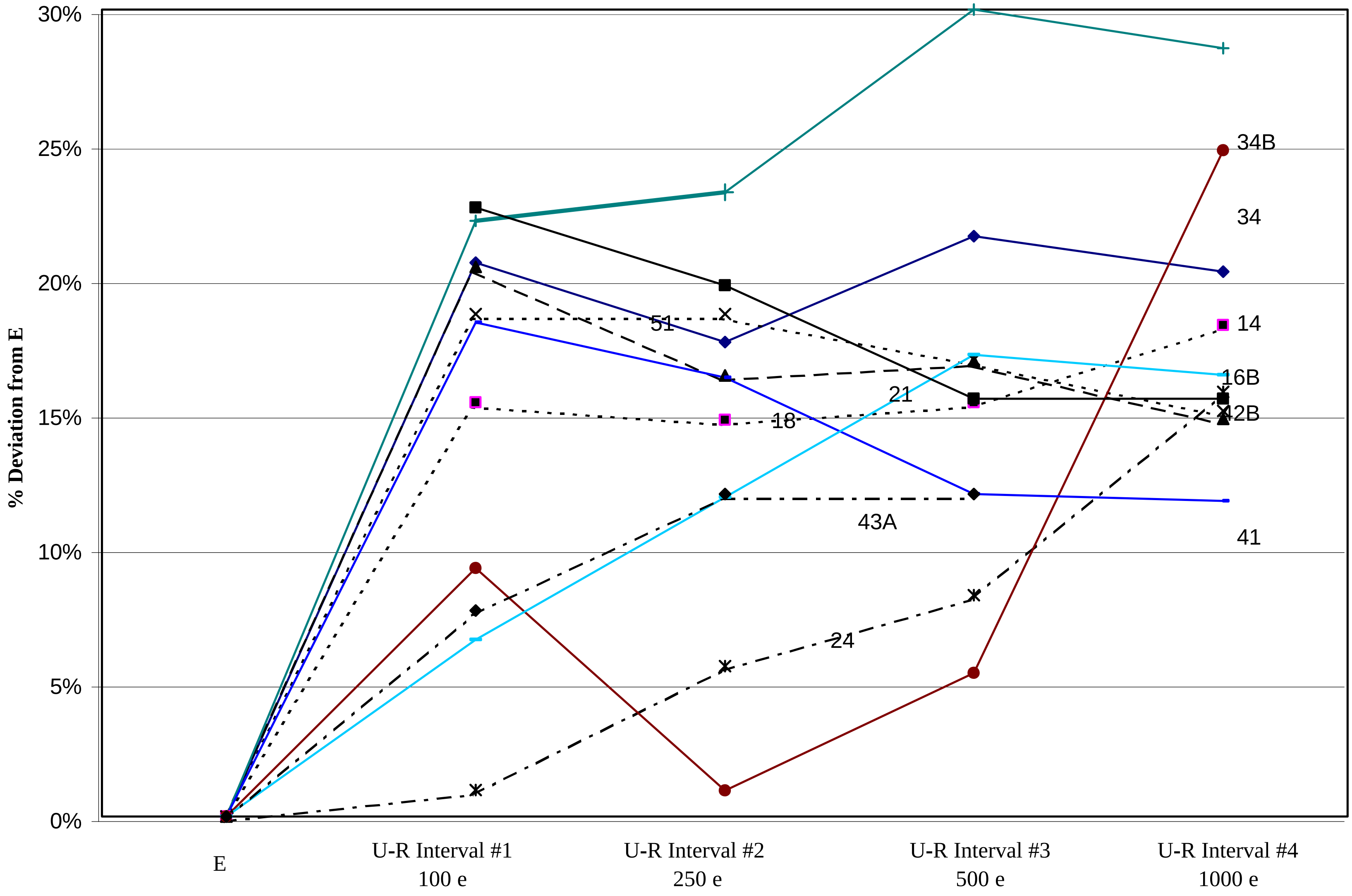
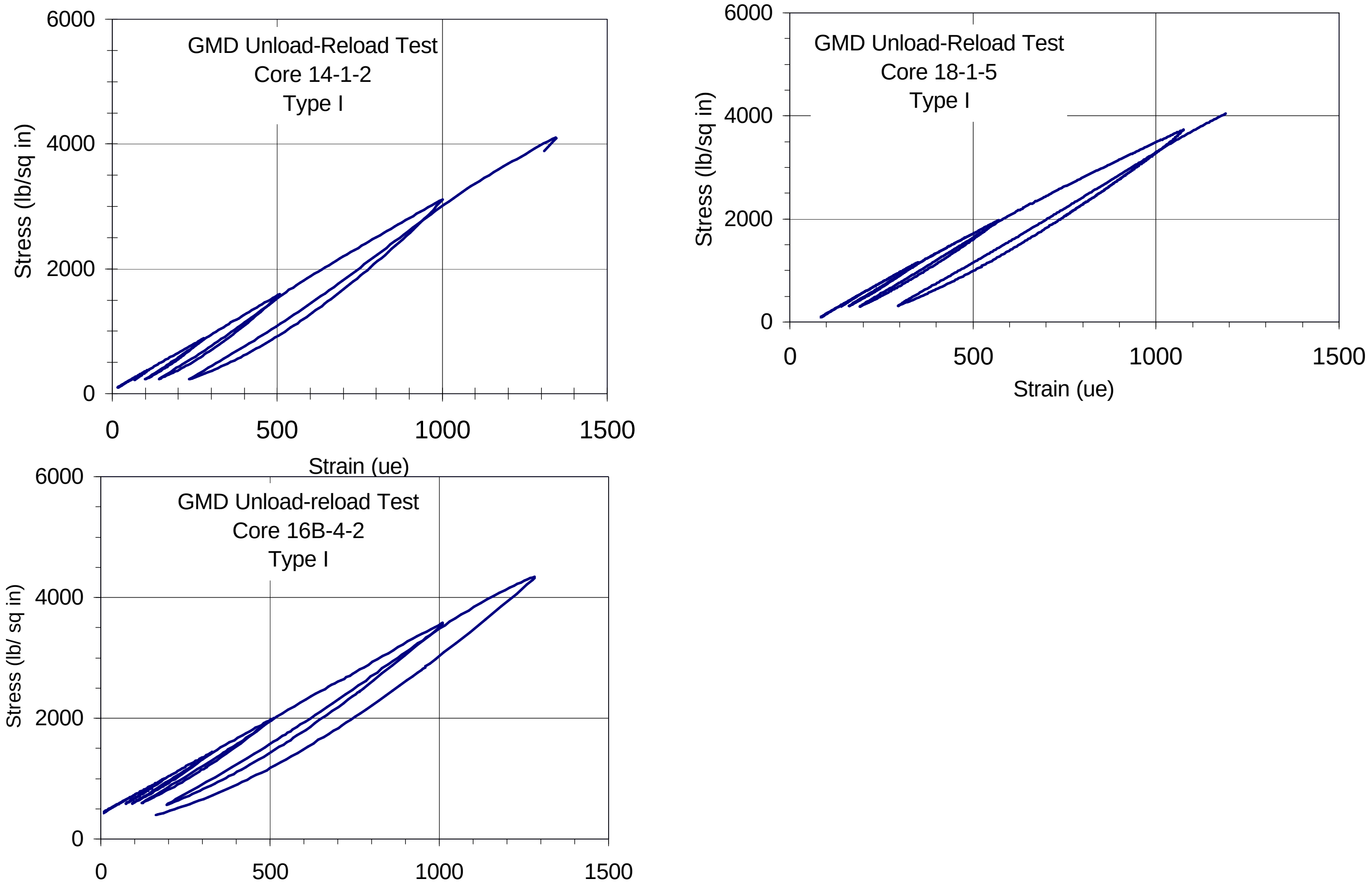
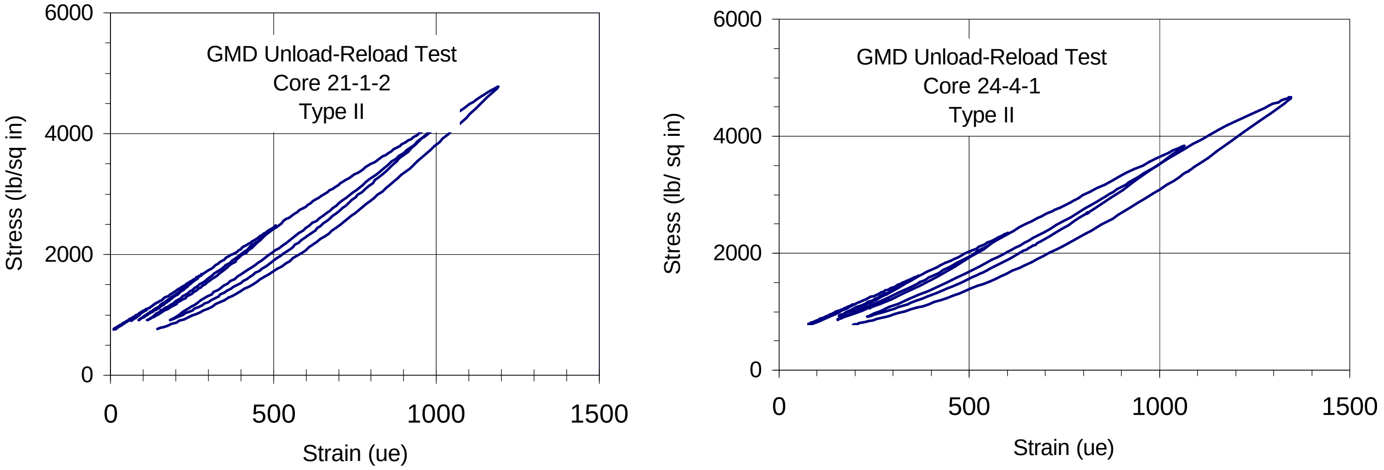


Figure 9. - Percent deviation of unload-reload (U-R) chord moduli from the static modulus of elasticity at various U-R intervals, Green Mountain Dam, CO.

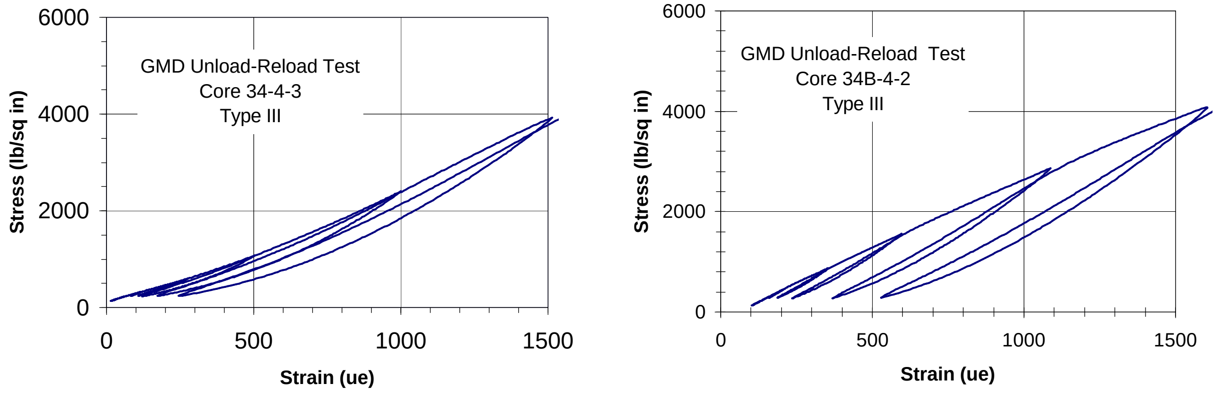


Type I Unload-Reload Plots

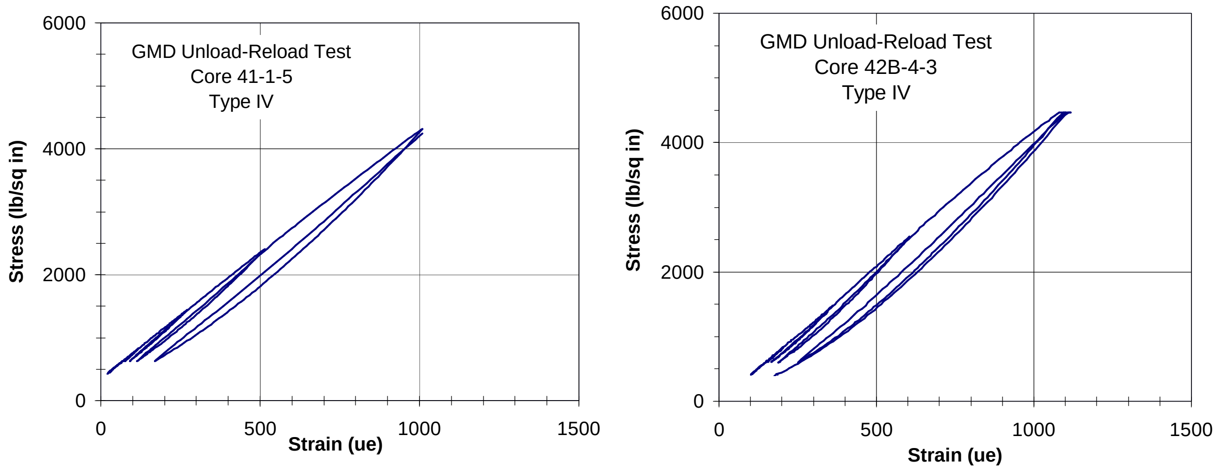


Type II Unload-Reload Plots

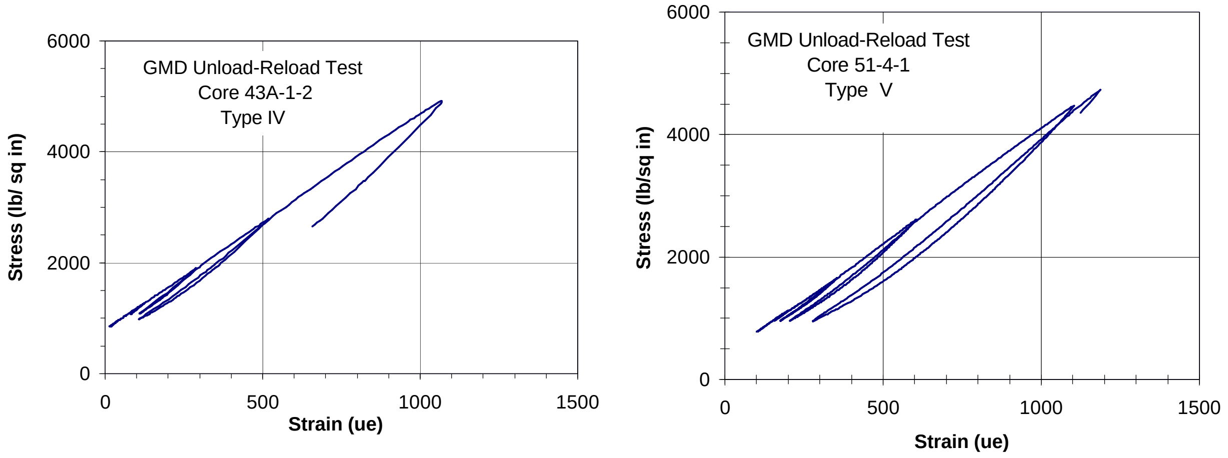
Figure 10. - Cyclic (non-linear) compression plots. Loading cycles are projected to the horizontal axis to calculate the plastic strain (from origin to horizontal intercept) and the elastc strain (from intercept to strain at which loading begins), Green Mountain Dam, CO.



Type III Unload-Reload Plots



Type IV Unload-Reload Plots



Type IV, V Unload-Reload Plots

Figure 10. - Cyclic (non-linear) compression plots (cont).

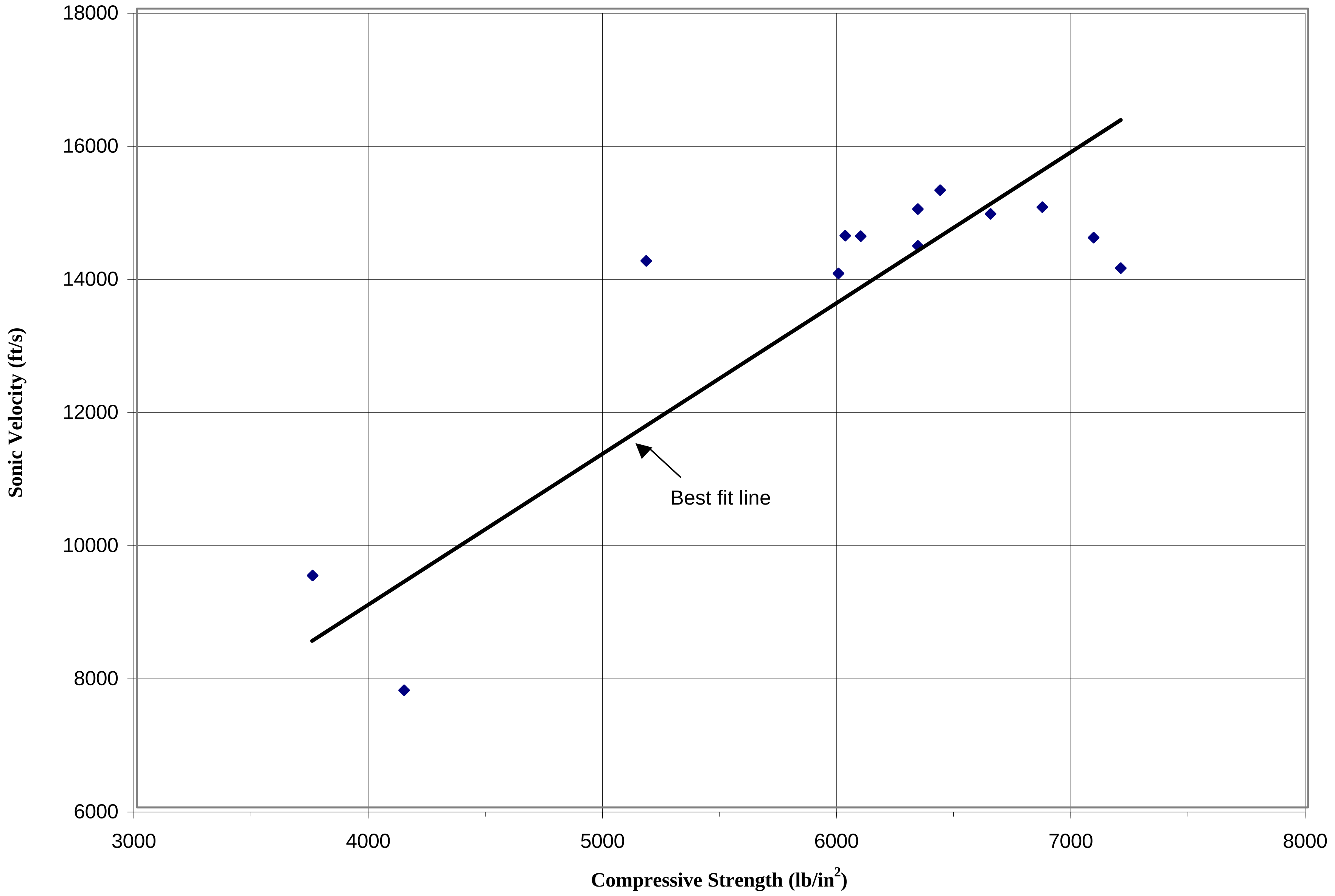


Figure 11. - Compressive strength versus laboratory pulse velocity for cored samples, Green Mountain Dam, CO.

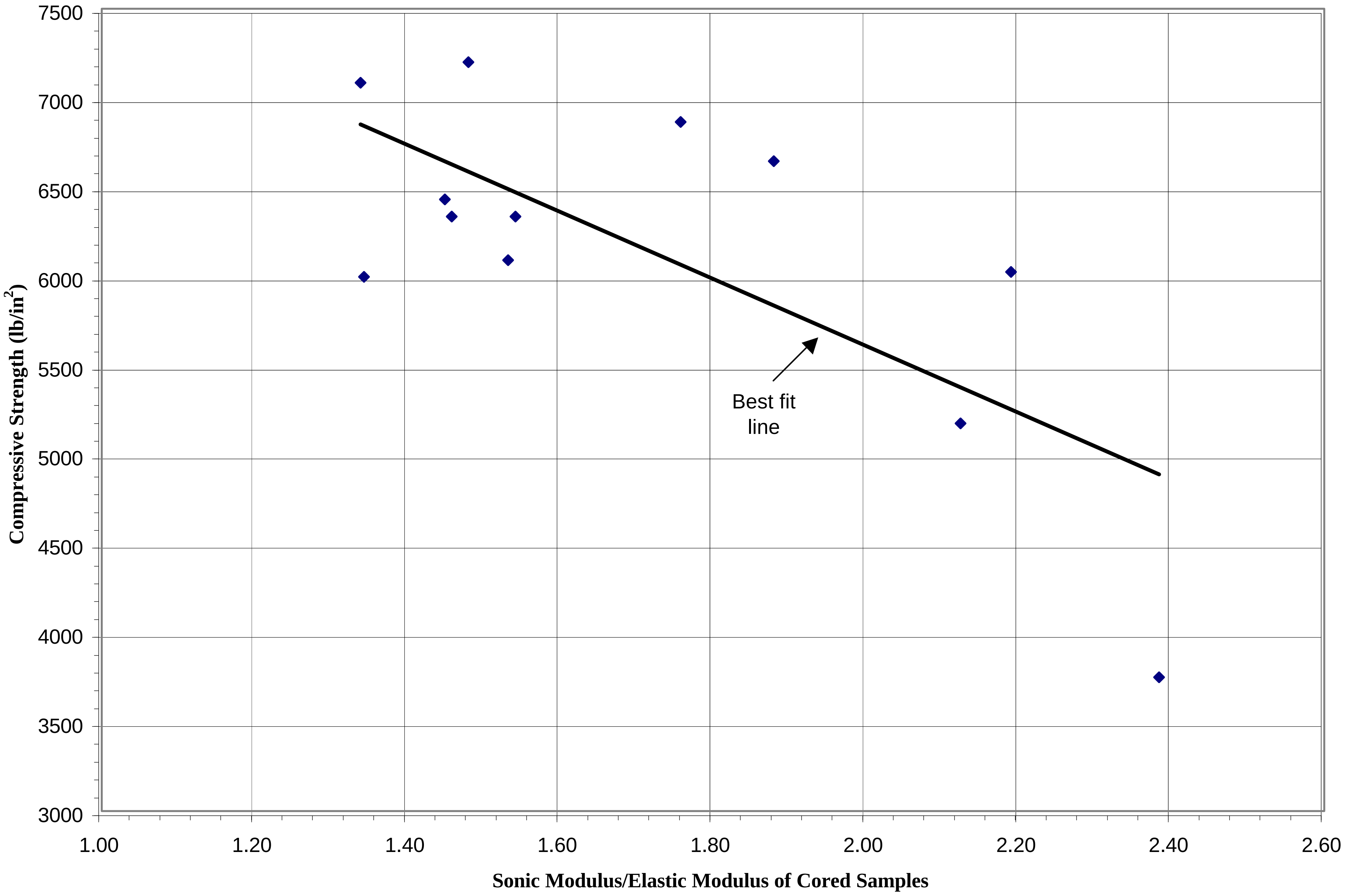


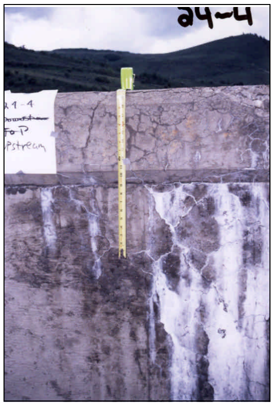
Figure 12. - Ratio of laboratory sonic modulus to elastic modulus versus compressive strength for cored samples, Green Mountain Dam, CO.

Type I, mix 14, panel 1

Type I, mix 16, panel 1

Type I cement, mix 18, panel 1

Type II cement, mix 21, panel 1



Type II cement, mix 24, panel 4

Type II cement, mix 24, panel 4

Figure 13. – Photographs of tested panels from parapet wall, Green Mountain Dam, CO.

Type III, mix 31, panel 1

Type III cement, mix 34, panel 1

Type IV cement, mix 41, panel 1

Type IV cement, mix 42, panel 4

Type IV cement, mix 42B, panel 4

Type IV cement, mix 43, panel 1

Figure 13 (cont.). – Photographs of tested panels from parapet wall, Green Mountain Dam, CO.

Type IV cement, mix 43A, panel 4

Type V cement, mix 51, panel 1

Figure 13 (cont.). – Photographs of tested panels from parapet wall, Green Mountain Dam, CO.