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EVALUATION OF CONCRETE CORES, ARROWROCK DAM, IDAHO

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16. ABSTRACT
Construction of Arrowrock Dam was completed in 1915. This structure is unique in that it is one of three dams constructed with what was called "sand-cement." In 1978, concrete cores were drilled from six locations in the dam. The evaluation of these cores will be used in a feasibility study for the possible modification of the structure. Compressive strength tests indicate a low compressive strength but no significant reduction from the control strengths established during construction. The difference in strength and modulus of elasticity of the conrete when tested in a wet condition, compared to cores tested in a dry condition, was greater than usually observed between wet and dry concrete. No explanation for this behavior was determined. Minor evidence of silica gel was observed but not to the extent that the structure would be affected by an alkali aggregate reaction.

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EVALUATION OF CONCRETE CORES, ARROWROCK DAM, IDAHO

by

Edward M. Harboe

Concrete Laboratory
Fifty Years

SI METRIC

Concrete and Structural Branch
Division of Research
Engineering and Research Center
Denver, Colorado
March 1982

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

This study was conducted by members of the Concrete and Structural Branch under the direction of James R. Graham, Chief of the Branch. Significant contributions to the report were made by C. A. Bechtold, Applied Sciences Branch, who performed the petrographic examination; and by members of the Geotechnical Branch, who performed the shear and sliding friction tests.

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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INTRODUCTION

Arrowrock Dam, located on the Boise River in Idaho, is a concrete dam of the thick arch type with a structural height of 107 m (350 ft). The dam was completed in 1915. During 1935-37, the dam and spillway were raised 1.5 m (5 ft).

Cement used in the construction of the dam was a sand-cement consisting of 55 percent portland cement and 45 percent pulverized granite for interior concrete, and 66 percent portland cement and 34 percent pulverized granite for exterior concrete. The granite was pulverized so 90 percent would pass through a 75-μm (No. 200) sieve and was blended with the portland cement at the damsite. Maximum-size aggregate in the concrete was 115-mm (4½-in). However, large stones (plums) were added, when available, to a maximum of 20 percent of the volume of the concrete.

CORE TEST PROGRAM

In 1978, 150-mm (6-in) diameter concrete cores were drilled at six locations in the dam (fig. 1). The evaluation of these cores will be used in a feasibility study for the possible modification of the structure.

Drill hole 1A duplicates the top 11 feet of drill hole 1. It was drilled because too few usable test specimens were recovered from the upper elevations of drill hole 1. Drill holes 1, 2, 3, and 1A were drilled from the operating gallery at elevation 942 m (3090.5 ft). Drill holes 4 and 5 were drilled from the inspection gallery at elevation 908 m (2980 ft). Figures 2 through 10 are photographs of the extracted cores. The elevations for drill holes 4 and 5 (figs. 7-10) are in error. These elevations should be 2980 instead of the 3003.5 shown.

The identification of the individual test specimens follows: The first number desginates the drill hole number; the second character is an alphabetical designation starting with A at the highest elevation and going downhole with the alphabet. Thus, specimen 2C would be the third test specimen out of drill hole 2. Drill hole 1A has a double alphabet notation because of the identification of the hole, such as 1AA, 1AB, and 1AC.

From the cores shipped to the laboratory, 89 pieces were selected to be evaluated for:

Compressive strength
Modulus of elasticity
Poisson's ratio
Density
Absorption
Shear strength and sliding friction

A petrographic examination was also conducted. Tests for compressive strength, modulus of elasticity, and sliding friction were conducted with approximately one-half of the specimens in a moist condition and the remainder in a laboratory-dry condition. The specimens tested in a moist condition were kept in a room maintained at 100 percent relative humidity. The dry specimens were left uncovered in laboratory air until tested.

CONCLUSIONS

1. Most of the concrete in the mass section of the dam is of relatively low strength. This strength does not seem to be decreasing significantly as the structure ages.

2. The difference in strength and modulus of elasticity of the concrete when tested in a wet condition as compared to similar cores tested in a dry condition

is greater than usually observed between wet and dry concrete. No explanation for this behavior was determined.

3. Minor evidence of alkali aggregate reaction was observed but not to the extent that it would deleteriously affect the concrete.

TEST RESULTS

Compressive Strength

Cores to be tested for compressive strength were sawed into 300-mm (12-in) lengths and then capped for testing. Test results on cores less than 300 mm long, giving a length to diameter ratio of less than 2, were corrected for compressive strength in accordance with Designation 33 of the eighth edition of the *Concrete Manual*[1].

The average compressive strength of 12 cores tested in a laboratory-dry condition was 14.4 MPa (2090 lb/in^2), while the average for 11 cores tested in a wet condition was 8.6 MPa (1250 lb/in^2) (tables 1 and 2). The difference between the averages is nearly twice that normally experienced between wet and dry concrete. No identifiable reason for this difference was observed.

Although these strengths are low by today's standards, there does not appear to be any appreciable deterioration from the original strength in the interior concrete. "Special Cements for Mass Concrete"[2] discusses the sand-cement used at Arrowrock Dam and lists the laboratory tests on concrete cubes made during the con-

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[1]*Concrete Manual*, 8th ed., rev. reprint, Bureau of Reclamation, Denver, Colorado, 1981.

[2]Savage, J. L., "Special Cements for Mass Concrete," the Second Congress of the International Commission on Large Dams, World Power Conference, Washington, D.C., 1936, Bureau of Reclamation, Denver, Coio., 1936.

struction period. At 1 year, the strengths of the cubes representative of two concretes used in the interior of the dam were 10.6 and 14.4 MPa (1540 and 2090 lb/in^2). Twenty-five 120-mm (4¾-in) diameter drill cores taken from the body of the dam 15 years after its completion were reported to have an average compressive strength of 11.0 MPa (1590 lb/in^2).

Modulus of Elasticity and Poisson's Ratio

Elastic property tests were conducted on the same core specimens selected for the compressive strength tests. The modulus of elasticity and Poisson's ratio were determined using an extensometer-compressometer frame with dial gages measuring longitudinal and lateral deformations as loads were applied. On the dry specimens, deformations were observed at 0-, 0.69-, and 6.9-MPa (0-, 100-, and 1000-lb/in^2) loads. Computations for modulus of elasticity and Poisson's ratio were based on net strain measured between 0.69 and 6.9 MPa. Because of the low strength of the concrete in a wet condition, these cores were only loaded to 2.07 MPa (300 lb/in^2), and calculations were based on strain measured between 0.69 and 2.07 MPa (100 and 300 lb/in^2). The modulus of elasticity of the dry cores averaged 11.2 GPa (1.62×10^6 lb/in^2), while the wet cores averaged 6.39 GPa (0.93×10^6 lb/in^2). The same wide discrepancy between wet and dry core results found in the compressive strength tests was also noted in the elastic tests.

The Poisson's ratio values were too variable to produce an average that would have statistical significance. Weak surface concrete or loose aggregate particles did not allow solid contact for the two screw points of the extensometer; therefore, erratic readings were obtained.

Density and Absorption

For all specimens tested, the average density was 2290 kg/m^3 (143 lb/ft^3), and the average absorption was 3.8 percent (tables 1 and 2). These values are within the expected range.

Shear and Sliding Friction

There are three generally accepted tests used to determine the shear strength of concrete: (1) triaxial, (2) break bond or direct, and (3) sliding friction. Currently, in the Bureau, the direct (break bond) shear test is used for integral concrete specimens and specimens with intact construction joints, while the sliding friction test is used for specimens with "open" or disbonded construction joints and for tests subsequent to the direct shear test. To determine the shear strength, data from these tests were analyzed by both the "linear regression" method and the "angle-envelope" method.[3] The respective values for cohesion and friction angle, Ø, are summarized in table 3 for cores tested under dry conditions and in table 4 for cores tested under wet conditions.

A straight line (linear regression method) was fitted through the sliding friction test data from all 15 cores tested dry (fig. 11 A&B) and all 11 cores tested wet (fig. 12 A&B). Also, a linear regression line was fitted through all the break bond shear points in the two figures. These regression lines give an average value for cohesion and friction angle for all the specimens tested. A typical post-shear and-sliding friction test specimen is shown in figure 13.

A normal loading sequence of 0.69, 1.38, and 2.07 MPa (100, 200, and 300 lb/in^2) was used for the shear tests and 0.69, 1.38, 2.07, and 2.41 MPa (100, 200, 300, and 350 lb/in^2) for the sliding friction tests for both wet and dry cores.

Specimen 3D was tested before the loading range was selected in an attempt to obtain a strength range for the test program. This specimen was run at 0.52-MPa (75-lb/in^2) normal load for the shear test and 0.52, 1.38, and 2.41 MPa (75, 200, and 350 lb/in^2) for the sliding friction test.

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[3]Haverland, M. L., "The Angle-Envelope Method of Analyzing Tests," Bureau of Reclamation Report No. GR-15-76, E&R Center, Denver, Colo., January 1976.

Specimens 5H and 5I were initially subjected to a normal load of 2.07 MPa (300 lb/in^2) but could not be sheared utilizing the maximum capacity of the shear machine. The normal load was reduced to 1.72 MPa (250 lb/in^2), and the specimens were successfully sheared. Also, specimen 4L was initially subjected to a normal load of 1.38 MPa (200 lb/in^2) and not sheared. When the load was reduced to 0.69 MPa (100 lb/in^2), the specimen sheared.

Specimen 4Q should be considered a shear test of rock rather than concrete. Ninety percent of the material sheared was rock. Specimen 3U was only tested in shear because of the large aggregate exposed after the shear test.

A correlation factor, r, of ±1.0000 utilizing the linear regression method is considered ideal. The test data correlation factors for 14 specimens tested dry ranged from ±1.0000 to ±0.9960. Specimen 5H had a low correlation factor of ±0.9114 because of a lower sliding friction load at 2.07-MPa (300-lb/in^2) normal load than at 1.38-MPa (200-lb/in^2) normal load.

PETROGRAPHIC EXAMINATION

A petrographic examination of representative cores was conducted by C. A. Bechtold and reported in Petrographic Memorandum 80-12.

Material and Method of Study

The sand-cement drill cores were given a cursory examination in the Concrete Laboratory to select fragments for futher examination and testing in the Petrographic Laboratory. The concrete was examined megascopically, microscopically, by XRD (X-ray diffraction), by DTA (differential thermal analysis), and by other physical and chemical tests.

Petrographic Laboratory Examination

Some drilling corrosion of the concrete was observed in the form of a softened paste.

Moderately to slightly softened concrete in the top 50 to 300 mm (2 to 12 in) suggested freeze-thaw deterioration due to atmospheric influences, although an overall examination of the core samples indicated most of the concrete was not affected by this type of exposure.

Large entrapped air voids and less than the average amount of sand were observed in some cores suggesting variability in the mixing and the placing of the concrete.

The coarse aggregate particles were mostly subrounded to subangular in shape. The fine sand consisted of mostly subangular to angular shaped particles. The sand and gravel were composed primarily of granitic rocks, gneiss, basalt, quartz, and feldspar with lesser amounts of glassy and altered rhyolite, diorite, and schist, and a few wood fragments. The sand contained increasing amounts of monomineralic grains of quartz, feldspar, mica, and amphibole, and a few miscellaneous minerals. A few alkali-reactive glassy rhyolites were observed. The sand and gravel would probably be considered petrographically of fair physical quality and chemically innocuous.

The concrete paste appeared chalky, porous, dull, white to light gray when dry and tan when wet, and was absorptive. The concrete broke with light to hard hammer blows generally around aggregate particles, indicating a weak or poor bond between paste and aggregate. The paste and gravel were evenly distributed; however, a few areas of poorly compacted concrete with large void spaces and deficient amounts of paste were observed.

Secondary products observed in the concrete included calcium carbonate, ettringite, an ettringite-like complex mineral, and silica gel. Calcium carbonate was present in the paste but was generally absent in the voids and fractures. Most of the observed air voids and rock sockets were unfilled; however, many were lined or coated with a thin film of calcium carbonate, ettringite, and an ettringite-like complex mineral. A trace of silica gel was observed lining a few glassy volcanic rock sockets. A fragment of the concrete was soaked in Denver tapwater for several weeks with no silica gel development. Petrographic Memorandum No. 51-38 indicated some evidence of an alkali aggregate reaction based on an examination of one piece of drill core. This reaction does not appear to be a significant problem with the concrete examined at this time. Unusually large (to 2-mm-sized) flat crystals identified as similar to ettringite ($CaSO_4 \cdot Al_2O_3 \cdot 33H_2O$) were observed in fractures, voids, and rock sockets. The formation of crystals this large no doubt has exerted some disruptive forces on the concrete.

Portlandite and calcium silicates (alite and belite) are normal constituents of hydrated cement. Portlandite was detected in minute amounts by XRD and DTA. The amounts of water of hydration and calcium silicates were somewhat less than for most old concrete, possibly due to the removal of cement minerals by ground or reservoir water or replacement of some portland cement with sand-cement. An unusually high percentage of quartz and feldspar was detected in the handpicked paste by XRD analysis. A probable cause for this percentage is the addition of about 40 percent crushed granite and gneiss, which primarily contained these minerals, to the sand-cement.

The mineral similar to calcium sulfoaluminate hydrate (ettringite) was picked out and analyzed separately. This mineral is a monoclinic, uniaxial negative mineral with an index of refraction of about 1.520. XRD shows major peaks at 8.26, 4.13, and 2.75 angstroms. DTA indicates three major endotherms at 130, 209, and 297 °C. These data are not an exact fit for any of the known calcium sulfoaluminate hydrate minerals, but a comparison with other experimental test data indicates this mineral to be the closest fit.

Thin section and polished specimens showed few microfractures; however, many microscopic vugs and cavities were observed in the paste suggesting the possibility of some corrosion by aggressive water. The ettringite-like mineral was not positively identified in the paste in either the thin section or the polished surface specimens.

Summary of Petrographic Examination

The petrographic examination of the Arrowrock Dam cores revealed the following:

1. Petrographic evidence of freeze-thaw was minimal.

2. The sand and gravel would probably be considered of fair physical quality and chemically innocuous.

3. Weak or poor bond was observed between paste and aggregate particles.

4. The gravel, sand, and paste were generally well distributed with a few areas of poorly compacted concrete and a few areas deficient in sand-size particles.

5. Minor evidence of alkali aggregate reaction was observed but should not deleteriously affect the concrete.

6. Some damage in a few areas from sulfate reaction was indicated by the presence of the large ettringite-like crystals even though their presence could not be detected in the paste.

7. Some corrosion due to natural waters is indicated by reduced amounts of water of hydration, calcium silicate, and portlandite as well as a general lack of calcium carbonate deposits and the presence of numerous microscopic vugs and cavities in a very porous concrete.

8. The sand-cement concrete exhibited moderate deterioration indicated primarily by poor bond between paste and aggregate, probable effects of corrosive water, and possible sulfate reactions.

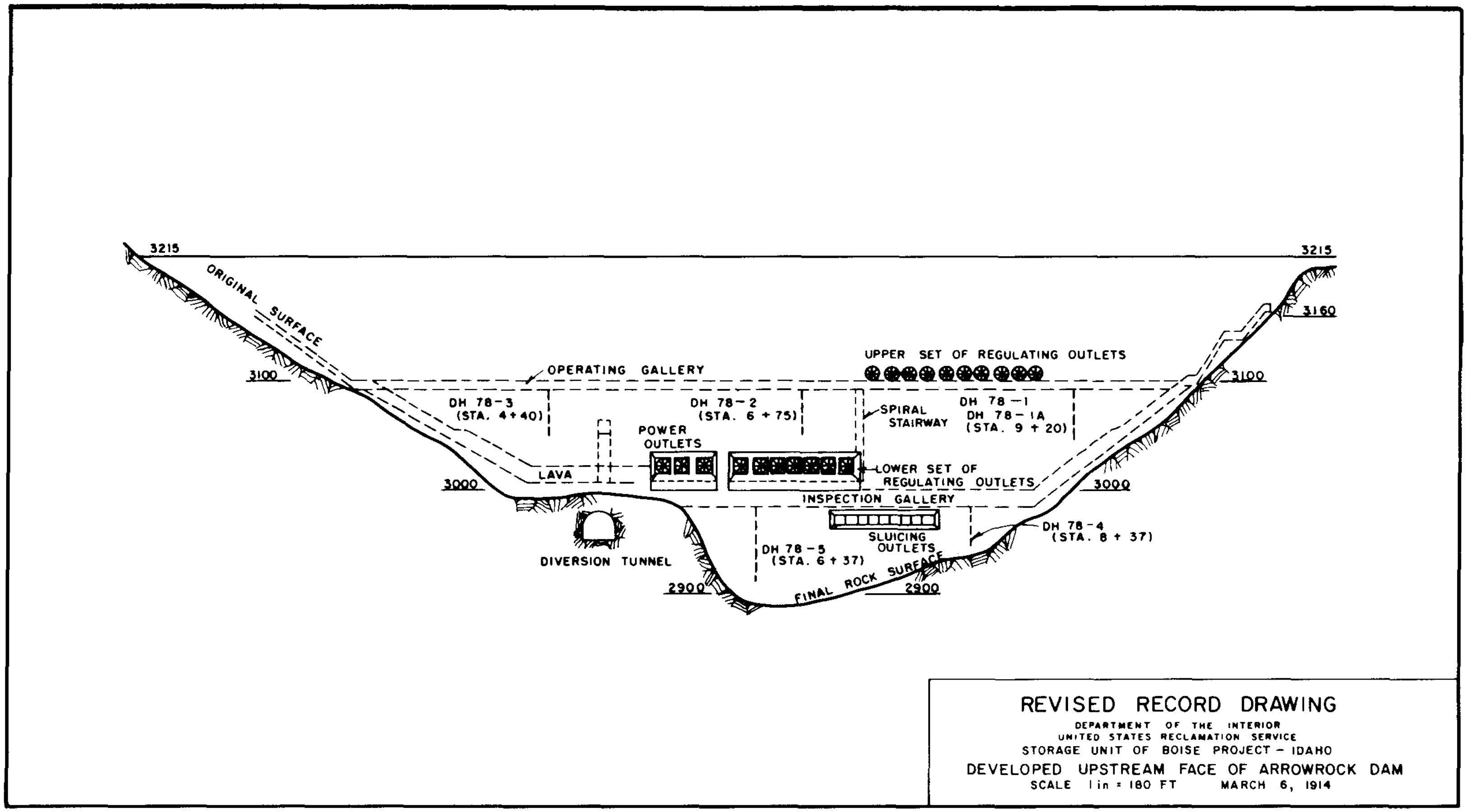

Figure 1.—Upstream face of Arrowrock Dam indicating 1978 sample drill holes. (4-102-470 or 1-E-216)

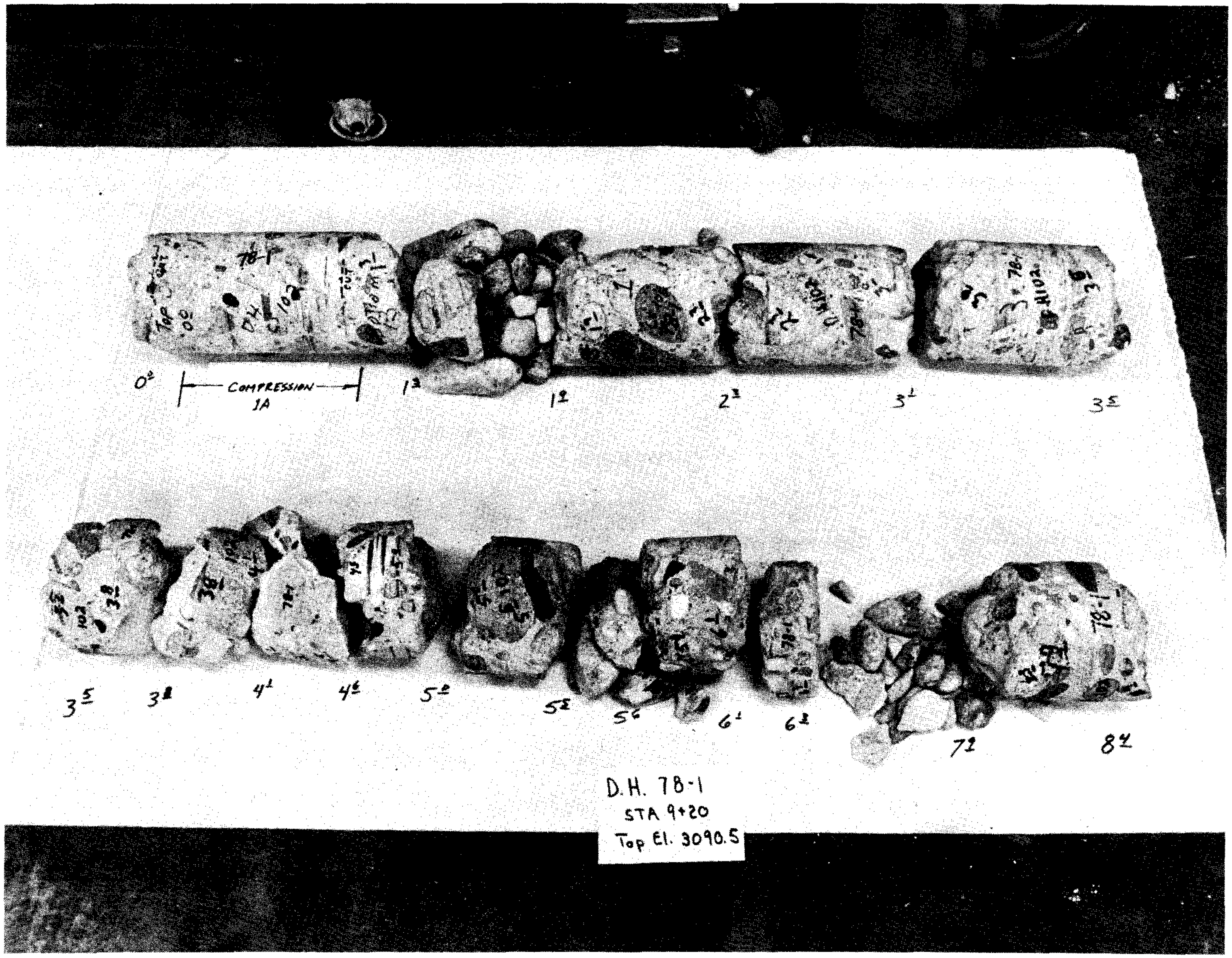

Figure 2.—Arrowrock Dam Core No. 1. P801-D-79780

Figure 3.—Arrowrock Dam Core No. 1. P801-D-79781

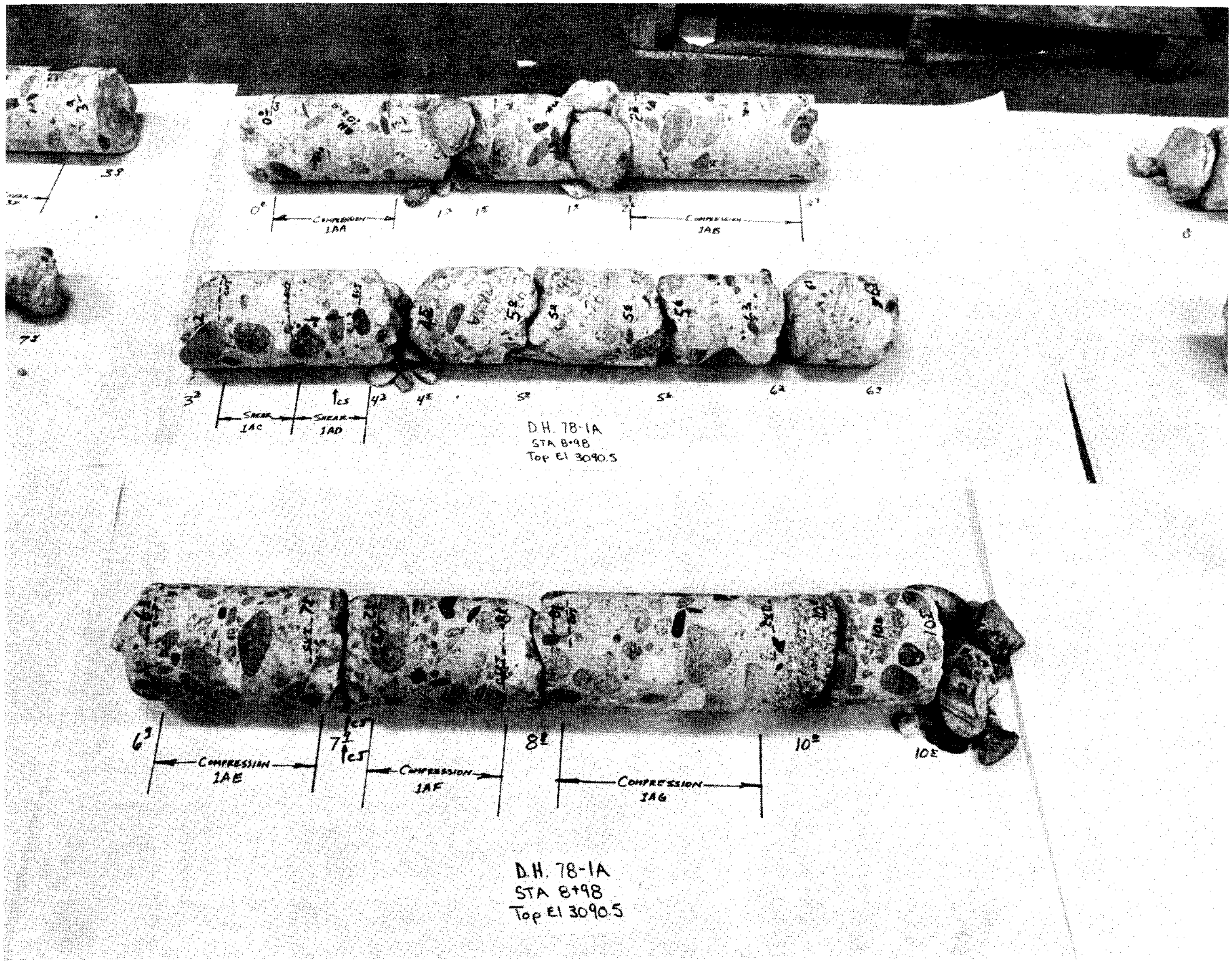

Figure 4.—Arrowrock Dam Core No. 1A. P801-D-79782

Figure 5.—Arrowrock Dam Core No. 2. P801-D-79783

Figure 6.—Arrowrock Dam Core No. 3. P801-D-79784

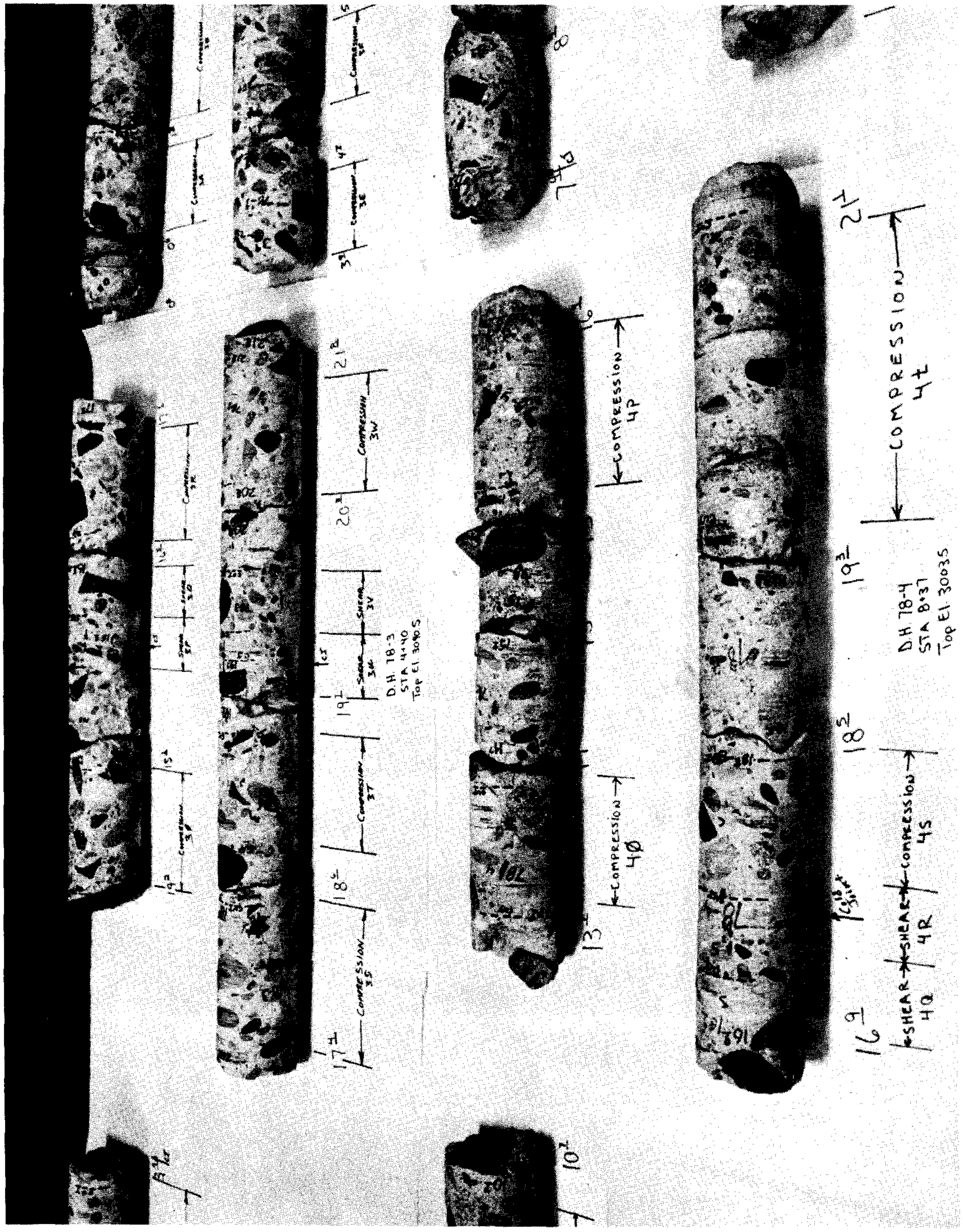

Figure 7.—Arrowrock Dam Core Nos. 3 and 4. P801-D-79785

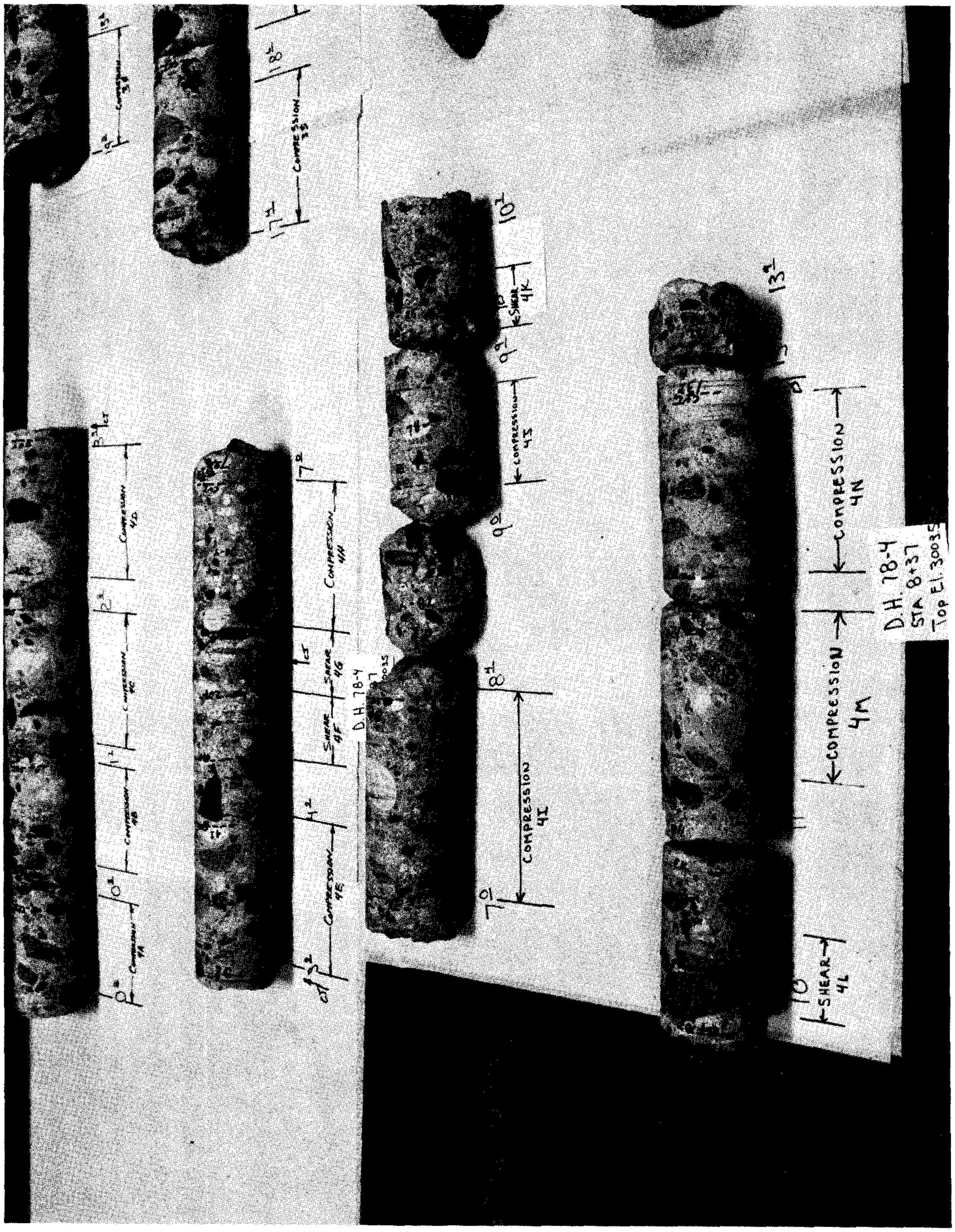

Figure 8.—Arrowrock Dam Core No. 4. P801-D-79786

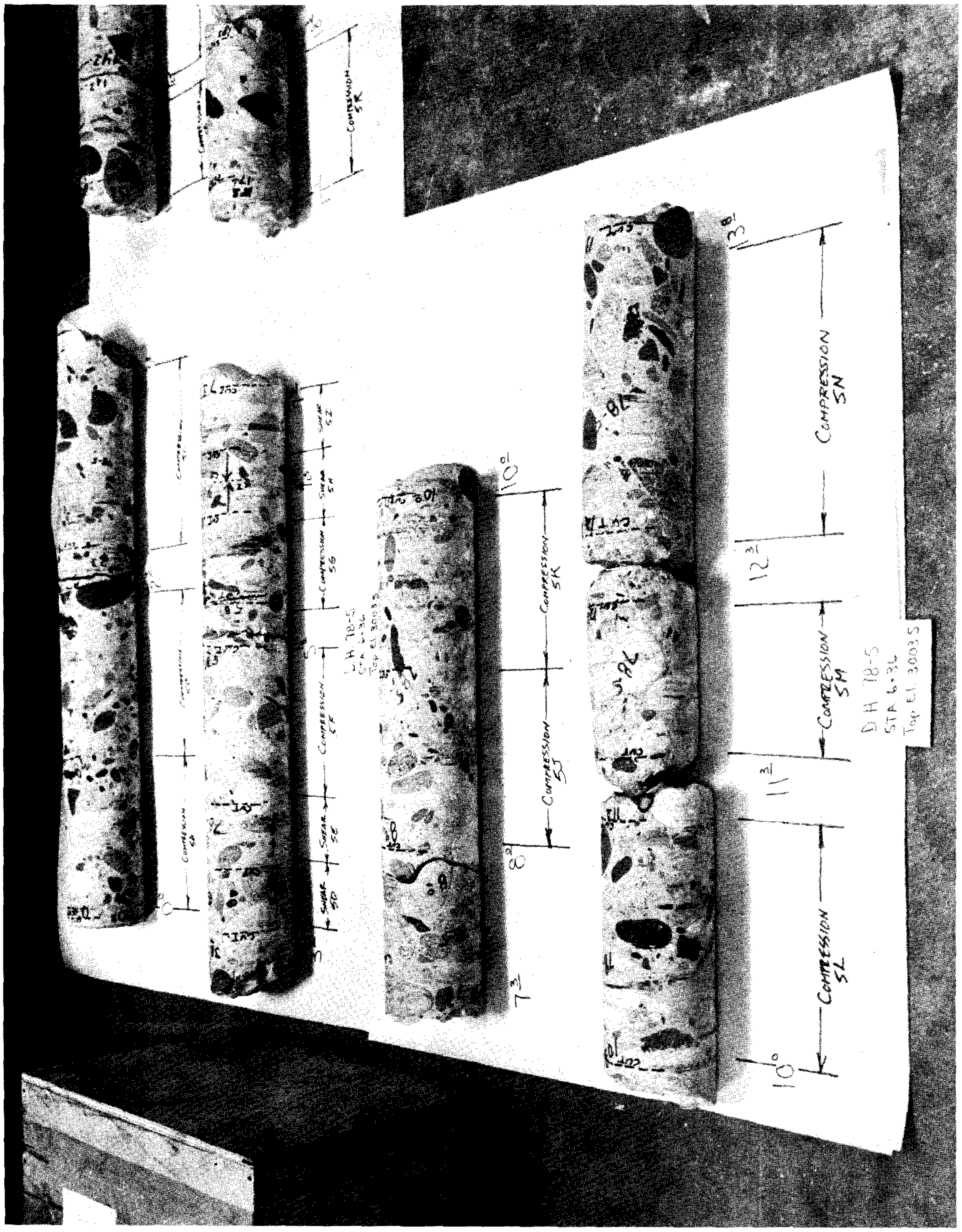

Figure 9.—Arrowrock Dam Core No. 5. P801-D-79787

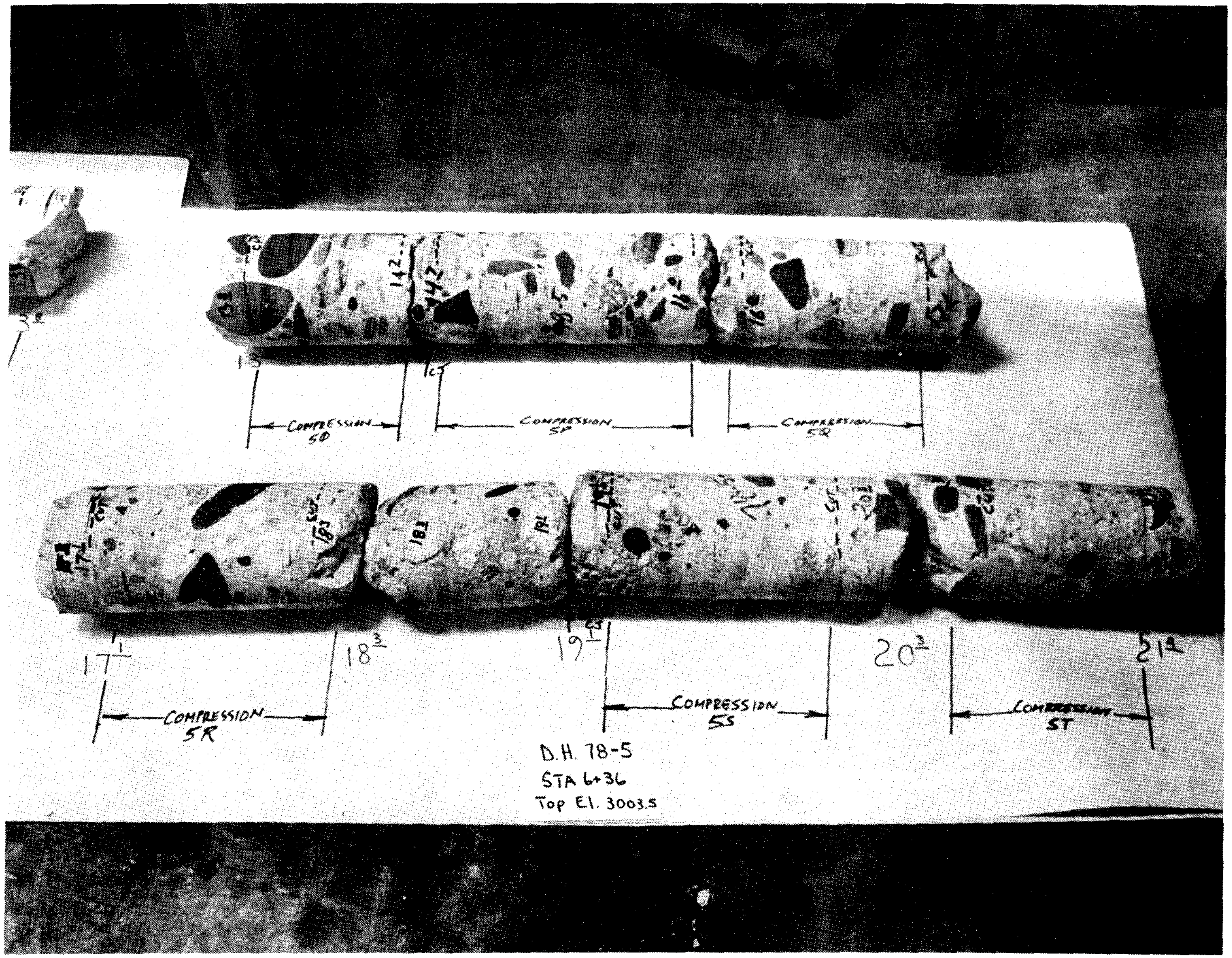

Figure 10.—Arrowrock Dam Core No. 5. P801-D-79788

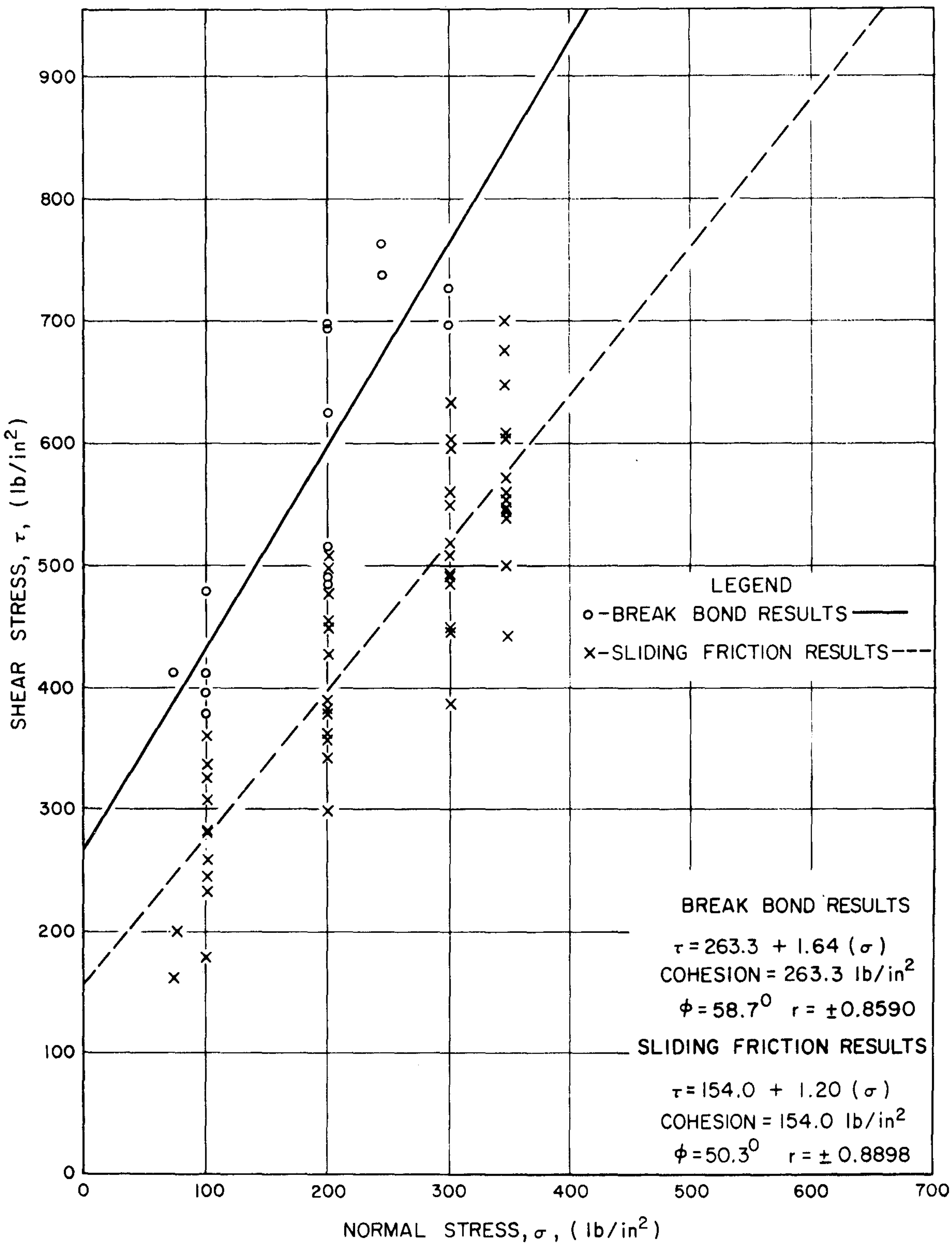

Figure 11A.—Direct shear test linear regression results Arrowrock Dam, dry [inch-pound units]

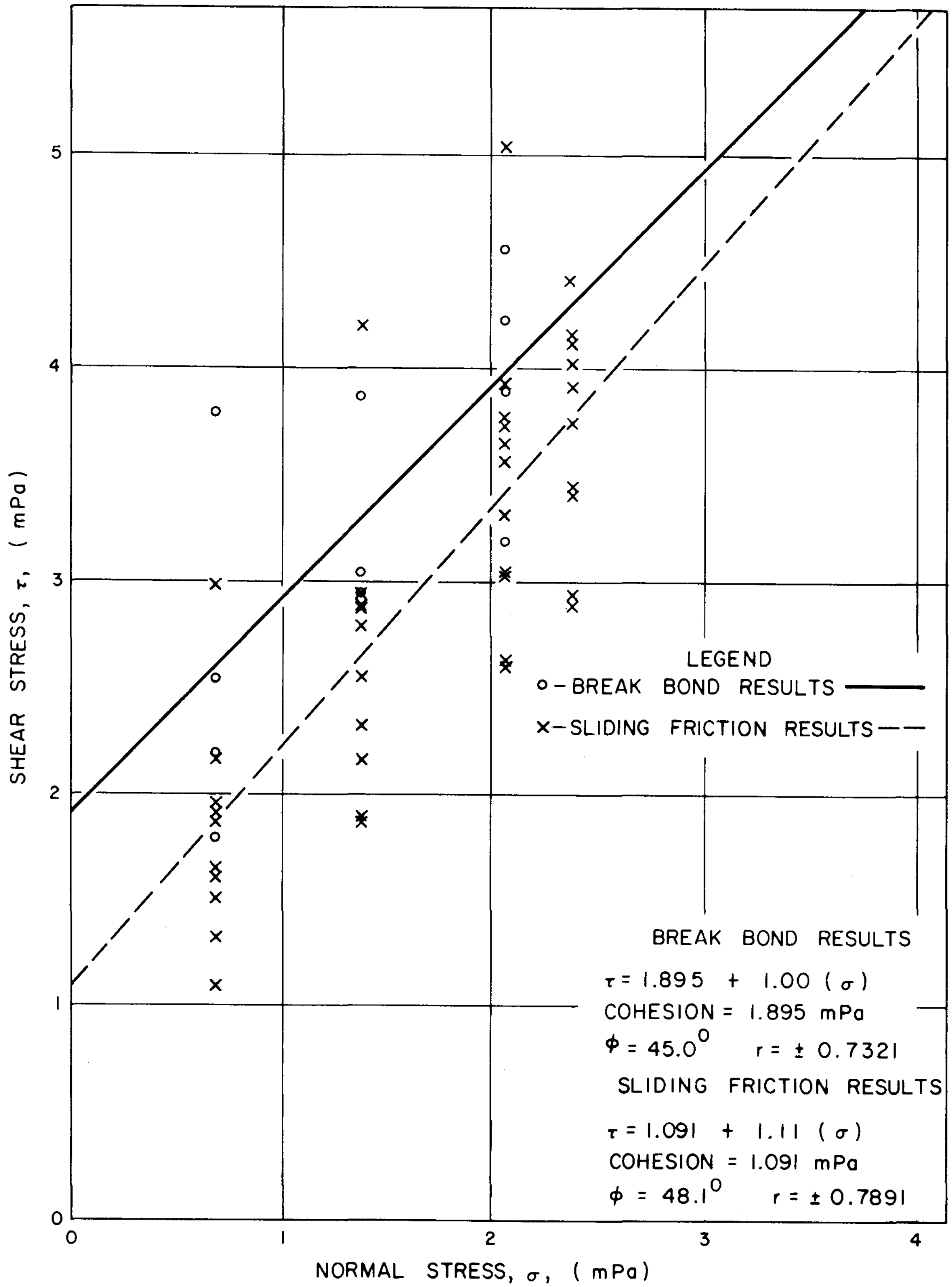

Figure 11B.—Direct shear test linear regression results Arrowrock Dam, dry [SI metric units]

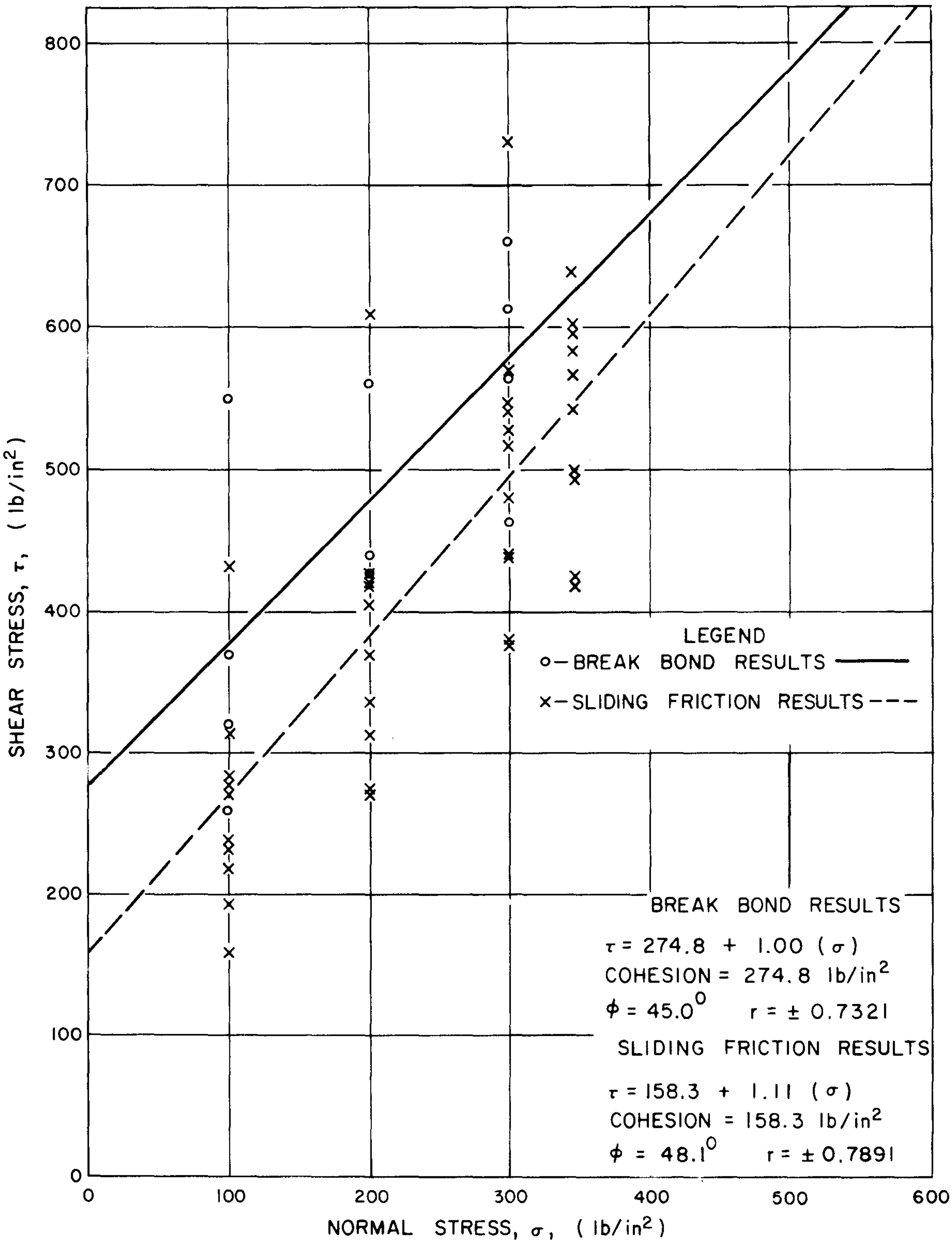

Figure 12A.—Direct shear test linear regression results Arrowrock Dam, wet [inch-pound units]

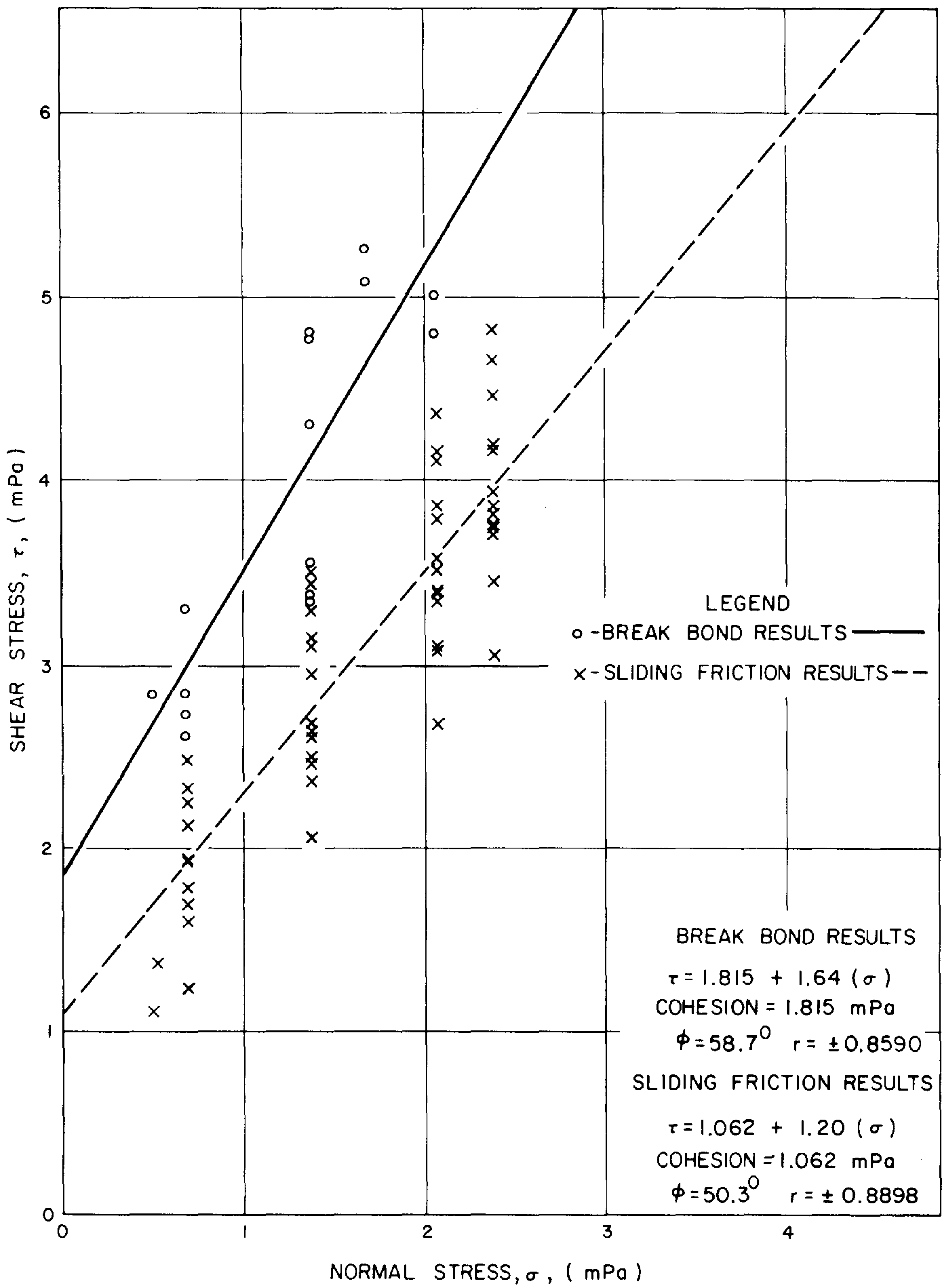

Figure 12B.—Direct shear test linear regression results Arrowrock Dam, wet [SI metric units]

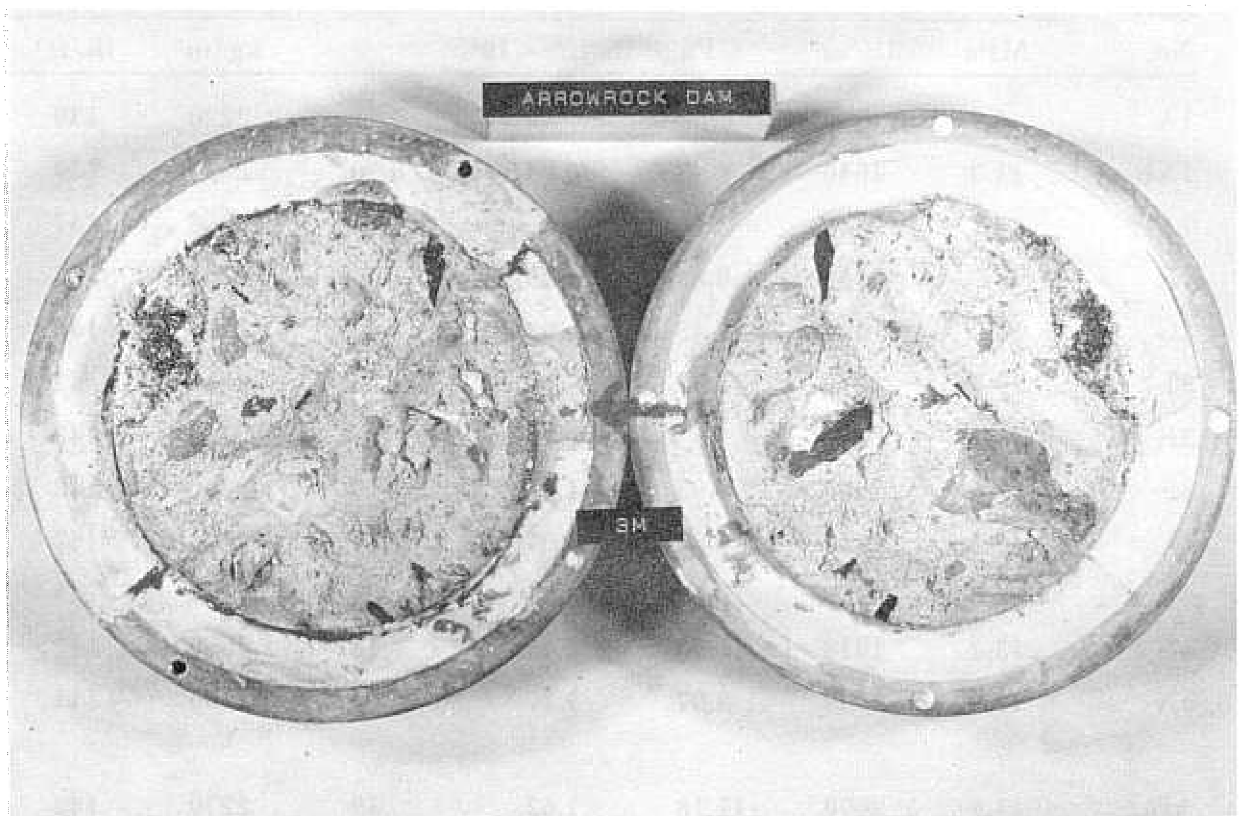

Figure 13.—Typical direct shear and sliding friction test specimen. P801-D-79789

Table 1.—Properties of concrete cores (dry) — Arrowrock Dam

Core No.	Compressive strength		Modulus of elasticity		Poisson's ratio	Density	
	MPa	lb/in²	GPa	lb/in² × 10⁶		kg/m³	lb/ft³
1A	6.9	1000	*	*	*	2220	139
1AB	11.3	1640	6.48	0.94	0.70	2220	139
1AE	14.2	2060	*	*	*	2200	137
1E	14.9	2160	8.83	1.28	.50	2200	137
2G	10.5	1520	7.45	1.08	.62	2340	146
2J	19.1	2770	13.03	1.89	.25	2270	142
3R	16.2	2360	*	*	*	2270	142
3S	15.6	2260	9.93	1.44	.17	2280	142
4I	17.4	2520	14.27	2.07	.17	2290	143
4P	22.3	3230	15.58	2.26	.03	2330	145
5B	13.2	1910	16.96	2.46	.45	2350	147
5N	11.0	1600	8.07	1.17	.64	2260	141
Avg.	14.4	2090	11.18	1.62	.39	2270	142

* Core too short for elasticity frame.

Table 2.—Properties of concrete cores (wet) — Arrowrock Dam

Core No.	Compressive strength		Modulus of elasticity		Poisson's ratio	Density		Absorption
	MPa	lb/in^2	GPa	$lb/in^2 \times 10^6$		kg/m^3	lb/ft^3	%
1D	7.4	1070	9.79	1.42	0.10	2330	145	3.5
1AF	7.9	1150	*	*	*	2290	143	4.2
1AG	8.5	1240	5.52	0.80	.22	2290	143	3.5
2C	12.0	1740	10.00	1.45	.08	2300	144	3.7
2D	8.3	1200	6.89	1.00	.22	2330	145	3.6
3Q	8.2	1190	4.83	0.70	.13	2360	147	3.7
3T	7.9	1150	2.90	0.42	.17	2310	144	4.1
4C	8.2	1190	4.62	0.67	.15	2280	142	4.1
4D	7.8	1130	6.34	0.92	.45	2300	144	3.6
5J	5.7	830	3.45	0.50	.21	2270	142	4.3
5K	12.5	1810	9.52	1.38	.18	2360	147	3.2
Avg.	8.6	1250	6.39	0.93	.19	2310	144	3.8

* Core too short for elasticity frame.

Table 3.—Direct shear and sliding friction test data on 150-mm (6-in) diameter concrete cores tested in a dry condition — Arrowrock Dam

Specimen No.	Normal stress, σ MPa	Normal stress, σ lb/in²	Shear stress, τ MPa	Shear stress, τ lb/in²	Sliding friction MPa	Sliding friction lb/in²	Linear regression: Equation τ =	Linear regression: ∅ degrees	Linear regression: Cohesion MPa (lb/in²)	Angle envelope: ∅ degrees max.	∅ degrees min.	∅ degrees avg.	Cohesion for max. ∅ MPa (lb/in²)	Cohesion for min. ∅ MPa (lb/in²)	Cohesion for avg. ∅ MPa (lb/in²)	Remarks
1B	0.69	100	2.73	396					2.02	67.9	55.1	60.9	1.04	1.74	1.51	BB[1]
	0.69	100			1.70	246			(293)				(151)	(253)	(219)	SF
	1.38	200			2.36	343										SF
	2.07	300			3.10	450										SF
	2.41	350			3.46	502	140.9 + 1.0287σ	45.8								SF
1C	0.69	100	2.61	379					1.72	70.4	60.1	65.2	0.68	1.41	1.12	BB
	0.69	100			1.93	280			(249)				(98)	(205)	(162)	SF
	1.38	200			3.10	450										SF
	2.07	300			3.86	560										SF
	2.41	350			4.19	608	165.7 + 1.3011σ	52.5								SF
1F	1.38	200	4.31	625					2.62	66.7	57.0	61.7	1.10	2.19	1.75	BB
	0.69	100			1.60	232			(380)				(160)	(317)	(254)	SF
	1.38	200			2.63	382										SF
	2.07	300			3.39	492										SF
	2.41	350			3.72	539	120.4 + 1.2253σ	50.8								SF
1G	1.38	200	3.32	481					1.57	68.8	58.6	63.1	0.	1.06	0.60	BB
	0.69	100			1.78	258			(227)				(0)	(154)	(87)	SF
	1.38	200			2.68	388										SF
	2.07	300			3.59	520										SF
	2.41	350			3.95	573	133.1 + 1.2699σ	51.8								SF
2E	1.38	200	3.38	490					1.79	68.8	57.1	62.1	0.	1.25	0.78	BB
	0.69	100			1.78	258			(260)				(0)	(181)	(113)	SF
	1.38	200			2.47	358										SF
	2.07	300			3.36	487										SF
	2.41	350			3.73	541	138.2 + 1.1488σ	49.0								SF
2F	1.38	200	4.81	697					3.16	68.8	57.7	62.7	1.25	2.63	2.14	BB
	0.69	100			1.78	258			(459)				(182)	(381)	(310)	SF
	1.38	200			2.63	382										SF
	2.07	300			3.47	503										SF
	2.41	350			3.82	554	140.7 + 1.1921σ	50.0								SF
2H	2.07	300	4.80	696					2.61	70.5	57.3	63.2	0.	1.58	0.70	BB
	0.69	100			1.94	282			(378)				(0)	(229)	(101)	SF
	1.38	200			2.63	381										SF
	2.07	300			3.41	494										SF
	2.41	350			3.76	545	173.4 + 1.0612σ	46.7								SF
2I	2,07	300	5.02	728					2.36	70.6	59.9	64.9	0.	1.45	0.61	BB
	0.69	100			1.95	283			(343)				(0)	(210)	(88)	SF
	1.38	200			2.96	429										SF
	2.07	300			3.79	550										SF
	2.41	350			4.16	604	162.2 + 1.2809σ	52.0								SF
3D	0.52	75	2.84	412					2.12	65.2	57.3	61.6	1.72	2.03	1.88	BB
	0.52	75			1.12	162			(308)				(249)	(295)	(273)	SF
	1.38	200			2.50	363										SF
	2.41	350			3.76	545	68.4 + 1.3841σ	54.2								SF

Table 3.—Direct shear and sliding friction test data on 150-mm (6-in) diameter concrete cores tested in a dry condition — Arrowrock Dam—Continued

Specimen No.	Normal stress, σ		Shear stress, τ		Sliding friction		Linear regression: Equation	Linear regression: ∅	Linear regression: Cohesion	Angle envelope: ∅ degrees			Angle envelope: Cohesion for			Remarks
	MPa	lb/in²	MPa	lb/in²	MPa	lb/in²	τ =	degrees	MPa (lb/in²)	max.	min.	avg.	max. ∅ MPa (lb/in²)	min. ∅ MPa (lb/in²)	avg. ∅ MPa (lb/in²)	
3P	0.69	100	2.85	413					2.13	60.8	51.7	55.6	1.61	1.97	1.84	BB
	0.69	100			1.23	179			(309)				(234)	(286)	(267)	SF
	1.38	200			2.06	299										SF
	2.07	300			2.67	387										SF
	2.41	350			3.05	443	$80.5 + 1.0377\sigma$	46.1								SF
3Q	0.69	100	3.31	480					2.29	72.0	62.6	66.7	1.22	1.98	1.70	BB
	0.69	100			2.12	308			(332)				(172)	(287)	(247)	SF
	1.38	200			3.14	456										SF
	2.07	300			4.16	603										SF
	2.41	350			4.66	676	$160.9 + 1.4730\sigma$	55.8								SF
4Q	1.38	200	3.56	517					1.50	72.9	63.5	67.9	0.	0.81	0.17	BB
	0.69	100			2.24	325			(218)				(0)	(117)	(25)	SF
	1.38	200			3.43	498										SF
	2.07	300			4.36	633										SF
	2.41	350			4.83	701	$184.3 + 1.4948\sigma$	56.2								SF
4R	1.38	200	4.77	692					2.94	68.9	58.0	62.8	1.21	2.56	2.09	BB
	0.54	78			1.39	201			(426)				(175)	(372)	(303)	SF
	1.38	200			2.61	379										SF
	2.07	300			3.51	509										SF
	2.41	350			3.87	561	$103.7 + 1.3316\sigma$	53.1								SF
5H	1.72	250	5.09	738					4.14	73.4	55.1	65.2	0.	2.62	1.36	BB
	0.69	100			2.31	335			(600)				(0)	(380)	(197)	SF
	1.38	200			3.30	478										SF
	2.07	300			3.08	446										SF
	2.41	350			3.46	502	$309.1 + 0.5525\sigma$	28.9								SF
5I	1.72	250	5.27	764					3.32	74.5	61.7	68.2	0.	2.06	0.96	BB
	0.69	100			2.48	360			(481)				(0)	(300)	(140)	SF
	1.38	200			3.50	508										SF
	2.07	300			4.11	596										SF
	2.41	350			4.47	649	$259.7 + 1.1305\sigma$	48.5								SF

[1]BB = Break bond
SF = Sliding friction

Table 4.—Direct shear and sliding friction test data on 150-mm (6-in) diameter concrete cores tested in a wet condition — Arrowrock Dam

Specimen No.	Normal stress, σ		Shear stress, τ		Sliding friction		Linear regression			Angle envelope						Remarks
							Equation	∅	Cohesion	∅ degrees			Cohesion for			
	MPa	lb/in²	MPa	lb/in²	MPa	lb/in²	τ =	degrees	MPa (lb/in²)	max.	min.	avg.	max. ∅	min. ∅	avg. ∅ MPa (lb/in²)	
1AC	2.07	300	4.55	660					1.82	69.8	59.8	64.4	0.	0.99	0.23	BB[1]
	0.69	100			1.88	272			(264)				(0)	(144)	(33)	SF
	1.38	200			2.90	420										SF
	2.07	300			3.76	545										SF
	2.41	350			4.14	601	146.2 + 1.3197σ	52.8								SF
1AD	0.69	100	2.21	320					1.38	62.6	54.6	57.8	0.88	1.23	1.11	BB
	0.69	100			1.33	193			(200)				(128)	(179)	(161)	SF
	1.38	200			2.17	314										SF
	2.07	300			3.01	436										SF
	2.41	350			3.40	493	72.4 + 1.2061σ	50.3								SF
3C	1.38	200	2.94	427					1.85	66.7	50.5	57.0	0.	1.26	0.82	BB
	0.69	100			1.60	232			(268)				(0)	(185)	(119)	SF
	1.38	200			1.90	275										SF
	2.07	300			2.61	379										SF
	2.41	350			2.92	424	138.8 + 0.7943σ	38.5								SF
3L	2.07	300	3.19	463					0.90	65.3	54.9	59.3	0.	0.25	0.	BB
	0.69	100			1.50	218			(130)				(0)	(36)	(0)	SF
	1.38	200			2.32	336										SF
	2.07	300			3.03	439										SF
	2.41	350			3.43	498	108.9 + 1.1108σ	48.0								SF
3M	1.38	200	3.86	560					2.32	72.4	59.5	65.5	0.	1.52	0.84	BB
	0.69	100			2.17	314			(336)				(0)	(221)	(122)	SF
	1.38	200			2.93	425										SF
	2.07	300			3.72	539										SF
	2.41	350			4.10	594	201.8 + 1.1210σ	48.3								SF
4F	0.69	100	1.79	259					0.96	67.2	57.1	61.5	0.14	0.72	0.52	BB
	0.69	100			1.64	238			(139)				(21)	(104)	(75)	SF
	1.38	200			2.54	369										SF
	2.07	300			3.31	480										SF
	2.41	350			3.74	542	121.7 + 1.2028σ	50.3								SF
4G	1.38	200	3.03	439					1.43	70.1	58.2	64.2	0.	0.80	0.18	BB
	0.69	100			1.91	277			(208)				(0)	(116)	(26)	SF
	1.38	200			2.92	424										SF
	2.07	300			3.63	527										SF
	2.41	350			3.90	565	173.8 + 1.1550σ	49.1								SF
4K	2.07	300	4.22	612					1.77	70.6	59.0	64.1	0.	0.78	0.	BB
	0.69	100			1.95	283			(257)				(0)	(113)	(0)	SF
	1.38	200			2.79	405										SF
	2.07	300			3.56	517										SF
	2.41	350			4.01	582	165.8 + 1.1833σ	49.8								SF
4L	0.69	100	3.79	549					2.76	77.0	67.6	73.0	0.81	2.11	1.54	BB
	0.69	100			2.98	432			(400)				(117)	(306)	(223)	SF
	1.38	200			4.19	608										SF
	2.41	300			5.03	729	292.3 + 1.4871σ	56.1								SF

Table 4.—Direct shear and sliding friction test data on 150-mm (6-in) diameter concrete cores tested in a wet condition — Arrowrock Dam—Continued

Specimen No.	Normal stress, σ MPa	Normal stress, σ lb/in²	Shear stress, τ MPa	Shear stress, τ lb/in²	Sliding friction MPa	Sliding friction lb/in²	Linear regression: Equation τ =	Linear regression: Ø degrees	Linear regression: Cohesion MPa (lb/in²)	Angle envelope: Ø degrees max.	Angle envelope: Ø degrees min.	Angle envelope: Ø degrees avg.	Angle envelope: Cohesion for max. Ø MPa (lb/in²)	Angle envelope: Cohesion for min. Ø MPa (lb/in²)	Angle envelope: Cohesion for avg. Ø MPa (lb/in²)	Remarks
5D	0.69	100	2.55	370					1.55	70.1	61.3	65.1	0.64	1.29	1.06	BB
	0.69	100			1.91	277			(225)				(93)	(187)	(154)	SF
	1.38	200			2.95	428										SF
	2.07	300			3.92	568										SF
	2.41	350			4.40	638	$135.0 + 1.4435\sigma$	55.3								SF
5E	2.07	300	3.89	564					1.74	57.9	50.0	53.4	0.59	1.42	1.10	BB
	0.69	100			1.10	159			(252)				(86)	(206)	(159)	SF
	1.38	200			1.87	271										SF
	2.07	300			2.59	375										SF
	2.41	350			2.88	418	$58.7 + 1.0400\sigma$	58.7								SF

[1]BB = Break bond
SF = Sliding friction

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

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