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The Structural Properties of Ross Dam Mass Concrete

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STRUCTURAL PROPERTIES

OF

ROSS DAM CONCRETE

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STRUCTURAL PROPERTIES OF ROSS DAM CONCRETE

by

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Introduction

As a part of the program to determine the feasibility of raising Ross Dam to its ultimate height of 661 feet as a thin arch dam, it was necessary to make a detailed evaluation of the structural properties of the mass concrete in place in the existing dam.

In accordance with agreements between International Engineering Co., Inc., and the University of California, twelve 4-inch diameter and seventeen 19-inch diameter cores were drilled from the mass concrete of Ross Dam and sent to the University for determination of the structural properties of the mass concrete. For shipment, all cores were packed in wet sawdust in steel containers.

All of the 4-inch cores and nine of the 19-inch cores were used in splitting tests for determining the tensile strength of the concrete. Six of the 19-inch cores were used for determining elastic modulus, Poisson's ratio, and ultimate compressive and shear strength under triaxial loading conditions. The remaining two 19-inch cores were used for the determination of creep of this 20-year old concrete.

Uniaxial Compression Tests

Six 19-inch diameter by 38-inch long cores were used in the determination of elastic modulus, Poisson's ratio, compressive strength, shear strength, and angle of internal friction. Each cylinder was capped with Hydrostone into the 4,000,000 lb universal testing machine at the Richmond Field Station and fitted with a compressometer frame employing four linearly variable differential transformers recording on an X-Y-Y' plotter, as shown in Figure 1. In addition, check tests were run on four of these cylinders using 6-in SR-4 gages bonded directly to the surface of the cylindrical cores. Elastic modulus and Poisson's ratio were taken as the slope of the recorded stress-strain plots at loads up to one-fourth the ultimate.

For two of the cylinders, ultimate strength was determined by loading to failure in the 4,000,000 lb universal testing machine. The remaining four cylinders were saved so that they could be placed in the chamber of the 4,000,000 lb rockfill testing machine for the triaxial tests.

The results of the uniaxial tests are summarized in Table 1. Incorrect operation of the compressometer resulted in loss of some Poisson's ratio readings, but all values given in Table 1 are confirmed by two independent series of measurements: the compressometer frame, and the bonded wire strain gages.

TABLE 1

Ultimate Strength, Modulus of Elasticity and Poisson's Ratio of 19-inch Cores.

Indicated Core Depth-ft.	Chamber Pressure-psi	Ultimate Strength-psi	Modulus of Elasticity psi x 10^{-6}	Poisson's Ratio
3.1 - 6.3	0	6,540	4.59	(a)
9.0 - 12.2	0	7,820	4.71	(a)
20.3 - 23.5	950	11,700	5.10	.16
25.5 - 28.7	750	11,050	4.68	.20
54.3 - 57.2	950	11,800	4.52	.20
60.4 - 63.6	750	10,460	4.58	.20

(a) Results unreliable due to faulty equipment operation

The average compressive strength of the mass concrete, by the usual criteria is thus 7180 psi, average elastic modulus is 4.7 x 10^6 psi, and Poisson's ratio is 0.19.

Triaxial Compression Tests

Fig. 2 shows the rockfill test machine at the Richmond Field Station of the University of California that was adapted for triaxial testing of the 19-inch concrete cores. It is of interest to note that these were probably the largest cores that have ever been tested in this fashion.

For the triaxial tests, axial load was applied through a ram with a load capacity of 4,000,000 lb. Lateral load was applied by pressure of water in a steel chamber on a rubber sleeve surrounding the test cylinder. The tight fitting rubber sleeve was slipped over the cylinder using a steel vacuum sleeve to expand the rubber. The surface of the cylinder was pointed up with plaster to eliminate any holes and discontinuities that might result in the rupture of the sleeve under pressure. The cylinder was capped to thick steel end plates, to which the sleeve was sealed with O-rings and stainless steel bands. The nominal maximum pressure for the chamber is 700 psi. However, with some modifications, two tests were run at 750 psi, and two at the absolute maximum of 950 psi, with all concerned keeping their fingers crossed.

For three of the tests, failure was indicated by the dropping off of the ram pressure as internal cracking allowed the cylinder to deform faster than the pumps could develop ram pressure. One cylinder deformed at failure faster than the operator could cut off load, and ruptured cleanly on a 68° slope, as shown in Figure 3.

For determining the shear properties of the mass concrete, failure stresses of the four 19-in. cylinders tested triaxially and the two 19-in. cylinders tested uniaxially were averaged and plotted in the Mohr's diagram shown in Fig. 4. When the envelope of failure is drawn, the shear strength is determined to be 1600 psi, and ϕ, the angle of internal friction, is found to be 42°.

Shear failure should theoretically take place on a plane at $(45° + \frac{\phi}{2})$ or 66° from the horizontal. This checks fairly well with the angle of 68° measured on the failed cylinder shown in Fig. 3.

Tension Tests

Direct tension tests are usually performed on specially shaped specimens with enlarged ends, because of the peculiar triaxial stress conditions at the end grips. Such tests were of course out of the question for testing cylindrical cores, hence the splitting tension test was used to determine the tensile strength of the mass concrete. For this test, the cylinder is laid on its side in the testing machine, and loaded in compression on two diametrically opposite elements. Although the stress in the immediate vicinity of the loaded area is compressive, for about 90 percent of the plane described by the two elements it is tensile and nearly uniform, and since the concrete is much weaker in tension than in compression, the cylinder fails in tension. Tensile strength is related to the load causing failure through Equation 1.

$$t = \frac{2P}{\pi L d} \qquad (1)$$

Where t = tensile strength, psi

P = maximum load at failure, lb

L = length of cylinder, in

d = diameter of cylinder, in

Two series of splitting tension tests were performed, one on nine 19-inch diameter cores, and the other on twelve 4-inch diameter cores. As shown in Table 2, the average tensile strength of the 19-inch cores was 414 psi. Table 3 gives results of the tests of the 4-inch cores, the average tensile strength of which was 622 psi. When the 4-inch cores exhibit a strength 50% higher than the 19-inch cores, the question must be asked, which is truly representative of the tensile strength of the concrete in the mass?

TABLE 2

Tensile Strength of 19-inch Cores

Depth of Sample (ft)	Diameter (in)	Length (in)	Load (kips)	Splitting Tensile Stress (psi)
14.6 - 16.1	19.00	18.19	262	482
16.4 - 17.9	19.00	17.75	215	406
24.1 - 25.6	19.00	18.00	262	488
38.9 - 40.2	19.00	15.25	167	367
40.6 - 42.6	18.94	24.22	303	420
44.5 - 46.5	18.90	24.14	340	475
46.8 - 48.3	18.87	17.87	174	328
50.4 - 52.4	18.89	24.14	280	390
63.6 - 65.1	19.00	17.38	190	366

Average splitting tensile strength, 414 psi
Coefficient of variation, 11 percent

TABLE 3

Tensile Strength of 4-inch Cores

Depth of Sample (ft)	Diameter (in)	Length (in)	Load (lb)	Splitting Tensile Stress (psi)
13.5 - 15.2	3.97	8.28	51,800	1000*
27.3 - 28.8	3.96	8.23	43,800	856
31.4 - 33.0	3.98	8.08	25,200	500
39.5 - 41.0	3.97	7.88	20,400	415
44.5 - 46.0	3.95	8.22	30,100	590
50.9 - 51.9	3.96	8.01	39,400	791
60.9 - 62.3	3.98	8.06	21.700	430
81.5 - 82.5	3.96	8.19	40,200	789
87.3 - 89.3	3.97	7.72	27,300	567
98.2 - 99.8	3.97	8.08	36,300	721
115.9 - 117.6	3.97	8.51	28,700	541
134.7 - 136.3	3.98	8.13	32,300	636

*Excluded in determining average strength and coefficient of variation
Average splitting tensile strength, 622 psi
Coefficient of variation, 24 percent

Both series of cores were cut from mass concrete containing 6-inch cobbles. In any such mass of concrete, there are a number of weak zones, particularly under the large cobbles, where water gain leaves either voids or laitance. Four-inch cores can cut completely through a single cobble, or alternatively through a single grain boundary. If it cuts through a single cobble, it would be expected that the apparent strength would be higher, reflecting the strength of solid unbroken rock. On the other hand, if a weak boundary between a cobble and the mortar matrix ran completely across a core, the chances are great that the core would break across this boundary during drilling and extracting operations. Thus it would be expected that there would be a bias toward higher apparent strength in the 4-inch cores, not truly indicative of the actual strength of the mass concrete.

The relative reliability of the two series can also be studied statistically by a comparison of their standard coefficients of variation. The 19-inch cores have a coefficient of variation of 11%, which is about normal for mass concrete with good control. The variability of the 4-inch series can be seen by an inspection of Table 3. Even omitting the highest value of 1000 psi, which is seen to be way out of line, the coefficient of variation of this series is 24%.

It must be concluded that the value of tensile strength of the mass concrete in Ross Dam should be based on the tests of the 19-inch cores, averaging 414 psi in the splitting tension test.

Creep

Two 19-inch diameter by 34-inch long cores were used to determine the creep of Ross Dam mass concrete initially loaded at 20-years. A 1.5-in diameter hole was diamond drilled at the longitudinal centerline of each cylinder to a depth of 27 inches, and a 20-inch gage length Carlson strainmeter was grouted in this hole using a fluid mixture of Hydrostone. By using special end plate adapters and high-strength tension rods, the laboratory 16-inch creep loading frames could be used to load the specimens, which were wrapped with Saran to prevent volume changes due to moisture loss.

When the specimens were first loaded, with an intensity of 1280 psi, it was found that the initial elastic strain of the two specimens differed by a factor of roughly two to one, and the specimens were at once unloaded to study this problem. Gage points for a 20-inch Whittemore extensometer were bonded to two elements of each cylinder, and after all creep from the first loading and unloading had worked out of the specimens, they were once more loaded. Again it was found that the specimens deformed differently, but this difference being recorded by two independent systems of measurements, was adjudged valid and the test was allowed to continue. When the subsequent creep measurement showed the same substantial difference, it was concluded that these particular cores contain in their makeup some inclusions that markedly affect their behavior, that the data were valid, and that analysis would unravel the elastic and creep behavior of the mass concrete.

In the course of the various loadings, the instantaneous deformation of the two cylinders was recorded on the Carlson strainmeter a number of times, as shown on Table 4. It can be noted that specimen

A-706 with the higher elastic modulus, had much the more consistent series of strains upon loading. Nevertheless, each series is consistent and completely different from the other. There can be no doubt but that the cylinders behave differently, and as a matter of fact, different from the six 19-inch specimens previously tested for elastic modulus.

TABLE 4

Elastic Modulus from 19-inch Creep Cylinders

Cylinder No.	A-705	A-706
Total strain for change of stress of 1280 psi, millionths	370 372 329 323 299	205 211 213 200 212 208 204
Average	339	209
Elastic modulus, psi	$\frac{1280}{339} = 3.77 \times 10^6$	$\frac{1280}{209} = 6.14 \times 10^6$
$\frac{1}{E}$, millionths per psi	.265	.162

The strains measured during the creep tests are all assembled and plotted in Fig. 5, with dots representing axial measurements on the Carlson strainmeter, and crosses representing external measurements on the Whittemore extensometer. The Carlson data appear much more consistent and reliable than the Whittemore data, and the discrepancy in the behavior of the two cylinders is clearly shown. It can also be seen that creep increases as elastic deformation increases. Creep coefficients are summarized in Table 5.

TABLE 5

Ross Dam Creep Coefficients

Cylinder No.	Depth ft	Data by	Creep Coefficients 1/E	f(k)	$\frac{f/k}{1/E}$	E
A-705	34.3-37.1	Carlson	.257	.0078	.0303	3.88
		Whittemore	.279	.0121	.0433	3.58
A-706	30.7-33.6	Carlson	.164	.0064	.0392	6.10
		Whittemore	.164	.0064	.0392	6.10
Average					.0380	

As the last two columns in Table 5 show, elastic moduli measured on these two particular cylinders differ markedly from those shown in Table 1, yet creep deformations are roughly proportional to elastic deformations. Assuming that these cylinders give just as valid readings as those of Table 1, the grand average elastic modulus for all cylinders is practically unchanged at:

$$E = 4.75 \times 10^6 \text{ psi.}$$

If the average proportionality between creep strain and elastic strain is combined with the average elastic modulus, we can write the creep equation for Ross Dam mass concrete loaded at 20 years as

$$e = 0.210 + .008 \log_e (t + 1)$$

The next problem is: how does this equation fit in with previously determined expressions for Ross Dam creep? The original studies for creep of Ross Dam concrete were made at the Materials

Laboratory of the Bureau of Reclamation, mostly on 6-inch mass concrete wet screened to 1 1/2 in concrete to fit inside 6-in diameter creep specimens. Results of these creep investigations have been published in four Bureau of Reclamation reports:

A. "A Ten-Year Study of Creep Properties of Concrete," U.S.B.R. Concrete Laboratory Report SP-38, July 28, 1953.

B. "Investigation of Creep Characteristics of Ross Dam Concrete," U.S.B.R. Concrete Laboratory Report G-787, March 16, 1955.

C. "Calculations of Stress from Strain in Concrete," U.S.B.R. Technical Memorandom No. 653, February 1955.

D. "Structural Behavior of Ross Dam, U.S.B.R. Report to Seattle Department of Lighting, May 1955.

There is also an internal U.S.B.R. report from the Concrete Laboratory to the Structural Behavior Group;

E. "Creep Functions for Use in Strain Meter Analysis of Ross Dam-City of Seattle, Washington," from J. A. Hanson to J. M. Raphael, dated July 3, 1950.

Slightly different values of the elastic and creep functions are found in these five sources, as shown in Table 6, all values being given in millionths per psi. It is understood that the U.S.B.R. internal memorandum (E) was the source of the creep data used in the stress analyses for Ross Dam and reported in Reference D. These values were also used by International Engineering Company in the current strainmeter data reduction effort. However, in the latest analysis, the creep data were modified in accordance with the difference in paste content between the full mass mis and the wet-screened mix, as shown in the column labeled IECO. At the bottom of Table 6, we have added the values found for the 20-year old cores.

TABLE 6

Creep Characteristics of Ross Dam Concrete

Source*	$\frac{1}{E}$		f(k)		
	A, B	C, D, E	A, B	C, D, E	IECO
Age, Days					
2	.480	.487	.0898	.081	.058
7	.285	.307	.0666	.061	.044
28	.245	.240	.0326	.035	.025
90	.213	.211	.0239	.028	.020
365	.180	.182	.0170	.015	.011
5 yr	.150		.0081		
20 year Cores	.210		.008		

*See text, page

It can be seen that the instantaneous deformation, 1/E, of .210 millionths per psi is the same as that measured in the U.S,B.R. specimens at age 90 days, and slightly above that for 1 and 5 years. The latter is reported to have been measured on the dam strain relief cores, and represents a richer mix of concrete at the face of the dam. It will also be recalled that the elastic modulus measured recently on 4-inch cores was about ten percent higher than that measured on 19-inch cores. Hence, it may be concluded that, in line with many other observations of the development of elastic modulus in mass concrete, the elastic deformation increases to a value of 0.21 at 90 days, and thence is constant.

As for the creep constant of .008, this value seems to fall in line with the IECO modified results, as shown in Fig. 6. This drawing is a log log plot of creep functions vs time, and eliminates the usual astronomical jump in 1/E and f(k) at very early ages. It is therefore concluded that the creep equation for Ross Dam concrete loaded at 20 years is

$$e = 0.210 + .008 \log_e (t + 1)$$

and that the dashed lines of Fig 6 can be used for the complete expression of the variation with time of the creep characteristics of Ross Dam concrete.

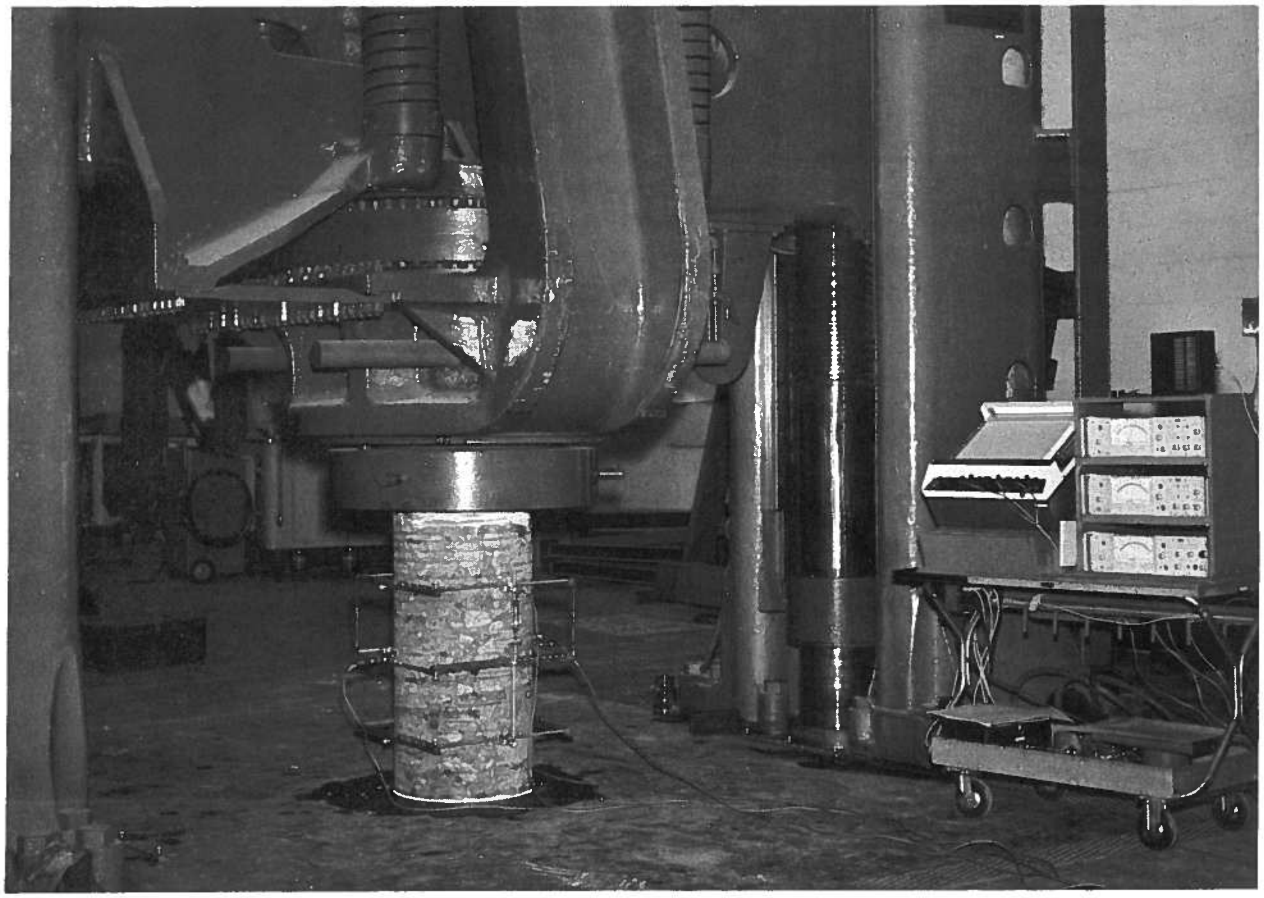

FIG. 1 SET UP FOR UNIAXIAL COMPRESSION TESTS

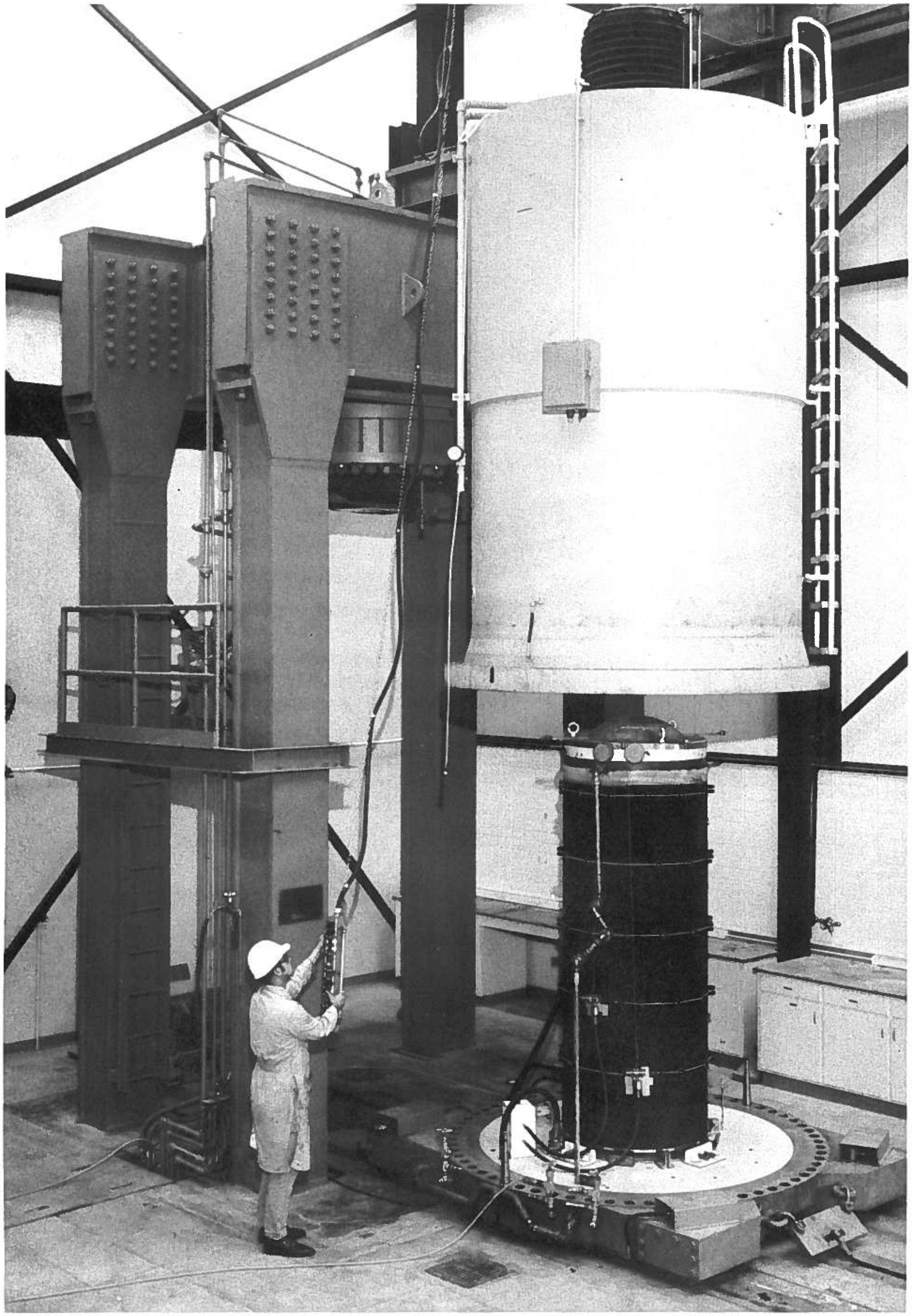

FIG. 2 TRIAXIAL TESTING MACHINE USED FOR 19-INCH CORES

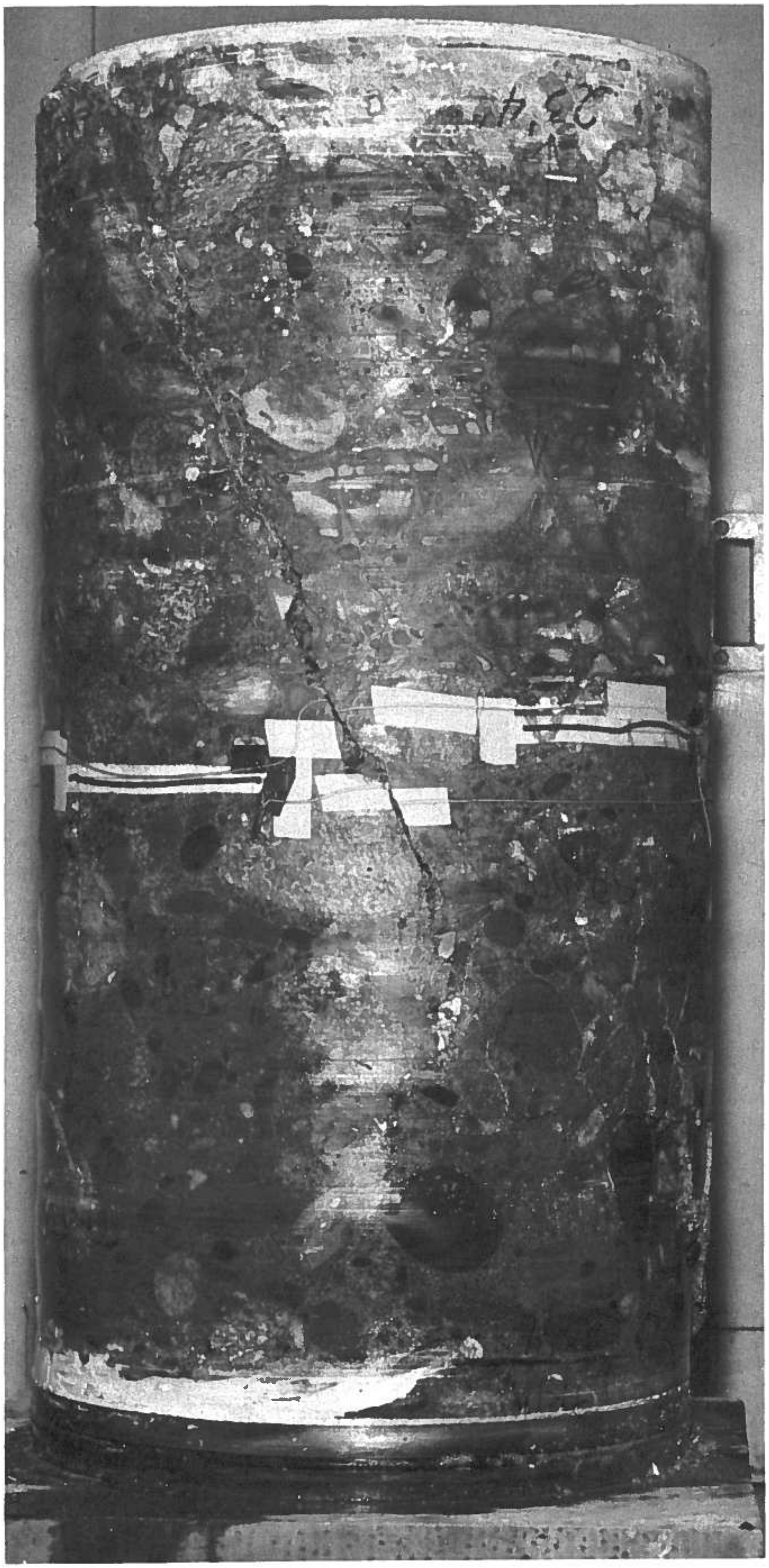

FIG. 3 SHEAR FAILURE OF CONCRETE CORE

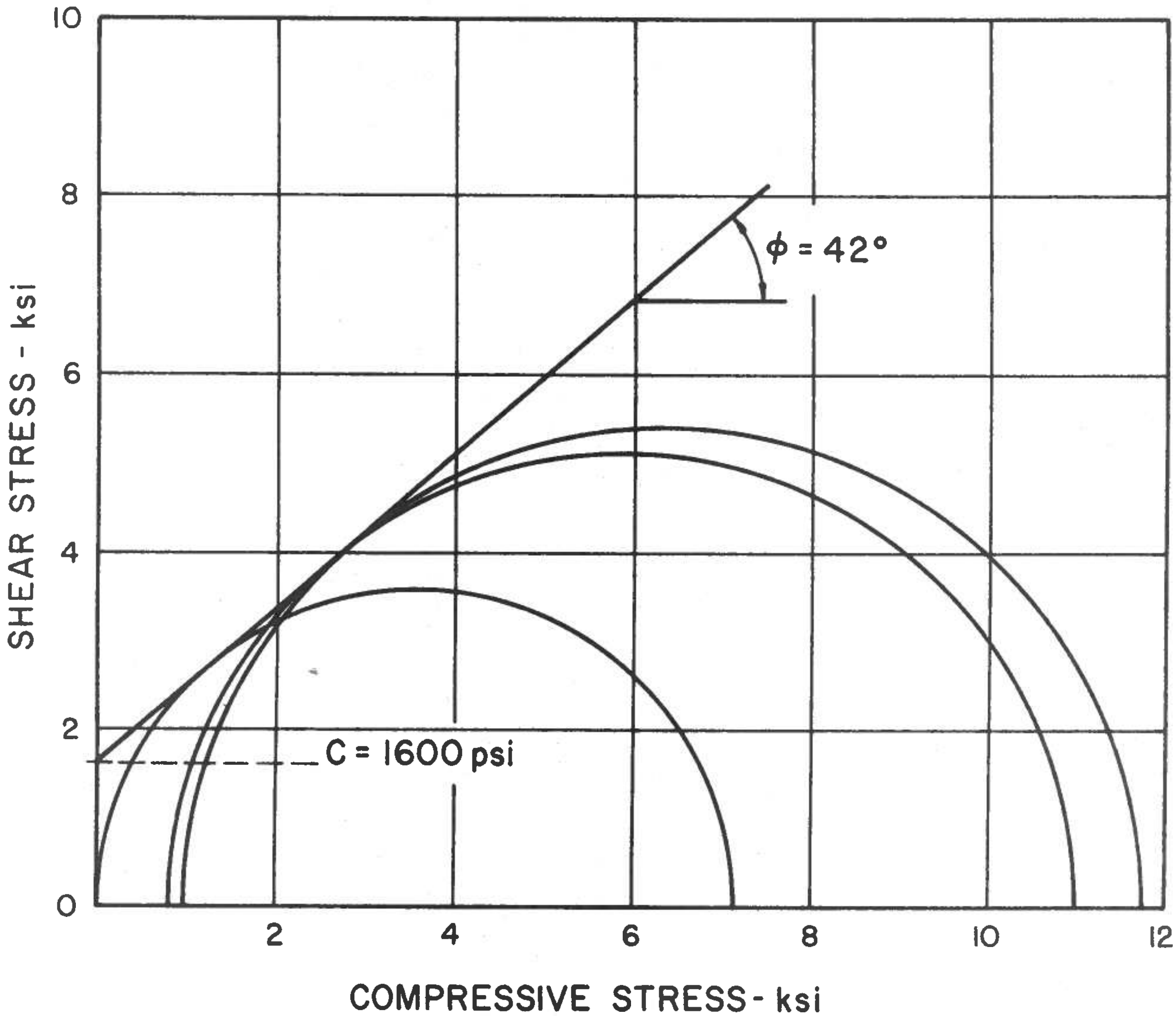

FIG. 4 TRIAXIAL TEST OF ROSS DAM CONCRETE

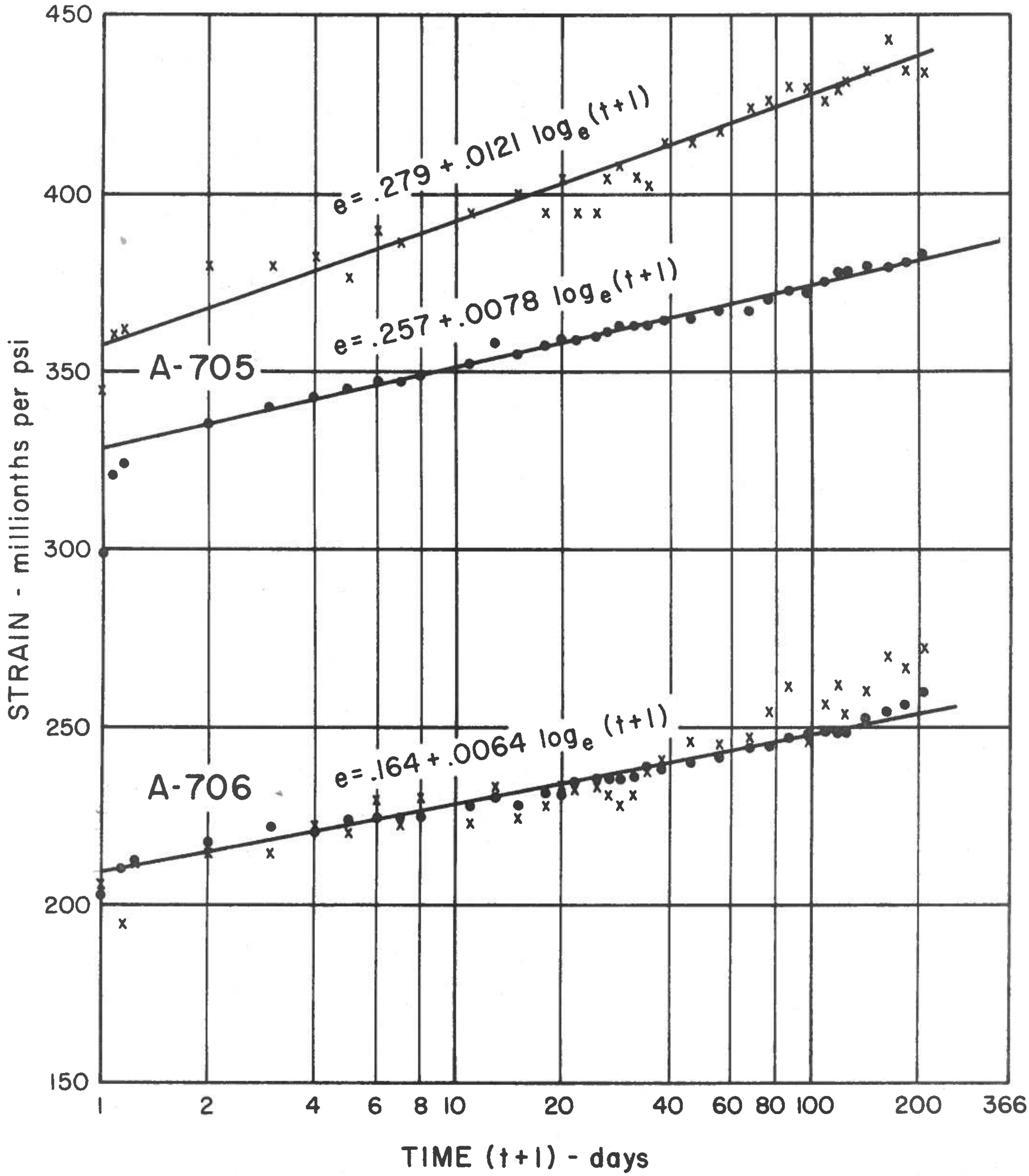

FIG. 5 MEASURED STRAINS OF CONCRETE CORES

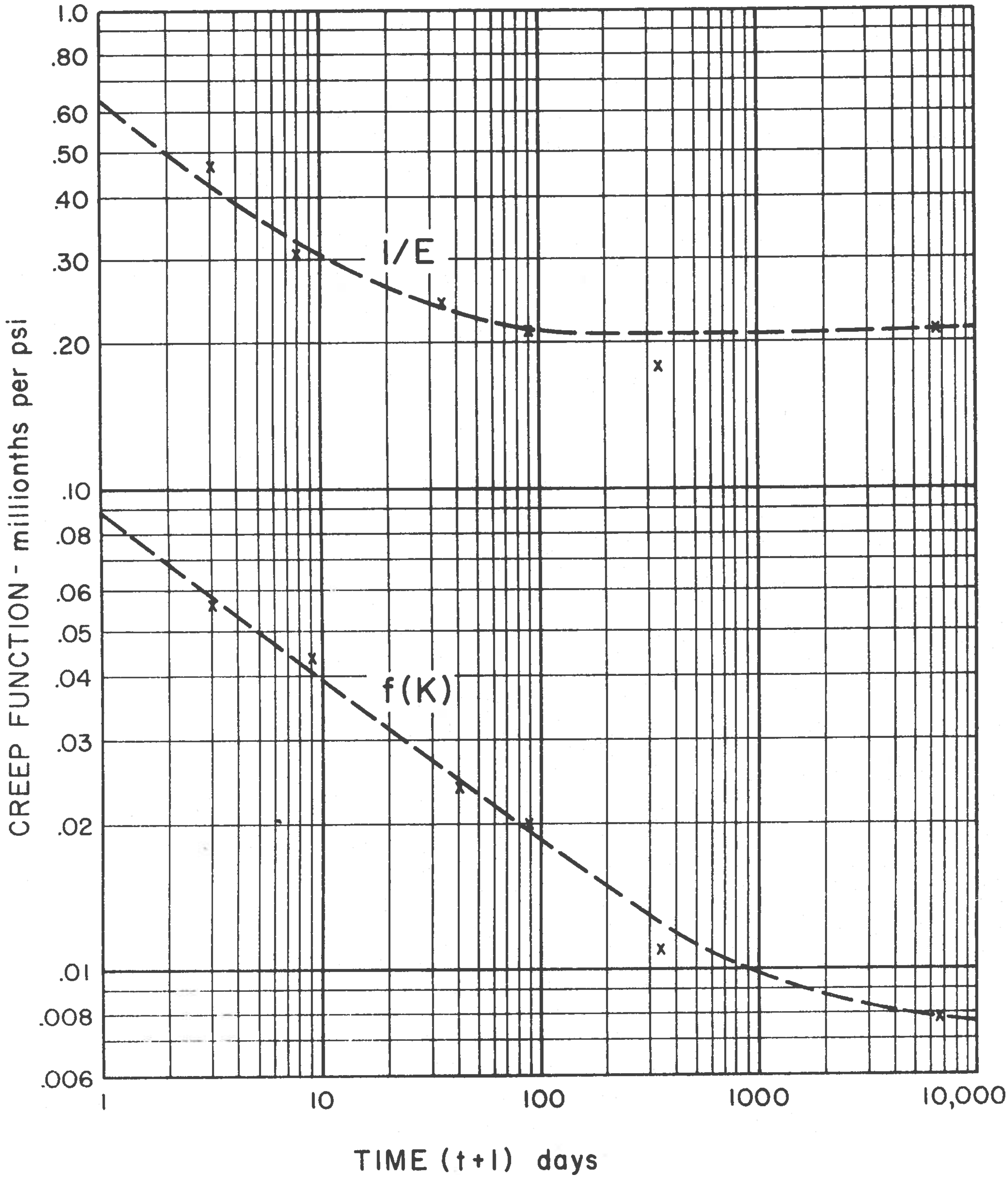

FIG. 6 ROSS DAM MASS CONCRETE CREEP CHARACTERISTICS