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Introduction

The dynamic properties of concrete are an important consideration in the analysis and review of the safety of structures such as concrete dams. Concrete tests can be designed to predict the behavior of a structure under various static and dynamic loading conditions. In laboratory tests, different dynamic conditions are modeled by varying the strain rate at which the test is performed. Thus, the strain rate of the tests is key to the interpretation of results.

Considerable work has been performed in the area of dynamic properties and much of the work has been summarized as a state-of-the-art paper by Bischoff and Perry, 1991.[1] Strain rates and their conceptual equivalent situation are tabulated below (Bischoff and Perry, 1991):

Condition	Strain rate: (in/in per second)
Creep	10^{-8} to 10^{-6}
Static	10^{-6} to 10^{-4}
Earthquake	10^{-3} to 10^{-2}
Hard Impact	10^{0} to 10^{1}
Blast	10^{2} to 10^{3}

The U.S. Bureau of Reclamation is particularly concerned with the performance of its dams when subject to earthquake loads. For approximately fifteen years, Reclamation's laboratory core test programs typically include dynamic tests performed at strain rates corresponding to seismic loads.

This paper summarizes the results of a Reclamation research project designed to provide a broad database of the behavior of mass concrete from existing dams under dynamic loading conditions that simulate earthquake loadings. Laboratory tests performed on cores at both traditional, static loading conditions (strain rates of 10^{-6} to 10^{-4}) and dynamic loading conditions (strain rates of 10^{-3}) are compared. Dynamic and static measurements of compressive strength, modulus of elasticity, compressive failure strain, Poisson's ratio and splitting tensile strength are summarized. In some cases, the core size or moisture condition among similar samples was varied to determine if either of these parameters affected test results. Linear, elastic assumptions that are typically used for finite element analyses of structural deformation and structural failure are reviewed for these data.

Data from previous and current test programs performed at the U.S. Bureau of Reclamation Materials Engineering and Research Laboratory, Denver, Colorado are provided . Results from Reclamation's past test programs that include similar dynamic and static compression and/or split tension data are summarized. An additional 103 cores from two dams were tested under dynamic and static compression and split tension loading conditions.

Test Program

The dams that provided test data for this study are summarized in Table 1. The 1998 "current" test data consists of data from Warm Springs Dam and Roosevelt Dam. Results were obtained from inventoried core and were tested May - September, 1998 at the Denver laboratory specifically for this study. The remaining data, hereby referred to as the "historical data", were extracted from previous test programs that were conducted at Reclamation's Denver laboratory.

All tests included in the historical data were performed according to current laboratory standards and with current testing apparatus. This constitutes data obtained from cylindrical core drilled from dams that were tested according to current laboratory standards, and at the strain rates defined for seismic (dynamic) and static compression and split tension tests. These data were obtained from files of the U.S. Bureau of Reclamation Laboratory and papers published by Gaeto, 1984,[2] and Peabody and Travers, 1986.[3,4]

The test data reflect the great variability among Reclamation's mass concrete mixture proportions. The structures were placed using mass concrete construction techniques, that include nominal maximum aggregate sizes of 3 in. or larger. Concrete mixes reflect the state-of-the-art concrete technology at the time of construction and were partly controlled by local conditions. Aggregate were obtained locally and reflect the geological history of the area. Such characteristics make mass concrete dependant on both the time period and location at which the mix was made. Details regarding the design and construction of each structure considered in this paper are also provided in Table 1.

Sample Preparation

All specimens considered in this study, with the exception of the static compression and static splitting tensile strength tests for Folsom, Pine Flat, and Englebright Dams, were prepared and tested at the Bureau of Reclamation's Materials Engineering and Research Laboratory, Denver, Colorado. Cores were typically obtained by Reclamation's regional drill crews, packed on site, and shipped to the Denver facility. Test specimens were cut to length by a diamond impregnated saw to obtain a length to diameter ratio of 2.0 whenever possible.

The static compression and split tension test results for Folsom, Pine Flat, and Englebright Dams were supplied by the U.S. Army Corps of Engineers (COE) when the dynamic tests were performed by Reclamation, for the purpose of comparison to Reclamation's dynamic test results.

Historical Data

Reclamation typically tests concrete in a saturated state. Upon extraction from the dam, drilled cores are sealed in plastic to best maintain their in-situ moisture content. At the Denver laboratory, cores are maintained either wrapped in saturated cloth and covered with plastic, or in a constant climate-controlled 100% humidity room prior to testing. The drilling and testing programs are usually completed within a few months.

All core samples from the historical data had a six-inch diameter, except the core from Monticello Dam, which had a ten-inch diameter.

Current Data

The test program for this study was designed not only to provide the specified comparisons of dynamic and static material properties, but also to study the effects of saturation and core size on these results. The Roosevelt and Warm Springs Dam cores used in this study had been stored and air-dried for approximately two to five years.

To study the effects of saturation, the 1998 samples from Roosevelt and Warm Springs Dams were tested at an air-dried and a surface-saturated moisture content. Since the core had been exposed for several years, air-dried samples were tested in the moisture condition at which they were found. Saturated specimens were submerged in lime water for at least 40 hours prior to testing, as suggested in the American Society for Testing and Materials procedure C 42.[5] The density of each sample was measured before and after the 7-day saturation to determine the absorption of the concretes.

To study the effects of core diameter size, both six-inch and 12-inch diameter cores from Roosevelt Dam were tested. All Warm Springs Dam cores measured six inches in diameter.

Sample Populations

Several test populations were developed from the 103 test specimens to isolate the moisture content and the core size parameters. The six-inch diameter Warm Springs core was evenly divided to test at both the air-dried (Group A) and the saturated (Group B) moisture state. Eight twelve-inch diameter samples were available from the Roosevelt core. Eight six-inch diameter saturated cores (Group 1(a)) and eight six-inch diameter air-dried cores (Group 1(b))were tested and compared to the eight twelve-inch diameter cores that were also tested air-dried (Group 2). All twenty-four specimens were extracted from a similar location in the dam. Each test group included dynamic and static compression and dynamic and static splitting tension tests.

To further isolate the effect of saturation on the remaining six-inch diameter Roosevelt Dam core, the population was evenly divided to perform additional dynamic and static compression and split tension tests at both the in-situ, air-dried and saturated condition.

In summary, the 1998 test specimens were grouped as follows:

Group Name	Dam Name	No. of Specimens	Diameter	Moisture Condition
Group A	Warm Springs	16	6 in.	saturated
Group B	Warm Springs	14	6 in.	air-dried
Group 1(a)	Roosevelt	8	6 in.	saturated
Group 1(b)	Roosevelt	8	6 in.	air-dried
Group 2	Roosevelt	8	12 in.	air-dried
Group 3	Roosevelt	16	6 in .	saturated
Group 4	Roosevelt	16	6 in.	air-dried
Group 5	Roosevelt	9	6 in.	saturated
Group 6	Roosevelt	8	6 in.	air-dried

Tests Performed

Static compressive strength was determined according to the American Society for Testing and Materials (ASTM) C 39 “Standard Test Method for Compressive Strength of Cylindrical Specimens”.[5] For the 6-inch diameter core, the modulus of elasticity and Poisson’s ratio were determined using 4-inch epoxied electrical strain gages, two secured laterally and two secured axially, as stated in ASTM C 469 “Standard Test Method for Modulus of Elasticity and Poisson’s Ratio in Compression”. The 12-inch diameter core required twelve 4-inch gages, bridged in four groups of three gages according to procedures previously described. Ultimate strain was measured from the axial gages and strain (μe) is reported in units of 10^{-6} in/in.

Static splitting tensile strength was determined according to ASTM C 496 “Splitting Tensile Strength of Cylindrical Concrete Specimens”.

Dynamic tests were performed according to the ASTM procedures for the static tests with the exception of loading rate. In the Denver laboratories, a uniaxial testing machine capable of providing failures within a strain rate of 10^{-3} and a time frame of 0.05 to 0.1 seconds was used. The equipment uses a hydraulic ram mobilized by an oil pump.

For all tests, strain gages directly provided strain measurements, while load was measured and converted to units of stress.

The density of the concrete was determined by dividing the weight of the specimen by the volume displaced in water. Specific gravity was first computed from the weight of the specimen in air divided by the specimen’s submerged displacement. The submerged displacement was determined by subtracting the specimen weight submerged in water from the specimen weight in air. Density was then calculated by multiplying the specific gravity by the density of water, which is dependent on its temperature.

Test Results

Nature of the test results

Tables 2 - 7 and Figures 1 - 5 summarize the average test results of the historical and current data according to the arrangement of the 16 test populations. The tables provide the range, average, and standard deviation of the data, as well as the ratio found between the average dynamic and average static material properties. Averages are derived from the average results of each population and are provided to summarize *trends* of the data. The number of tests performed for each test program varies. The data from the Warm Springs and Roosevelt core has been divided into several test groups to isolate particular parameters and each group is represented in the average. Thus the current data provided by Warm Springs and Roosevelt Dam test groups represent nine of the 16 test populations included in the average.

The averages should not be interpreted as indicative of mass concrete. The averages should simply be considered a guide that describes the trend of the test populations defined in Tables 2 - 7.

Current test results for the Warm Springs and Roosevelt Core are summarized according to group Tables 8 and 9. Individual test results are presented in Appendix A, Tables A-1 through A-9, for the current data, and in Appendix B, Tables B-1 through B-34 for the historical data. All available cumulative stress and strain Figures, used to calculate modulus of elasticity, are provided in Appendix C, Figures C-1 through C-11. For the current data, individual stress and strain curves are provided in Appendix D for the static compressive strength tests and Appendix E for the dynamic compressive strength tests. Plots of lateral strain versus axial strain, used to compute Poisson's ratio, are provided in Appendices F and G for the static and dynamic compressive strength tests.

Ultimate Compressive Strength

Data for compression tests are summarized in Table 2. The average dynamic compressive strengths of the 16 test populations are generally slightly higher than the average static compressive strengths. The average dynamic to static compressive strength ratio of these results is 1.07, with a coefficient of variation of 20 percent. The ratio ranges from 0.73 to 1.45. Due to the significant variation within the test population, the dynamic to static compressive strength ratio for mass concrete should be determined on a case by case basis.

The dynamic to static compressive strength ratio and the average static compressive strength for each test population in Table 2 is plotted in Figure 1. Although the ratios tend to decrease as the static compressive strength increases, the data is too dispersed to draw any statistical conclusions. The coefficient of determination (r^2 value) is only 0.1674. Consequently, no significant statistical correlation was found among compressive strength and dynamic to static compressive strength ratio.

Modulus of Elasticity

For the 15 mass concrete test populations summarized in Table 3, the dynamic moduli of elasticity tend to be slightly lower than the static moduli of elasticity. Although the average dynamic to static compressive strength ratio is slightly greater than one, the average dynamic to static modulus of elasticity ratio is 0.89, with a coefficient of variation of 17 percent.

As illustrated in Figure 2, the ratio of dynamic to static modulus of elasticity ranges from about 0.7 to 1.1 for all moduli values. Results indicate that the modulus of elasticity is similar at strain rates corresponding to static and seismic loading conditions. Thus, dynamic moduli did not tend to increase as the dynamic strength increased relative to the static compression test (Figure 3).

Stress and strain curves for data for Warm Springs, Roosevelt, Deadwood, Elephant Butte and Monticello Dams are provided in Appendix C. A typical example of stress and strain data from Roosevelt Dam for a static compressive strength test and a dynamic compressive strength test is provided in Figure 4. The test pair was extracted within one concrete construction lift. The ultimate dynamic compressive strength is slightly higher than the ultimate static compressive strength.

The curves in Figure 4 are essentially linear and similar in slope from the origin to a stress corresponding to approximately one-half of the ultimate static compressive strength. After this stress is reached, the curves diverge. The slope of the static compressive strength curve becomes non-linear, decreasing asymptotically to the failure stress. Mass concrete typically yields before it fails in this manner at static loading rates.

At dynamic loading rates, yielding is not observed in the stress and strain data. The stress-strain response for the dynamic test in Figure 4 is predominately linear from initial loading to failure of the specimen. This linear response is representative of the dynamic test results. Under compressive loads, the yielding phenomena was typically eliminated from the test data when the test strain rate was increased from the static load rate to the dynamic load rate.

The modulus of elasticity is typically calculated as either a secant or a chord modulus. A secant modulus is calculated from the origin to a defined point on the curve, usually within thirty to sixty percent of the sample's ultimate strength. The chord modulus, typically used in all Reclamation test programs and most recent data, is measured according to ASTM C 469 between the stress and strain pairs at 50 micro strains and at 40 percent of the ultimate compressive strength. Since the dynamic and static stress and strain curves considered in this study were generally linear within the boundary conditions defined for these moduli, measurements of secant and chord moduli would be similar.

Results for Folsom Dam were excluded from the moduli study. Results provided a dynamic to static modulus of elasticity ratio of 2.15, which significantly deviated from the others. The value for static modulus of elasticity was provided by the COE without any background data or supporting calculations. Thus, the reason for this deviation could not be checked.

Failure strains

Failure strain data is provided in Table 4. For this study, failure strain is defined as the strain measured at the ultimate compressive strength of the sample. The average dynamic to static compressive failure strain ratio is slightly less than one for most test populations. The average ratio of dynamic to static failure strain of eight ratios reported in Table 4 is 0.93 with a coefficient of variation of 12 percent. The average excludes the ratio of 1.58 from the Roosevelt Group 1(a) test population, which deviates drastically from the rest of the test population and is considered an outlier.

The average ratio implies that concrete tends to be more brittle under dynamic loading conditions. Failure strain is further considered in the discussion of the effects of saturation.

Poisson’s ratio

Data for Poisson’s ratio are summarized in Table 5, and individual plots for the current data from Warm Springs and Roosevelt Dams are provided in Appendices F and G. The average dynamic to static ratio of Poisson’s ratio for the 15 populations summarized in Table 5 is 1.09, with a coefficient of variation of 29 percent.

For most test populations, the average static Poisson’s ratio and the average dynamic Poisson’s ratio are slightly higher than 0.20. Increases or decreases of Poisson’s ratio do not correlate with changes in average compressive strength. The average Poisson’s ratio ranges from 0.14 to 0.29 for the static compression test population, and from 0.18 to 0.44 for the dynamic compression test population.

Splitting Tensile Strength

Data for splitting tensile strength are shown in Table 6. For 15 mass concrete test populations, the average ratio of dynamic to static splitting tensile strength is 1.44, with a coefficient of variation of 15 percent.

Figure 5 indicates that the dynamic to static splitting tensile strength ratio tended to slightly decrease as the static compressive strength increased. However, the dispersion of results at higher strengths in Figure 5 makes it difficult to correlate a relationship between dynamic to static splitting tensile strength ratio and increasing splitting tensile strength. The linear regression produced by a computer function provides a coefficient of determination (r^2 value) of only 0.0714. The variation in data suggests that site specific data should be used to evaluate critical structures.

Ratios of splitting tensile strength to compressive strength for both the static and dynamic test populations are provided in Table 7. The average ratio of static splitting tensile strength to static compressive strength is 0.10, with a standard deviation of 0.03. The ratio of dynamic splitting tensile strength to dynamic compressive strength is 0.13, with a standard deviation 0.04.

Parameters Studied

Submergence of core prior to testing

Pairs of similar Warm Springs 1998 core populations and Roosevelt core populations (Groups 1(a) and 1(b), Groups 3 and 4, and Groups 5 and 6) that were tested at an air-dried and a saturated condition are represented in summary Tables 2 through 5.

In general, surface saturation of specimens tended to decrease the static and dynamic compressive strengths and increase the static and dynamic split tensile strengths.

Almost all dynamic to static failure strain ratios were greater for the saturated cores than for the air-dried cores. However, too little data providing failure strain at different surface moisture contents is available to draw conclusions from these results.

For these variations in material properties, the corresponding affect of the saturation process on the density of the samples was extremely small. The average density of all 30 specimens from Warm Springs Dam prior to soaking was 128.8 lb/in^3. For the sixteen saturated samples, submergence did not change the density. The average density of 68 samples from Roosevelt Dam was 147.0 lb/in^{3,} , and the density of the 26 saturated samples increased about one percent after soaking.

Although the effects of submergence on core samples tended to vary among test populations, the saturation process does seem to effect the elastic properties of the test specimens. These changes were observed even though increases in the density due to soaking were extremely small To most accurately predict the material properties of a structure, mass concrete samples should be maintained and tested as close as possible to an in-situ moisture state.

Core size

Core from Roosevelt Dam was tested and compared for diameters of 6 inches (Group 1(b)) and 12 inches (Group 2). The larger core generally provides lower strengths and strains for both static and dynamic compression and split tensile loading, but higher moduli of elasticity. ASTM specifies that core diameters measure at least twice the length of the maximum aggregate size. Since the maximum aggregate size at Roosevelt dam appears to be approximately 5 inches, the 12-inch diameter core test results are considered more representative.

Conclusions

1. Almost all dynamic compression tests provide an increase in strength compared to the static compressive strength. For 16 test populations, the average dynamic to static compressive strength ratio is 1.07, with a coefficient of variation of 20 percent. This ratio does not depend upon the magnitude of the dynamic and static compressive strengths. The variability of the results indicate that compressive strength measurements should be determined on a case by case basis.

2. Almost all dynamic splitting tension tests provided a significant increase in strength compared to static splitting tensile strength values. The average dynamic to static splitting tensile strength ratio was 1.44, with a coefficient of variation of 15 percent. This ratio does not depend upon the magnitude of the dynamic and static compressive strengths. The variability of the results indicate that splitting tensile strength measurements should be determined on a case by case basis.

3. The dynamic compression tests provide a decrease in moduli of elasticity compared to the static moduli of elasticity. The average ratio of dynamic to static modulus of elasticity (using the ASTM standard for calculation) was 0.89 with a coefficient of variation of 17 percent. Consequently, the average dynamic moduli did not tend to increase as the dynamic strengths increased.

4. For air-dried test specimens, failure strains are generally smaller for dynamic tests, indicating that the materials are more brittle under dynamic loading conditions.

5. Saturation tended to decrease the static and dynamic compression strengths and increase the static and dynamic splitting tensile strengths, and did not significantly change the density of the sample.

6. Larger diameter core generally yielded lower strength and strain values and higher moduli values.

7. The concrete tends to yield before failing under static, but not dynamic, load rates. Dynamic tests provide stress-strain curves which are generally linear in nature from the origin to failure. The stress-strain curves of the static compression tend to begin as linear and then decrease in slope and flatten as they approach failure.

References

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4. Peabody, M and F. Travers (undated but approximately 1986), "Testing of Cores from Englebright Dam, Folsom Dam, Pine Flat Dam," Memo reporting test results, U.S. Bureau of Reclamation, Denver, CO.

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Table 1. - Concrete Dams used for core sources

Dam Name	Location	Design Type	Date Constr. Com-pleted	Structural Height	General Core Location	Nominal Maximum Aggregate Size	Water/ cement Ratio	Data Source
Deadwood	Boise National Forest, ID	concrete thick arch	1931	165 ft.	vertical core from crest to foundation	6 in	0.51	USBR (Mohorovic, 1998)
Elephant Butte	New Mexico	concrete gravity	1916	301 ft.	vertical core from crest	3.5 in	0.80	USBR (Snorteland, 1998)
Monticello	California	concrete medium to thick arch	1957	304 ft.	vertical core from crest to foundation	6 in	0.57	USBR (Harris, 1998)
Warm Springs[1]	Oregon	concrete thin arch	1919	106 ft.	vertical core from crest, to foundation			USBR (1997)
Hoover	Nevada/ Arizona	concrete thick arch	1936	726 ft	varies	9 in	0.53	USBR (Harris, 1997)
Stewart Mountain[1]	Arizona	concrete thin arch	1930	207 ft.				USBR (Gaeto, 1983)

Dam Name	Location	Design Type	Date Constr. Com-pleted	Hydraulic Height	General Core Location	Nominal Maximum Aggregate Size	Water/ cement Ratio	Data Source
Englebright[2]								USBR (Peabody and Travers, 1983)
Folsom[1]	California	concrete gravity	1956	340 ft.	Vertical from dam crest			USBR (Peabody and Travers, 1983)
Pine Flat[2]								USBR (Peabody and Travers, 1983)
Roosevelt (modification)	Arizona	mod. - mass concrete buttress	1911 (mod. 1995)	280 ft.	varies	5 in (mod.)	0.50 (mod.)	USBR (1998)

1. Warm Springs, Folsom and Stewart Mountain Dams were not constructed by Reclamation, but are now owned by Reclamation.
2. Englebright and Pine Flat Dams are not owned by Reclamation. Dynamic testing was performed by Reclamation at the Denver laboratory.

Table 2 - Compressive Strength Test Data

Project	Static Compressive Strength (lb/in^2)				Dynamic Compressive Strength (lb/in^2)				Avg Dyn/Stat ratio
	Min	**Max**	**Avg (#)[1]**	**Stand. Dev.**	**Min**	**Max**	**Avg (#)[1]**	**Stand. Dev.**	
Deadwood	3200	6020	4940 (15)	755	4470	7500	5930 (15)	980	1.20
Elephant Butte	1270	4510	2520 (21)	1010	1680	5400	3650 (15)	1460	1.45
Monticello	3080	5200	4760 (6)	925	3640	5570	4870 (6)	125	1.02
Warm Springs (‘96)	1970	4000	3080 (21)	585	1900	3063	2540 (5)	430	0.82
Hoover	5120	9230	7230 (8)	1400	6420	10040	8040 (4)	1570	1.11
Stewart Mtn	3590	6670	5050 (12)	910	2830	8690	5350 (23)	1490	1.06
Englebright			6530 (?)		4814	8931	6660 (19)	1060	1.02
Folsom			4250 (?)		2509	7139	4760 (21)	1220	1.12
Pine Flat			3890 (?)		4183	8038	5280 (6)	2050	1.36
Warm Springs (‘98) - sat. (Group A)	1480	2500	2020(4)	419	2140	3660	2730(4)	688	1.35
Warm Springs (‘98) - air-dried (Group B)	2320	3740	3260(3)	811	2180	4820	3300(3)	1366	1.01
Roosevelt - sat. (Group 1(a)	5630	5630	5630(2)	NA	3390	4790	4090(2)	NA	0.73
Roosevelt - air-dried (Group 1(b))	4710	4950	4830(2)	NA	3910	5290	4600(2)	NA	0.95
Roosevelt - 12" dia. - air-dried (Group 2)	4070	4580	4330 (2)	NA	3430	4020	3730(2)	NA	0.86
Roosevelt - sat. (Group 3)	4370	6180	5090(8)	520	5000	7290	6430(8)	750	1.26
Roosevelt - air-dried (Group 4)	5800	7080	6130(8)	440	2990	7440	4850(8)	1670	0.79

[1] Number in parentheses indicates number of specimens included in average value.

Table 3 - Moduli of Elasticity Test Data

Project	Static Mod. of Elasticity (10^6 lb/in^2)				Dynamic Mod. of Elasticity (10^6 lb/in^2)				Avg Dyn/Stat ratio
	Min	**Max**	**Avg (#)[1]**	**Stand. Dev.**	**Min**	**Max**	**Avg (#)[1]**	**Stand. Dev.**	
Deadwood	2.91	4.31	3.47 (15)	0.46	2.78	5.01	3.83 (14)	0.60	1.10
Elephant Butte	1.55	4.44	2.76 (21)	0.75	1.25	3.80	2.71 (15)	0.71	0.98
Monticello	4.12	7.18	5.76 (6)	1.15	5.77	6.68	6.12 (5)	0.34	1.06
Warm Springs (‘96)	1.96	5.36	3.59 (20)	0.64	1.41	5.13	2.89 (4)	1.66	0.81
Hoover	6.13	7.52	6.59(7)	0.59	3.28	6.12	4.33 (4)	1.29	0.66
Stewart Mtn	2.05	5.76	3.89 (12)	1.16	2.85	5.52	3.99 (23)	0.78	1.03
Englebright			4.74		3.80	5.61	4.63 (19)	0.60	0.98
Pine Flat			3.88		2.31	4.63	3.43 (6)	1.00	0.88
Warm Springs (‘98) -sat (Group A)	2.24	3.75	3.02 (4)	.067	1.92	3.57	2.67 (4)	0.10	0.88
Warm Springs (‘98) - air-dried (Group B)	2.49	3.62	3.08 (3)	0.57	1.92	3.61	2.60 (3)	0.89	0.84
Roosevelt - sat. Group 1(a)	5.85	6.06	5.96 (2)	NA	3.03	5.39	4.21 (2)	NA	0.71
Roosevelt -air-dried(Group 1(b)	3.91	6.39	5.15 (2)	NA	3.66	4.51	4.09 (2)	NA	0.79
Roosevelt - 12" dia. air-dried (Group 2)	5.78	7.13	6.46 (2)	NA	5.47	5.92	5.70 (2)	NA	0.88
Roosevelt - sat. (Group 3)	2.72	5.23	4.45 (8)	0.84	4.70	5.04	4.84 (8)	0.12	1.09
Roosevelt - air-dried (Group 4)	5.31	7.96	6.23 (8)	1.27	2.90	4.87	4.10 (3)	1.05	0.66

1. Number in parentheses indicates number of specimens included in average value.

Table 4 - Compressive Strength Failure Strain Test Data

Project	Static Compression Failure Strain (10^{-6} in/in)				Dynamic Compression Failure Strain (10^{-6} in/in)				Avg Dyn/Stat ratio
	Min	**Max**	**Avg (#)[1]**	**SD**	**Min**	**Max**	**Avg (#)[1]**	**SD**	
Deadwood	1460	2240	1830(15)	250	970	2820	1670(14)	500	0.91
Elephant Butte	950	2060	1450(21)	330	1000	1810	1390(10)	260	0.96
Monticello	960	1400	1180 (6)	145	820	1150	920 (5)	160	0.78
Warm Springs (‘98) sat.	810	1190	1060 (4)	175	895	1285	1170 (4)	230	1.10
Warm Springs (‘98) air-dried	1150	1790	1360 (3)	335	1330	1480	1410 (3)	75	1.04
Roosevelt saturated Group 1(a)	820	910	870 (2)	NA	1170	1560	1370 (2)	NA	1.58
Roosevelt air-dried (Group 1(b)	990	1380	1190 (2)	NA	NA	NA	1040 (1)	NA	0.87
Roosevelt - 12" dia. air-dried (Group 2)	730	880	810 (2)	NA	620	700	660 (2)	NA	0.81
Roosevelt saturated (Group 3)	1190	1600	1360 (8)	160	1080	1550	1350 (6)	200	0.99
Roosevelt air-dried (Group 4)	780	1625	1150 (8)	310	NA	NA	NA	NA	NA

1. Number in parentheses indicates number of specimens included in average value.
NA: data not available

Table 5 - Poisson’s Ratio Data

Project	Static Poisson’s ratio				Dynamic Poisson’s ratio				Avg Dyn/Stat ratio
	Min	Max	Avg (#)[1]	Stand. Dev.	Min	Max	Avg (#)[1]	Stand Dev	
Deadwood	0.17	0.29	0.24 (14)	0.05	-	-	-	-	-
Elephant Butte	0.05	0.46	0.26(25)	0.18	0.13	0.51	0.28 (15)	0.14	1.08
Monticello	0.21	0.44	0.28 (6)	0.09	0.22	0.3	0.25 (5)	0.04	0.89
Warm Springs (‘96) (’96)n))	0.06	0.49	0.26 (19)	0.13	0.34	0.55	0.44 (3)	0.11	1.69
Hoover	0.18	0.23	0.21 (5)	0.02	0.07	0.51	0.21 (4)	0.21	1.00
Stewart Mtn	0.14	0.65	0.29 (12)	0.17	0.10	0.38	0.20 (24)	0.09	0.69
Englebright			0.14		0.11	0.27	0.21(19)	0.06	1.50
Folsom			0.17		0.11	0.53	0.21(17)	0.10	1.24
Pine Flat			0.15		0.11	0.22	0.18(6)	0.05	1.20
Warm Springs (‘98) - sat. (Group A)	0.25	0.29	0.28 (4)	0.02	0.19	0.41	0.26 (4)	0.10	0.93
Warm Springs (‘98) - air-dried (Group B)	0.02	0.22	0.15 (3)	0.11	0.19	0.36	0.25 (3)	0.09	1.67
Roosevelt - sat. (Group 1(a))	0.20	0.24	0.22 (2)	0.03	0.19	0.24	0.22 (2)	0.04	1.00
Roosevelt - air-dried (Group 1(b)	0.20	0.26	0.23 (2)	0.04	0.17	0.28	0.23 (2)	0.08	1.00
Roosevelt - air-dried (Group 2)	0.25	0.29	0.27		0.18	0.22	0.20 (2)		0.74
Roosevelt - sat. (Group 3)	0.17	0.25	0.21 (8)	0.03	0.13	0.26	0.20 (8)	0.05	0.95
Roosevelt - air-dried (Group 4)	0.18	0.34	0.28 (8)	0.05	0.17	0.26	0.21 (3)	0.05	0.75

1. Number in parentheses indicates number of specimens included in average value.

Table 6 - Splitting Tensile Strength Test Data

Project	Static Split Tensile Strength (lb/in^2)				Dynamic Split Tensile Strength (lb/in^2)				Avg Dyn/Stat ratio
	Min	**Max**	**Avg (#)[1]**	**Stand. Dev.**	**Min**	**Max**	**Avg (#)[1]**	**Stand. Dev.**	
Deadwood	350	610	455 (15)	80	475	960	690 (15)	145	1.52
Elephant Butte	100	420	310 (13)	100	310	800	500 (12)	150	1.61
Monticello	270	425	335 (6)	70	425	595	505 (6)	70	1.51
Warm Springs ('96)	250	435	330 (9)	70	455	540	510 (3)	50	1.55
Hoover	350	710	565 (14)	95	863	1086	975 (2)	155	1.73
Stewart Mtn REC-ERC 1984.	270	410	340 (5)	65	285	850	515 (36)	120	1.51
Englebright			595 (?)		489	698	585 (15)	90	0.98
Folsom			480 (?)		366	624	510 (21)	85	1.06
Warm Springs ('98) -sat. (Group A)	220	445	335 (4)	90	445	635	540 (4)	90	1.61
Warm Springs ('98) - air-dried (Group B)	260	415	335 (4)	70	345	540	460 (4)	90	1.37
Roosevelt - sat.(Group 1(a))	455	495	475 (2)	NA	735	775	755 (2)	NA	1.59
Roosevelt -air-dry (Group 1(b))	385	480	435 (2)	NA	460	505	485 (2)	NA	1.11
Roosevelt - 12" dia. - in-situ (Group 2)	370	470	420 (2)	NA	470	680	575 (2)	NA	1.37
Roosevelt - sat. (Group 5)	385	795	530 (6)	160	795	890	840 (3)	50	1.58
Roosevelt - air-dried (Group 6)	485	685	580 (4)	85	705	930	840 (4)	95	1.45

1. Number in parentheses indicates number of specimens included in average value.

Table 7. Ratio of Splitting Tensile and Compressive Strength Results

Project	**Static Strengths (lb/in^2) and Ratio**			**Dynamic Strengths (lb/in^2) and Ratio**		
	Splitting Tensile (SST)	**Compressive (SC)**	**Ratio (SST/SC)**	**Splitting Tensile (DST)**	**Compressive (DC)**	**Ratio (DST/DC)**
Deadwood	455	4940	0.09	690	5930	0.12
Elephant Butte	310	2520	0.12	500	3650	0.14
Monticello	335	4760	0.07	505	4870	0.10
Warm Springs (‘96)	330	3080	0.11	510	2540	0.20
Hoover	565	7230	0.80	975	8040	0.12
Stewart Mountain	340	5050	0.70	515	5350	0.10
Englebright	595	6530	0.90	585	6660	0.09
Folsom	480	4250	0.11	510	4760	0.11
Warm Springs (‘98) - sat. -Group A	335	2020	0.17	540	2730	0.20
Warm Springs (‘98) - air-dried Group B	335	3260	0.10	460	3300	0.14
Roosevelt - sat - Group 1(a)	475	5630	0.08	755	4090	0.18
Roosevelt - air-dried - Group 1(b)	435	4830	0.09	485	4600	0.11
Roosevelt (Group 2)	420	4330	0.10	575	3730	0.15

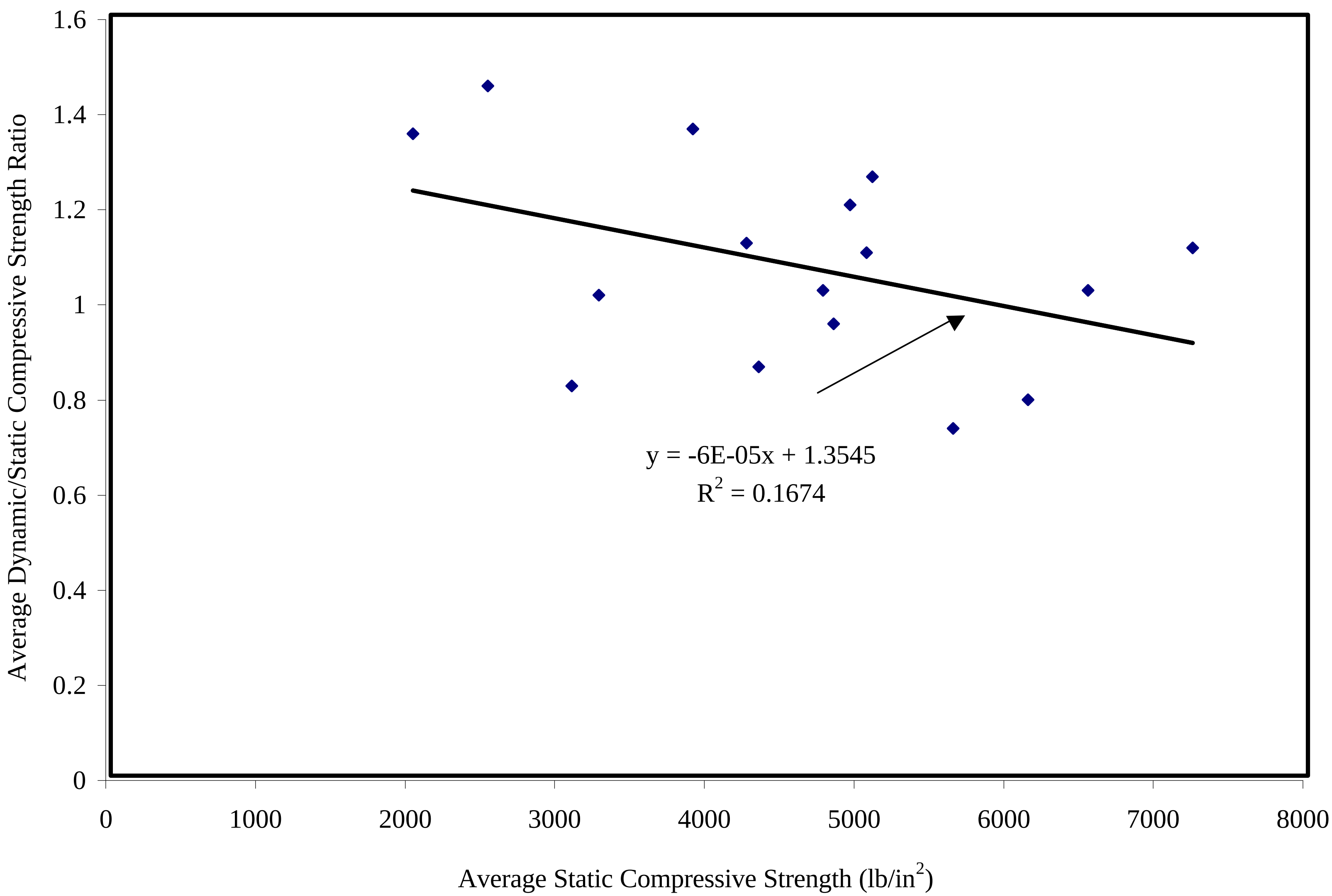

Figure 1. - Average Static Compressive Strength versus Average Dynamic to Static Compressive Strength Ratio for the 16 Test Populations provided in Table 2, Dynamic Properties Study, 1998.

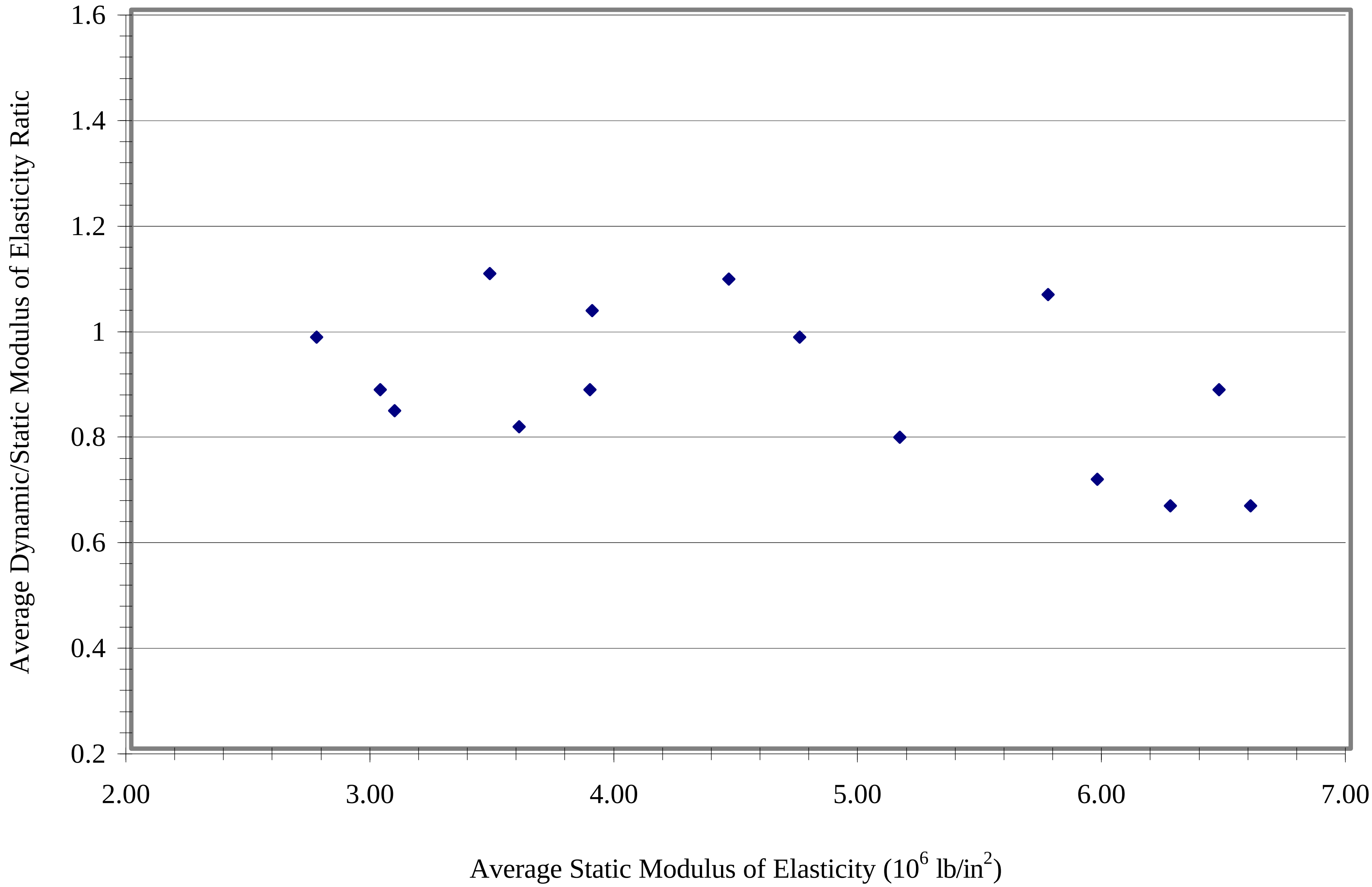

Figure 2. - Average Static Modulus of Elasticity versus Dynamic to Static Modulus of Elasticity Ratio for 15 Test Populations in Table 3, Dynamic Properties Study, 1998.

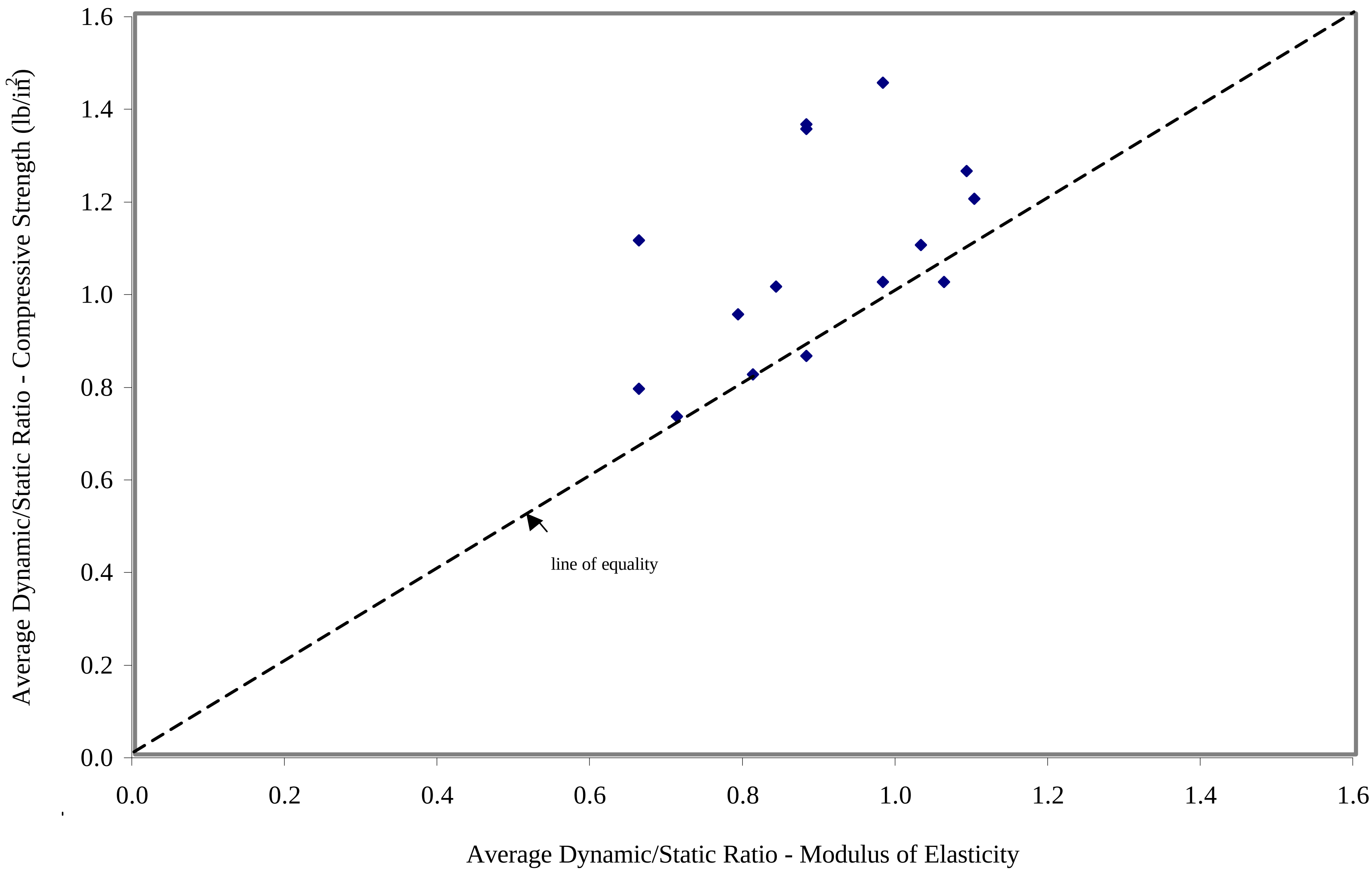

Figure 3. Average Dynamic to Static Properties Ratios, Compressive Strength versus Modulus of Elasticity, for the 15 Test Populations provided in Tables 2 and 3.

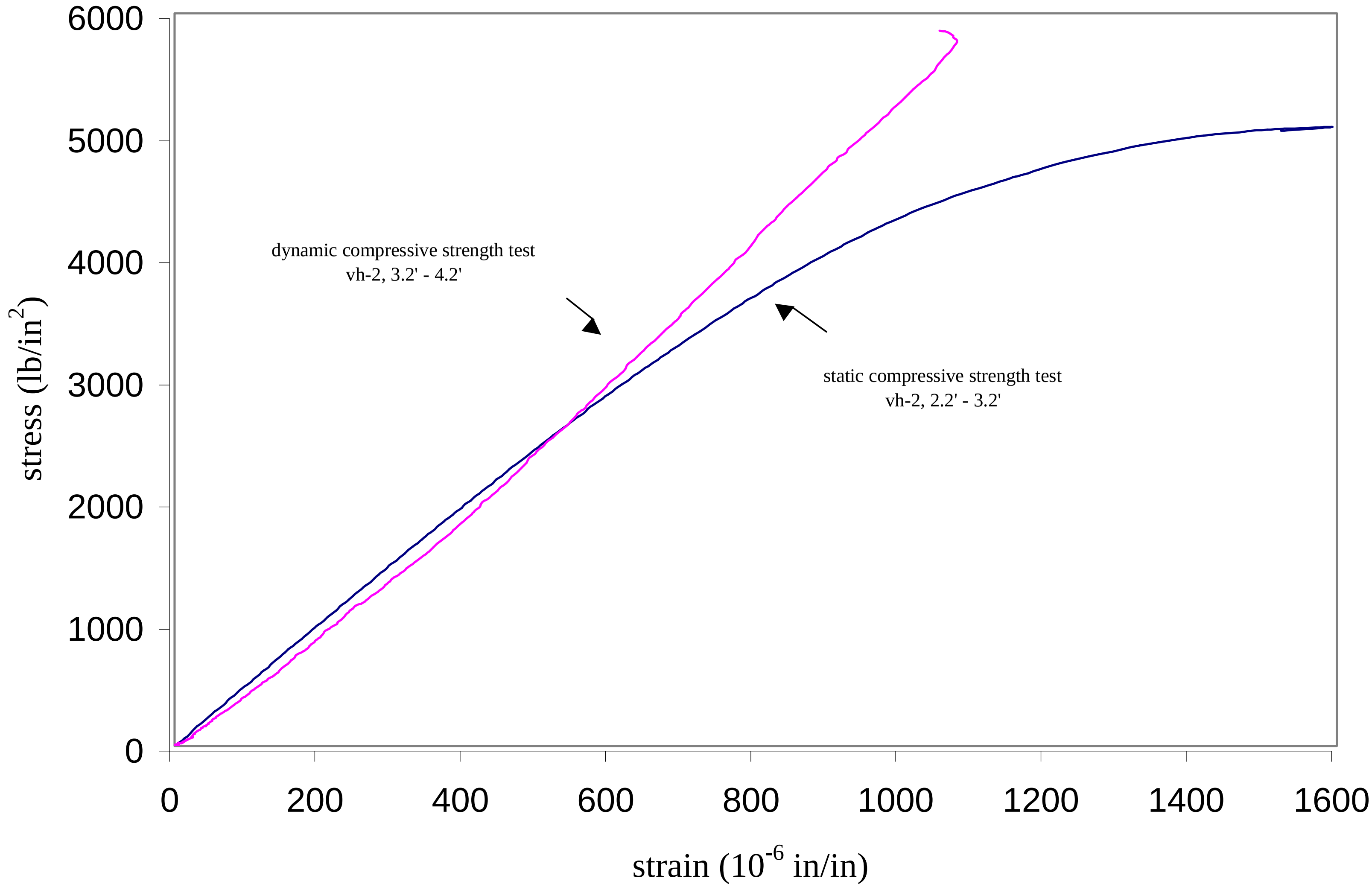

Figure 4. Typical Stress and Strain Curves for a Static and Dynamic Compressive Strength Test, Roosevelt Dam Test Cores, Dynamic Properties Study, 1998.

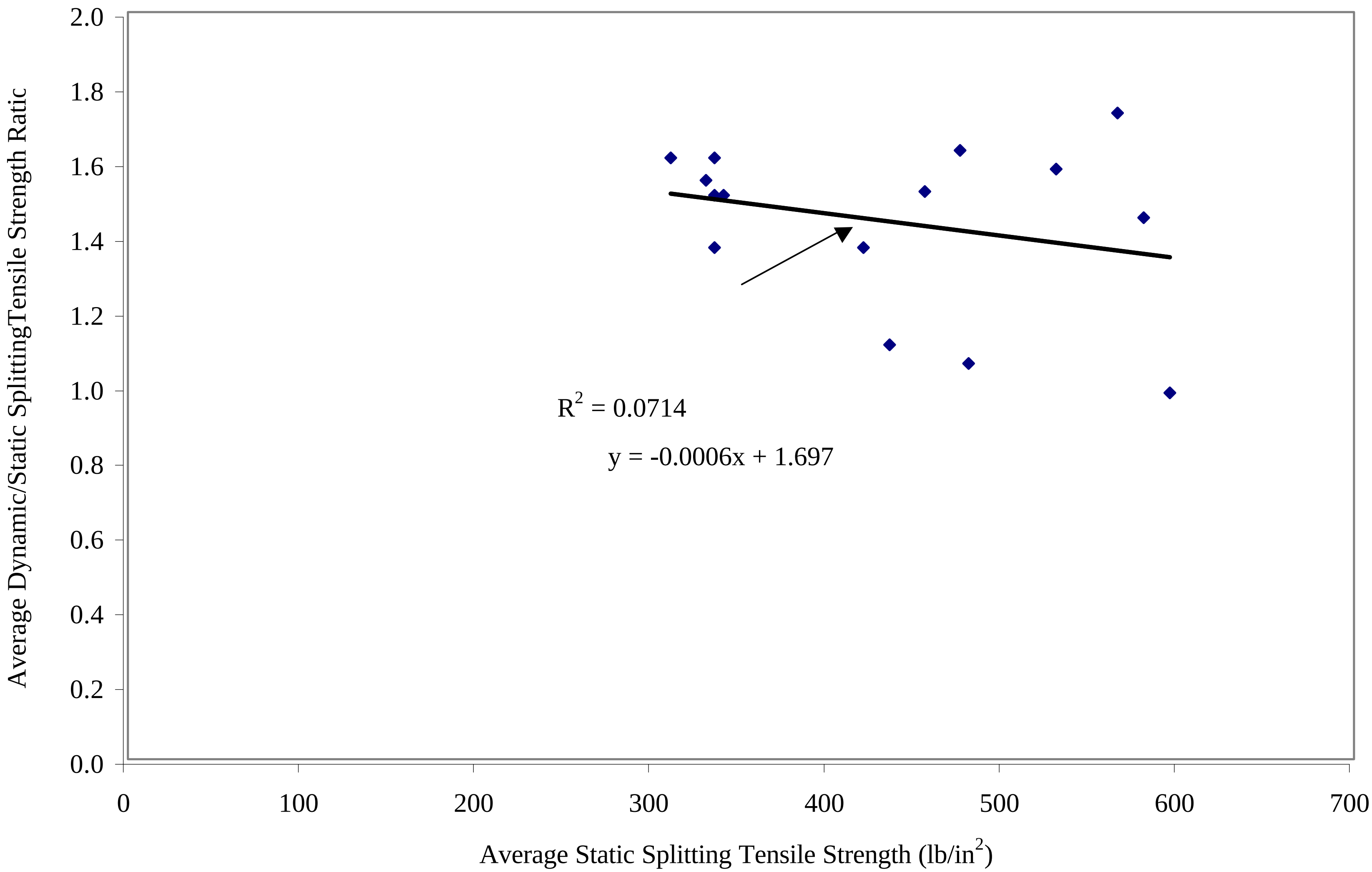

Figure 5. Average Splitting Tensile Strength versus Dynamic to Static Splitting Tensile Strength Ratio for the 15 Test Populations in Table 6, Dynamic Properties Study, 1998.