NATIONAL BUREAU OF STANDARDS REPORT

4550

A STUDY OF SOME PHYSICAL PROPERTIES
OF FIVE ROCK SAMPLES

by

Arthur Hockman, T. W. Reichard and E. W. Krussell

Report to
Bureau of Ordnance
Department of the Navy

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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A STUDY OF SOME PHYSICAL PROPERTIES OF FIVE ROCK SAMPLES

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Abstract

Physical tests were completed on five samples of rock (four granites and one gabbro) submitted by the Bureau of Ordnance. The first group of tests included determinations of flexural strength, compressive strength, shearing strength, porosity, toughness and modulus of elasticity by static method. The second group of tests included determinations by sonic methods of velocity of sound, modulus of elasticity, modulus of rigidity and Poisson's ratio.

All determinations except porosity were made both parallel and perpendicular to the rift (or bedding) directions of the rock samples. Some of test results are given for three mutually perpendicular directions of the samples.

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1. INTRODUCTION

At the request of the Bureau of Ordnance, Department of the Navy, the National Bureau of Standards made a study of some physical properties of five samples of rock (four granites and one gabbro), submitted by the Bureau of Ordnance.

The following properties were included in the first part of the study:

1. Flexural strength.
2. Compressive strength.
3. Shearing strength.
4. Toughness.
5. Porosity.
6. Modulus of elasticity by the static method.

The second part of the study included the following determinations by dynamic method:

1. Velocity of sound.
2. Modulus of elasticity.
3. Modulus of rigidity.
4. Poisson's ratio.

This report presents in detail the data obtained from these tests and also includes brief descriptions of the test methods.

2. DESCRIPTION OF SAMPLES

Four samples of granite and one sample of gabbro varying in size from 15 in. to 18 in. cubes were received from the Naval Proving Ground, Dahlgren, Virginia.

The first step in the preparation of the test specimens was to identify the rift direction[1/] in each sample. This was done by careful visual examination of the various surfaces of each sample.

The plane parallel to the rift direction was designated as plane "c" for each sample. One of the planes perpendicular to "c" was designated as plane "a". The plane perpendicular to both "c" and "a" was designated as plane "b". Figure 1 shows the location of rift direction and planes for each sample. Test specimens that were cut from any one sample and plane were numbered consecutively. The designations of the samples in this report are those used by the sponsor.

3. PHYSICAL TESTS: FIRST PART

3.1 Flexural strength

3.1.1 Test specimens

The test specimens were 4- by 8- by 2 1/4 in. and resembled a common building brick in shape and size. By means of a 22-in. diameter diamond-rimmed cutting wheel, three bricks were cut out of each of planes "a", "b", and "c", making a total of nine specimens tested for each sample. As shown in figure 2, the two

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1/ Rift is defined as the microscopic foliation along which the rock splits more easily than in any other direction.

bricks cut from plane "a" have the rift in a perpendicular direction (on edge) and one brick in a parallel direction with respect to the direction of loading in the flexure test. Of the three bricks cut from plane "b", two have the rift in the parallel direction and one in the perpendicular direction (on edge) with respect to the direction of loading in the flexure test. The three bricks cut from the "c" plane have the rift in perpendicular direction with respect to the direction of loading in the test. Following the cutting operation, the bricks were ground with No. 80 silicon carbide on a motor driven cast iron lap until all sides of each specimen were flat and opposite sides parallel.

3.1.2 Test procedure

After the specimens were dried for 24 hr at 105°C ± 2° and cooled to room temperature, they were tested in a Baldwin-Southwark 60,000-lb hydraulic testing machine. The specimen was laid flatwise on supporting knife edges spaced 7 in. apart and equidistant from the loading knife edge with all three knife edges parallel. (Figures 2b and 3). The load was applied at approximately 1000 lb per min until failure occurred.

A detailed description of the test method is given in ASTM Standards, 1955, C99-52, Modulus of Rupture of Natural Building Stone, page 1126.

3.1.3 Test results

The modulus of rupture of each specimen was calculated as follows:

$$R = \frac{3\ WL}{2\ bd^2}$$

where,

R = modulus of rupture
W = breaking load ~~in~~ lb
L = length of span ~~in~~ in.
b = width of specimen, ~~in~~ in.
d = thickness of specimen ~~in~~ in.

Table 1 gives the flexural strengths for all five samples, each tested in three mutually perpendicular directions of the rock.

3.2 Compressive strength

3.2.1 Test specimens

The test specimens consisted of cylinders 2 in. in diameter and approximately 2 1/4 in. high. Using a diamond core drill, five cores were cut out of each of planes "a", "b" and "c" making a total of 15 specimens tested for each sample. For convenience in preparation the test specimens were cored from the halves of bricks remaining after the flexure tests. As shown in figure 4a, the cores cut from planes "a" and "b" have the rift in the parallel direction with respect to the direction of the compressive load.

The ends of the test specimens were ground and polished until they were flat, parallel to each other, and perpendicular to the long dimension of the core.

3.2.2 Test procedure

After the specimens were dried in an oven at $105^{\circ}C \pm 2^{\circ}$ for 24 hr and cooled to room temperature, they were tested on a Tinius Olsen 200,000 lb capacity four screw mechanical machine. A specially designed spherically seated bearing block for use with a 2-in. specimen supported the specimen under test. Disks of hardened polished steel, 2 1/2 in. in diameter and 1/2 in. thick were placed between the ends of the specimen and the bearing plates. The load was applied at a rate of 100 lb per sq in. per sec until failure occurred. (Figures 4b, 5).

A detailed description of this method is given in ASTM Standards, 1955, C170-50, Compressive Strength of Natural Building Stone, page 1123.

3.2.3 Test results

The compressive strength of each specimen was calculated as follows:

$$C = \frac{W}{A}$$

where,

C = compressive strength of the specimen

W = ~~total~~ load ~~in lb~~ on the specimen

A = calculated area of bearing surface ~~in~~ sq in.

Table 2 gives the compressive strengths for all five samples each tested in three directions of the rock.

3.3 Shearing strength

3.3.1 Test specimens

The specimens were rectangular slabs 4- by 6- by 1-in. Three specimens were cut out of each of planes "a", "b" and "c" making a total of nine specimens tested for each sample. As shown in figure 6a, the six specimens cut from planes "a" and "b" have the rift in a parallel direction with respect to the direction of the load, while the specimens cut from plane "c" have the rift in a perpendicular direction. The faces of the specimens were ground with No. 80 silicon carbide on a cast iron lap until they were flat and parallel.

3.3.2 Test procedure

After the specimens were dried in an oven at 105°C ± 2° for 24 hr and cooled to room temperature, they were tested in a Baldwin Southwark 60,000 lb capacity hydraulic machine, with the aid of a special shear punching device (figures 6, 7). This device consists essentially of a base plate carrying two vertical guide rods and a 2-in. diameter plunger provided with a spherically seated bearing block at the bottom and a loading table at the top. A heavy coil spring supports the loading table and plunger at a convenient distance above the base plate while the specimen is placed in position. In making the tests, the load necessary to compress the spring until the plunger makes contact with the specimen is determined and subtracted from the load required to punch out a 2-in. disk.

3.3.3 Test results

The shearing strength of each specimen was computed by the formula:

$$S = \frac{P}{2\pi t}$$

where P is the total load minus the load required to compress the spring, and t is the thickness of the specimen.

Table 3 gives the shearing strength for all five samples each tested in three directions of the rock.

3.4 Porosity

In order to determine porosity it was first necessary to determine the bulk density and true density values.

3.4.1 Bulk density

3.4.1.1 Test specimens and procedure

Five cylindrical specimens of the same size as those used for the compression test and selected from different sections of the rock so as to represent the sample, were tested for bulk density. After drying for 24 hr at 105°C ± 2°, and cooled to room temperature in a desiccator the specimens were first weighed in air to the nearest 0.01 gm and after soaking in distilled water for 48 hr, were weighed suspended in water.

3.4.1.2 Test results

The bulk density values were computed by the formula:

$$\text{Bulk density} = \frac{A}{B - C}$$

where,

A = weight of the oven dried specimen

B = weight of the soaked and surface-dried specimen in air, and

C = weight of the soaked specimen in water

Bulk density results are given in table 4.

3.4.2 True density

3.4.2.1 Test specimens and procedure

True density determinations were made on 55 gm samples by determining the volumes with Le Chatelier flasks. First, about 400 gm of fragments for each sample of rock were selected from specimens used in the shear strength test. These pieces were ground in an iron mortar until all of the samples passed a No. 100 sieve. The powdered material was then dried in a large shallow tray for 24 hr at 105°C ± 2° and after being

cooled in a desiccator was stored in sealed glass jars until tested.

Although many precautions are necessary to maintain the accuracy and precision of this test, briefly, the method consists of taking an initial reading of a volume of kerosene in the Le Chatelier flask, adding the 55.00 gm of sample, followed by a final volume reading of the liquid, (figure 8). Each test was made over a 24 hr period at constant temperature, the latter never varying more than 0.1°C between the first and last volume readings.

3.4.2.2 Test results

The difference between the first and final readings taken on the Le Chatelier flask, represents the volume of liquid displaced by the weight of sample used in the test. The true density is calculated as follows:

$$\text{True density} = \frac{\text{weight of sample in gm}}{\text{displaced volume in m}\ell}$$

Table 4 gives the true density values for the five samples of rock. Three determinations were made for each sample.

3.4.2.3 Porosity calculations

Porosity values (table 4) were computed from the bulk density and true density values by the formula:

$$P = \frac{D_a - D_b\ (100)}{D_a}$$

where D_a and D_b are respectively the true density and bulk density. This method gives the total pore space regardless of whether the pores are open or closed.

Complete descriptions of bulk density, true density, and porosity tests are given in ASTM Book of Standards, 1955, part 3, page 1120.

3.5 Toughness - or impact resistance

3.5.1 Test specimens

The specimens were cylinders, 1-in. in diameter and 1-in. high. Nine specimens were cored out of each of planes "a", "b", and "c", making a total of 27 specimens for each rock sample. The 18 specimens cut from planes "a" and "b" have the rift parallel with respect to the direction of the impact load, while the specimens cut from plane "c" have the rift perpendicular with respect to the direction of the load. The ends of the specimens were ground with a No. 80 silicon carbide on a cast iron lap until they were flat and parallel.

3.5.2 Test procedure

After the specimens were dried in an oven at 105°C ± 2° for 24 hr and cooled to room temperature they were tested on a Page impact apparatus (figures 6a, 9). In this apparatus the specimen is mounted on a heavy cast iron base. A steel plunger with the lower end rounded rests on the specimen, and a 2 kg weight is dropped on the plunger by a motor driven sprocket chain. The height of the first drop is 1 cm and each succeeding drop is increased by 1 cm. Since the force of the impact is concentrated on the center of the specimen by hemispherical contact of the plunger, the specimen usually breaks in three or four approximately equal segments.

3.5.3 Test results

Table 5 gives the toughness values for all five samples tested in three directions of the rock. The values indicate the maximum height in cm of the 2 kg plunger just before the specimen fails.

This test is described in ASTM Standards, 1955, Part 3, p. 1239.

3.6 Summary of test results (sections 3.1 to 3.5)

Table 7 gives a summary of the average values obtained for all samples, for flexural, compressive and shearing strengths, bulk density, true density, porosity, and tough-

3.7 Modulus of elasticity - static method

3.7.1 Test specimens

The test specimens consisted of one compressive test specimen from each sample (Sec. 3.2.1). The rift direction in all five specimens was parallel to the direction of the applied load. Bonded wire rosette strain gages were cemented on opposite sides of each specimen with an epoxy resin cement. The specimens were placed in a 60°C oven for about 12 hr after the cement had cured for about 8 hr at room temperature. The specimens were allowed to reach an equilibrium temperature in the testing laboratory before the test was started.

3.7.2 Test procedure

The test specimens were loaded as described in Sec. 3.2.2 except that the loading rate was about 75 lb per sq in. per sec while strain measurements were being made. (Figure 10).

Opposite gages were connected in series so that all readings gave average values of the strain at 180° points on the specimen.

Measurements were made of the vertical and the circumferential strains in order to compute static values of Poisson's ratio.

3.7.3 Test results

All strain values were corrected for the effect of the interaction between the elements of the rosette gages by using an auxiliary factor provided by the manufacturer. Poisson's ratio was computed from the ratio of circumferential to the vertical strains. The modulus of elasticity was determined from the slopes of the tangents to the stress-strain curves.

Test results are plotted as stress-strain curves (figure 11).

Since the values of the modulus of elasticity increase as the stress increases two values of each are given in the table of results (table 7). The first value of the modulus of elasticity given is the minimum value of each as estimated from the slope of the initial tangent. The second value given is for the tangent drawn at a point corresponding to two thirds the maximum stress.

4. PHYSICAL TESTS: SECOND PART
(Sonic Methods)

4.1 Test specimens

The test specimens used in the sonic measurements were the flexural specimens described in Section 3.1.1.

4.2 Test procedure

The procedures followed were essentially those as outlined in ASTM C215-55T; Tentative method of test for fundamental transverse, longitudinal, and torsional frequencies of concrete specimens. Figure 12 is a photograph showing the equipment with a test specimen in position for the determination of a flexural (transverse) resonant frequency.

4.3 Velocity of sound, dynamic modulus of elasticity, modulus of rigidity, and Poisson's ratio.

4.3.1 Velocity of sound

The velocity of sound through the specimens was computed using the relation:

$$V = 2n\ell$$

where n = fundamental longitudinal frequency

ℓ = length of the specimen

Since Rayleigh's correction for these specimens was only about 0.5 percent, no corrections were made for shape.

4.3.2 Dynamic modulus of elasticity

4.3.2.1 Longitudinal vibrations

Dynamic modulus of elasticity (E_D) was computed using the relation:

$$E_D = V^2\rho$$

where V = velocity of sound from Sect. 4.3.1

ρ = weight/in.^{3}/g , $g = 386$ in./sec^2

4.3.2.2 Flexural (transverse) vibrations

Dynamic modulus of elasticity was computed using the relation:

$$E_D = CWn^2$$

where W = weight of specimen

C = shape factor which is also a function of Poisson's ratio

n = fundamental flexural frequency

The factor C was determined from the relation:

$$C = .00245 \frac{L^3 T}{b\ t^3}, \quad sec^2 \text{ per in.}^2$$

L = length of specimen in in.

t,b = dimensions of cross-section of specimen in in., t being in the direction in which it is being driven.

T = values as obtained by interpolation from a table given by Gerald Pickett in his paper "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders," Proc. ASTM, Vol. 45, page 846.

Since the value of C depends on the value of Poisson's ratio and since there is some question regarding the correct value of Poisson's ratio for these samples, the values obtained for E_D by flexural vibrations cannot be considered as precise as the values obtained from the longitudinal vibrations.

Two values of flexural E_D were obtained for each specimen by vibrating the specimens in two directions.

4.3.3 Modulus of rigidity (Modulus of elasticity in shear)

Dynamic modulus of rigidity G was computed using the relation:

$$G = B\ W n^2_t$$

where

B = shape factor value computed from relations developed by Pickett in his paper mentioned in Section 4.3.2.

n_t = fundamental torsional frequency

W = weight of specimen

4.3.4 Poisson's ratio

Poisson's ratio μ was computed from the dynamic moduli of elasticity and rigidity using the relation:

$$\mu = \frac{E_D}{2\ G} - 1$$

Negative values of Poisson's ratio were obtained for all specimens in which the rift was perpendicular to the specimen length with the exception of the G-1 sample which showed positive values for all specimens.

4.4 Test results

Table 8 gives the test values for velocity of sound, dynamic modulus of elasticity, modulus of rigidity, and Poisson's ratio for all specimens tested. Table 9 gives the average values for the same properties for the five samples of rock.

Table 1. Flexural strength.

Designation of sample	~~Flexural~~ strength	
	Parallel to bed	Perpendicular to bed
	psi	psi
<u>Sample No. 1-1</u>		
3 specimens cut from:		
Plane a	1,400	2,100* 1,900*
Plane b	1,400 1,400	2,500*
Plane c		2,500 2,500 2,500
<u>Sample No. 1-2</u>		
3 specimens cut from:		
Plane a	1,300	2,500* 2,400*
Plane b	1,400 1,500	2,500*
Plane c	--	2,000 2,000 2,000
<u>Sample No. 2-1</u>		
3 specimens cut from:		
Plane a	1,200	2,000* 1,900*
Plane b	1,100 1,100	1,900*
Plane c		1,700 1,500 1,500

Table 1. Flexural strength (continued).

Designation of sample	Flexural strength	
	Parellel to bed	Perpendicular to bed
	psi	psi
<u>Sample No. 2-2</u>		
3 specimens cut from:		
Plane a	1,400 1,100	2,300*
Plane b	1,000	2,000* 1,900*
Plane c	--	1,900 1,600 2,000
Sample G-1		
3 specimens cut from:		
Plane a	4,400	4,000* 4,100*
Plane b	4,000 3,800	4,200*
Plane c		3,900 3,800 4,000

*Perpendicular to bed on edge; (see figure 2).

Table 2. Compressive strength.

Designation of sample	Compressive strength — Specimens cut from: plane "a" tested parallel to bed	plane "b" tested parallel to bed	plane "c" tested perpendicular to bed
	psi	psi	psi
No.1-1			
15 specimens	30,700	30,400	34,800
	30,300	28,400	30,400
	29,800	26,500	31,500
	30,700	27,500	34,900
	32,900	31,500	28,900
Avg.	30,900	28,900	32,100
No.1-2			
15 specimens	28,900	33,400	30,700
	28,600	25,000	40,300
	32,800	36,000	34,100
	33,600	30,000	28,800
	33,900	36,700	30,000
Avg.	31,600	32,200	32,800
No.2-1			
15 specimens	24,800	25,800	25,000
	25,000	23,900	25,000
	26,100	24,800	22,800
	24,500	24,900	23,600
	25,900	24,700	25,200
Avg.	25,300	24,800	24,300

Table 2. Compressive strength (continued).

Designation of sample	Compressive strength — Specimens cut from: plane "a" tested parallel to bed	plane "b" tested parallel to bed	plane "c" tested perpendicular to bed
	psi	psi	psi
No.2-2			
14 specimens	27,600	26,600	28,600
	22,500	25,400	29,600
	25,100	25,000	25,800
	26,600	28,000	24,400
	26,600	25,300	---
Avg.	25,700	26,100	27,100
No.G-1			
15 specimens	53,500	49,200	49,300
	54,100	48,700	52,000
	52,500	52,600	44,700
	51,800	55,400	54,600
	52,500	51,800	55,400
Avg.	52,900	51,500	51,200

Table 3. Shearing strength.

Designation of sample	Shearing strength Specimens cut from: plane "a" tested parallel to bed	plane "b" tested parallel to bed	plane "c" tested perpendicular to bed
	psi	psi	psi
No. 1-1 9 specimens	4,700 6,000 5,600	5,000 6,100 4,900	6,400 5,400 6,000
Avg.	5,400	5,300	5,900
No. 1-2 9 specimens	5,700 5,400 5,900	6,800 7,200 6,700	7,900 7,900 6,400
Avg.	5,700	6,900	7,400
No. 2-1 9 specimens	5,800 6,100 4,800	5,200 5,000 5,100	5,600 6,600 6,800
Avg.	5,600	5,100	6,300
No. 2-2 9 specimens	3,000 2,900 3,000	2,800 2,800 3,100	2,800 3,000 4,300
Avg.	3,000	2,900	3,400
No. G-1 9 specimens	7,200 9,600 7,500	8,700 8,300 9,300	8,900 8,000 8,600
Avg.	8,100	8,800	8,500

Table 4. Bulk density, true density and porosity.

Designation of sample	Bulk density	True density	Porosity
			percent
No. 1-1	2.618	2.652	
	2.617	2.656	
	2.618	2.653	
	2.617		1.39
	2.616		
Avg.	2.617	2.654	
No. 1-2	2.603	2.635	
	2.605	2.634	
	2.603	2.635	1.18
	2.603		
	2.605		
Avg.	2.604	2.635	
No. 2-1	2.628	2.654	
	2.629	2.648	
	2.628	2.652	0.91
	2.623		
	2.626		
Avg.	2.627	2.651	
No. 2-2	2.631	2.648	
	2.632	2.648	
	2.626	2.648	0.72
	2.629		
	2.627		
Avg.	2.629	2.648	
No. G-1	3.030	3.042	
	3.036	3.044	
	3.033	3.042	0.33
	3.032		
	3.032		
Avg.	3.033	3.043	

Table 5. Toughness (Impact Hardness).

Designation of sample	Toughness — Specimens cut from: plane "a" tested parallel to bed	plane "b" tested parallel to bed	plane "c" tested perpendicular to bed
	Height of drop at failure (cm)		
No. 1-1 27 specimens	12, 10, 10 7, 12, 8 10, 11, 10	11, 12, 9 11, 11, 11 10, 11, 11	11, 11, 13 11, 13, 14 11, 10, 11
Avg.	10	11	12
No. 1-2 27 specimens	10, 10, 9 10, 10, 12 12, 11, 10	11, 11, 9 10, 10, 9 11, 14, 13	13, 11, 13 11, 12, 11 12, 13, 13
Avg.	10	11	12
No. 2-1 27 specimens	7, 7, 7 8, 6, 8 4, 7, 8	7, 7, 7 7, 6, 7 6, 7, 7	9, 9, 9 9, 10, 8 10, 9, 10
Avg.	7	7	9
No. 2-2 27 specimens	5, 5, 7 6, 6, 3 4, 6, 6	8, 6, 6 7, 6, 7 6, 5, 7	7, 8, 8 9, 10, 9 8, 9, 8
Avg.	5	6	8
No. G-1 27 specimens	24, 21, 23 26, 28, 24 20, 24, 24	24, 21, 24 25, 26, 23 24, 21, 27	20, 24, 25 24, 21, 23 23, 22, 22
Avg.	24	24	23

Table 6. Summary of test results (average values).

Property	Direction of test	Sample No. 1-1	1-2	2-1	2-2	G-1
Flexural strength psi	parallel to bed	1,400	1,400	1,100	1,200	4,100
	perpendicular to bed	2,500	2,000	1,600	1,800	3,900
	" to bed on edge	2,200	2,500	1,900	2,100	4,100
Compressive strength psi	parallel to bed	29,900	31,900	25,000	25,900	52,200
	perpendicular to bed	32,100	32,800	24,300	27,100	51,200
Shearing strength psi	parallel to bed	5,400	6,300	5,400	3,000	8,400
	perpendicular to bed	5,900	7,400	6,300	3,400	8,500
Bulk density	---	2.617	2.604	2.627	2.629	3.033
True density	---	2.654	2.635	2.651	2.648	3.043
Porosity %	---	1.39	1.18	0.91	0.72	0.33
Toughness or impact hardness (height of drop at failure)	parallel to bed	10	10	7	6	24
	perpendicular to bed	12	12	9	8	23

Table 7. Static stress-strain determinations.

Sample No.	Minimum value (estimated from initial tangent) E 1/ 10^6 psi	Values at 2/3 maximum stress		Maximum stress psi
		E 1/ 10^6 psi	Poisson's ratio	
1-1	3.8	8.7	+.20	30,700
1-2	4.2	9.4	+.17	29,000
2-1	3.5	9.4	+.25	26,800
2-2	3.4	8.5	+.24	22,500
G-1	9.4	15.1	+.22	51,800

1/ E = Modulus of elasticity

Table 8. Physical tests - sonic methods (all specimens).

Sample No.	Specimen	Cut from plane 1/	Longitudinal vibrations: Directions of vibrations and rift	Longitudinal vibrations: V_L 10^4 in./sec 2/	Longitudinal vibrations: E_L 10^6 psi 3/	Flexural vibrations: Directions of vibrations and rift	Flexural vibrations: E_{FE} edge 10^6 psi 4/	Flexural vibrations: E_{FF} flat 10^6 psi 5/	E_D average 10^6 psi 6/	G 10^6 psi 7/	Poisson's ratio 8/
1-1	1	a	⊥	99.7	2.44	//	2.54	2.61	2.53	1.51	-.16
	2	a	//	130.4	4.16	⊥	4.05	4.28	4.16	1.61	.29
	3	a	//	129.6	4.13	⊥	4.00	4.29	4.14	1.60	.29
	4	b	⊥	99.8	2.44	//	2.64	2.54	2.54	1.61	-.21
	5	b	⊥	100.0	2.45	//	2.65	2.55	2.55	1.59	-.20
	6	b	//	143.2	5.02	⊥	4.75	5.09	4.95	1.76	.41
	7	c	//	143.0	5.00	⊥	5.19	4.99	5.06	1.95	.29
	8	c	//	146.0	5.25	⊥	5.17	5.02	5.15	2.00	.29
	9	c	//	145.0	5.14	⊥	5.18	4.91	5.08	1.94	.31
1-2	1	a	//	144.2	5.54	⊥	4.90	5.25	5.23	1.68	.56
	2	a	//	144.7	5.56	⊥	4.80	5.16	5.21	1.62	.61
	3	a	⊥	92.7	2.28	//	2.30	2.19	2.26	1.54	-.27
	4	b	//	145.3	5.57	⊥	4.85	5.09	5.17	1.69	.53
	5	b	⊥	96.8	2.51	//	2.43	2.41	2.45	1.48	-.17
	6	b	⊥	96.9	2.51	//	2.43	2.43	2.46	1.52	-.19
	7	c	//	133.9	4.77	⊥	4.52	4.26	4.52	1.91	.18
	8	c	//	133.5	4.75	⊥	4.49	4.50	4.58	1.90	.20
	9	c	//	130.0	4.50	⊥	4.50	4.34	4.45	1.90	.17
2-1	1	a	//	139.3	4.76	⊥	4.51	4.75	4.67	1.76	.33
	2	a	//	142.2	4.95	⊥	4.64	4.90	4.83	1.93	.25
	3	a	//	132.5	4.33	⊥	4.25	4.50	4.36	1.84	.19
	4	b	⊥	109.5	2.93	//	3.12	3.13	3.06	1.72	-.11
	5	b	⊥	101.2	2.52	//	2.69	2.69	2.63	1.54	-.15
	6	b	⊥	101.4	2.54	//	2.71	2.72	2.66	1.55	-.14
	7	c	//	136.6	4.57	⊥	4.67	4.61	4.62	1.80	.22
	8	c	//	125.7	3.88	⊥	4.08	3.92	3.96	1.87	.06
	9	c	//	124.7	3.80	⊥	3.97	3.83	3.87	1.83	.06

Table 8. Physical tests - sonic methods (all specimens). (continued)

Sample No.	Specimen	Cut from plane 1/	Longitudinal vibrations: Directions of vibrations and rift	Longitudinal vibrations: V_L 10^4 in./sec 2/	Longitudinal vibrations: E_L 10^6 psi 3/	Flexural vibrations: Directions of vibrations and rift	Flexural vibrations: E_{FE} edge 10^6 psi 4/	Flexural vibrations: E_{FF} flat 10^6 psi 5/	E_D average 10^6 psi 6/	G 10^6 psi 7/	Poisson's ratio 8/
2-2	1	a	⊥	115.6	3.29	//	3.63	3.43	3.45	1.91	-.10
	2	a	⊥	100.6	2.49	//	2.80	2.70	2.66	1.54	-.14
	3	a	//	149.8	5.46	⊥	5.40	5.56	5.47	1.97	.39
	4	b	//	146.2	5.26	⊥	5.34	5.39	5.33	1.81	.47
	5	b	//	139.0	4.75	⊥	4.56	4.90	4.74	1.61	.47
	6	b	⊥	105.4	2.68	//	3.07	2.96	2.90	1.61	-.10
	7	c	//	140.7	4.87	⊥	4.80	4.61	4.76	1.85	.29
	8	c	//	130.8	4.18	⊥	4.53	4.11	4.27	2.01	.06
	9	c	//	142.7	5.02	⊥	5.07	4.98	5.02	1.90	.32
G-1	1	a	//	208.4	12.26	⊥	12.15	12.31	12.24	5.18	.18
	2	a	//	209.7	12.46	⊥	12.25	12.45	12.39	5.25	.18
	3	a	⊥	197.0	10.96	//	11.18	11.22	11.12	4.89	.14
	4	b	//	217.2	13.40	⊥	13.35	13.45	13.40	5.29	.27
	5	b	⊥	202.3	11.53	//	11.80	11.77	11.70	5.17	.13
	6	b	⊥	201.9	11.47	//	11.67	11.64	11.59	5.12	.13
	7	c	//	212.2	12.74	⊥	12.86	12.77	12.79	5.12	.25
	8	c	//	211.0	12.59	⊥	12.72	12.66	12.66	5.09	.24
	9	c	//	213.6	12.94	⊥	13.05	12.98	12.99	5.39	.21

1/ See figure 1.
2/ V = Longitudinal velocity of sound.
3/ E_L = Dynamic modulus of elasticity from longitudinal vibrations.
4/ E_{FE} = Dynamic modulus of elasticity from flexural vibrations when driven edge wise.
5/ E_{FF} = Dynamic modulus of elasticity from flexural vibrations when driven flat wise.
6/ E_D = Average of E_L, E_{FE}, and E_{FF}
7/ G = Dynamic modulus of rigidity from torsional vibrations.
8/ From E_D and G (see text).
9/ ⊥ - perpendicular
// - parallel

Table 9. Summary of sonic test results (average values).

Sample No.	Directions of specimen length and rift	V 10^4 in./sec	E_D 10^6 psi	G 10^6 psi	Poisson's ratio
1-1	perpendicular	99.8	2.54	1.57	-.19
1-1	parallel	139.5	4.76	1.81	+.31
1-2	perpendicular	95.5	2.39	1.51	-.21
1-2	parallel	138.6	4.86	1.78	+.38
2-1	perpendicular	104.0	2.78	1.60	-.13
2-1	parallel	133.5	4.38	1.84	+.18
2-2	perpendicular	107.2	3.00	1.69	-.11
2-2	parallel	141.5	4.93	1.86	+.33
G-1	perpendicular	200.4	11.47	5.06	+.13
G-1	parallel	212.0	12.75	5.22	+.22

V = Longitudinal velocity of sound.

E_D = Dynamic modulus of elasticity.

G = Modulus of rigidity.

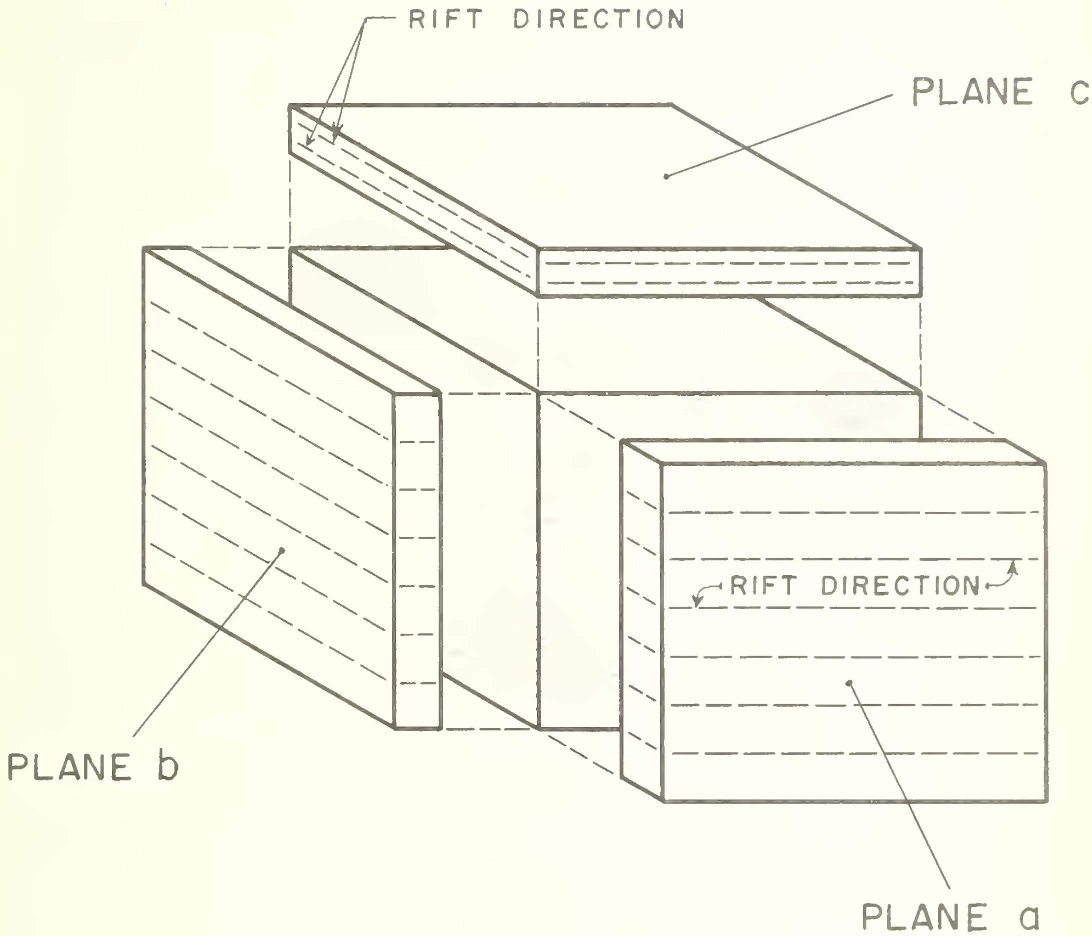

FIGURE 1. DIAGRAM SHOWING LOCATION OF RIFT AND DESIGNATION OF PLANES FOR EACH SAMPLE OF ROCK TESTED.

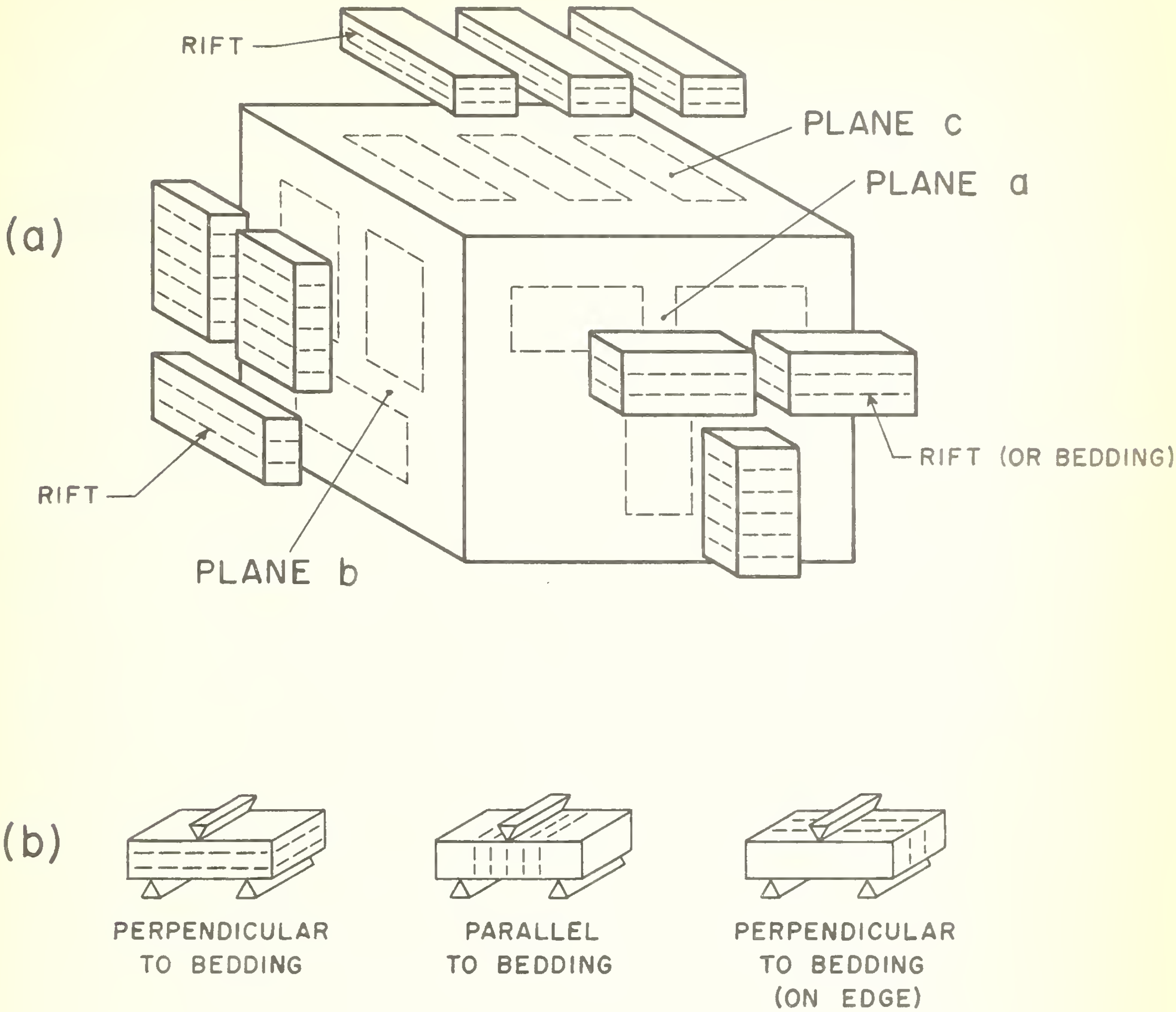

FIGURE 2 (a) DIAGRAM SHOWING HOW FLEXURE TEST SPECIMENS WERE CUT FROM PLANES a, b AND c, AND THEIR RELATIONSHIP TO RIFT DIRECTION OF SAMPLE.

(b) THE RELATIONSHIP OF RIFT DIRECTION TO DIRECTION OF LOADING IN FLEXURE TEST.

Fig. 3. Device for measuring flexural strength showing brick shaped specimen in position for test.

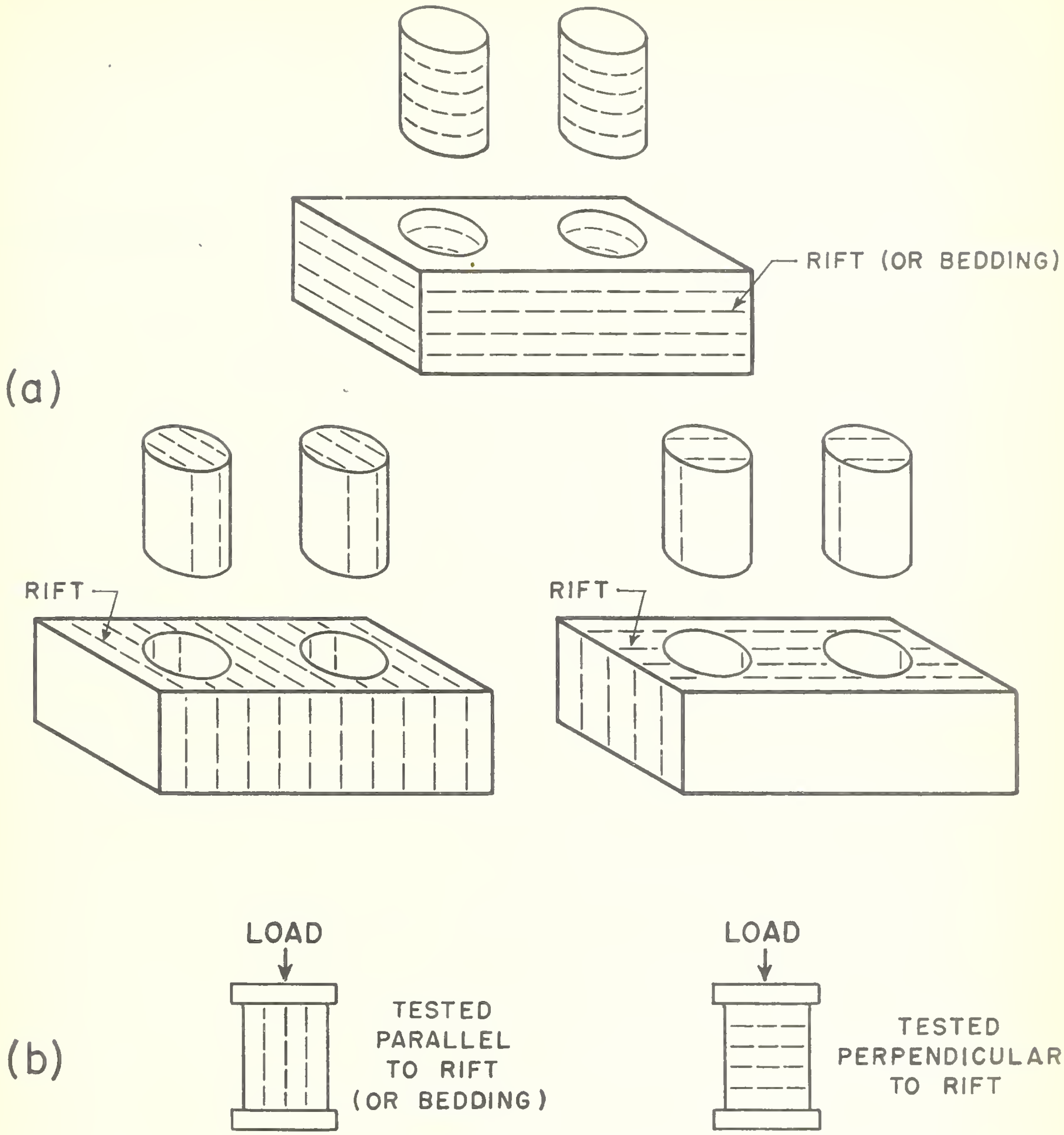

FIGURE 4 (a) DIAGRAM SHOWING HOW COMPRESSIVE TEST SPECIMENS WERE CUT FROM THE SPECIMENS USED IN THE FLEXURE TEST.

(b) THE RELATIONSHIP OF RIFT DIRECTION TO DIRECTION OF LOADING IN COMPRESSION TEST.

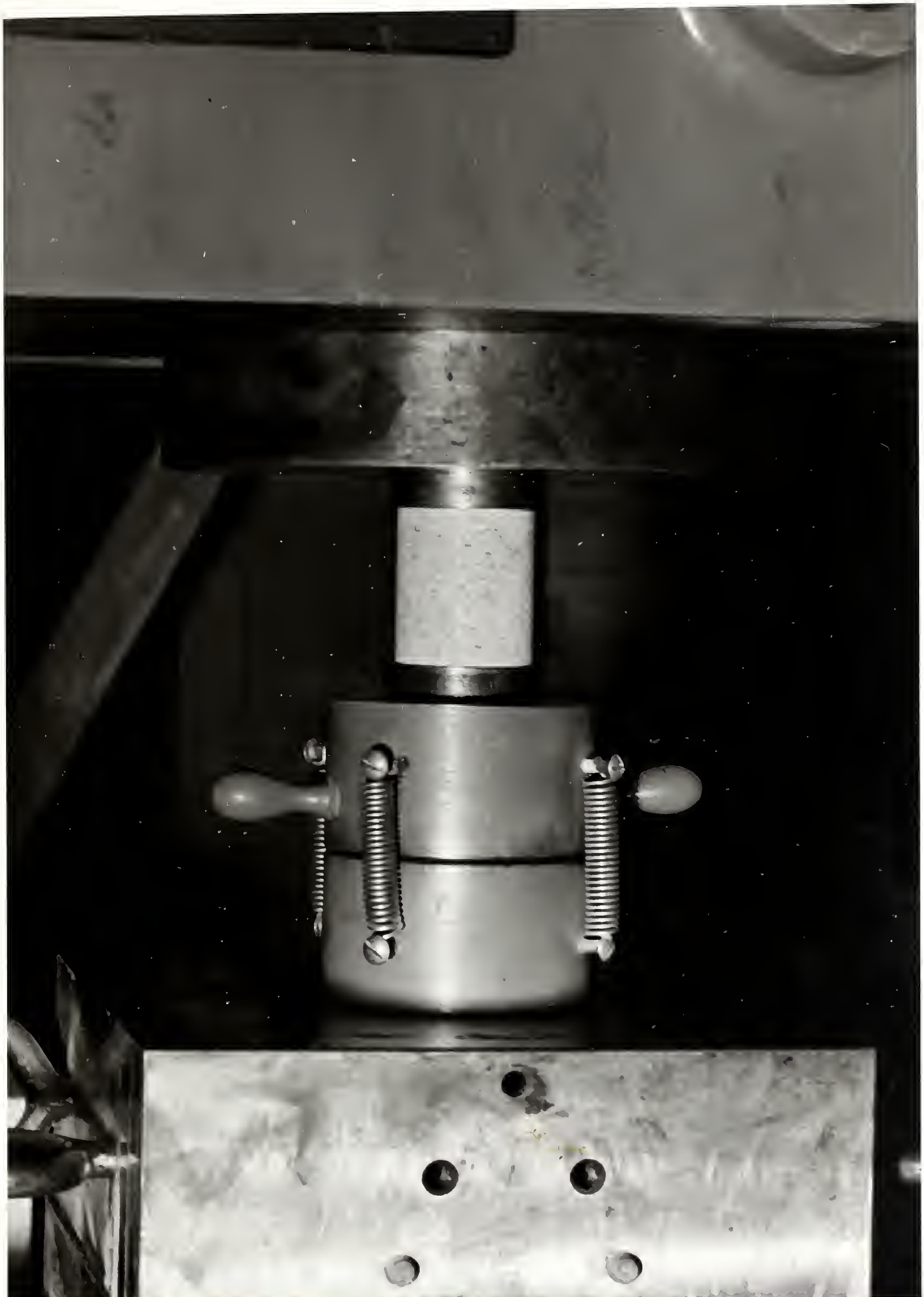

Fig. 5. Compression test, showing cylindrical specimen between 2 1/2 in. hardened steel bearing plates and specially designed spherically seated bearing block supporting the assembly.

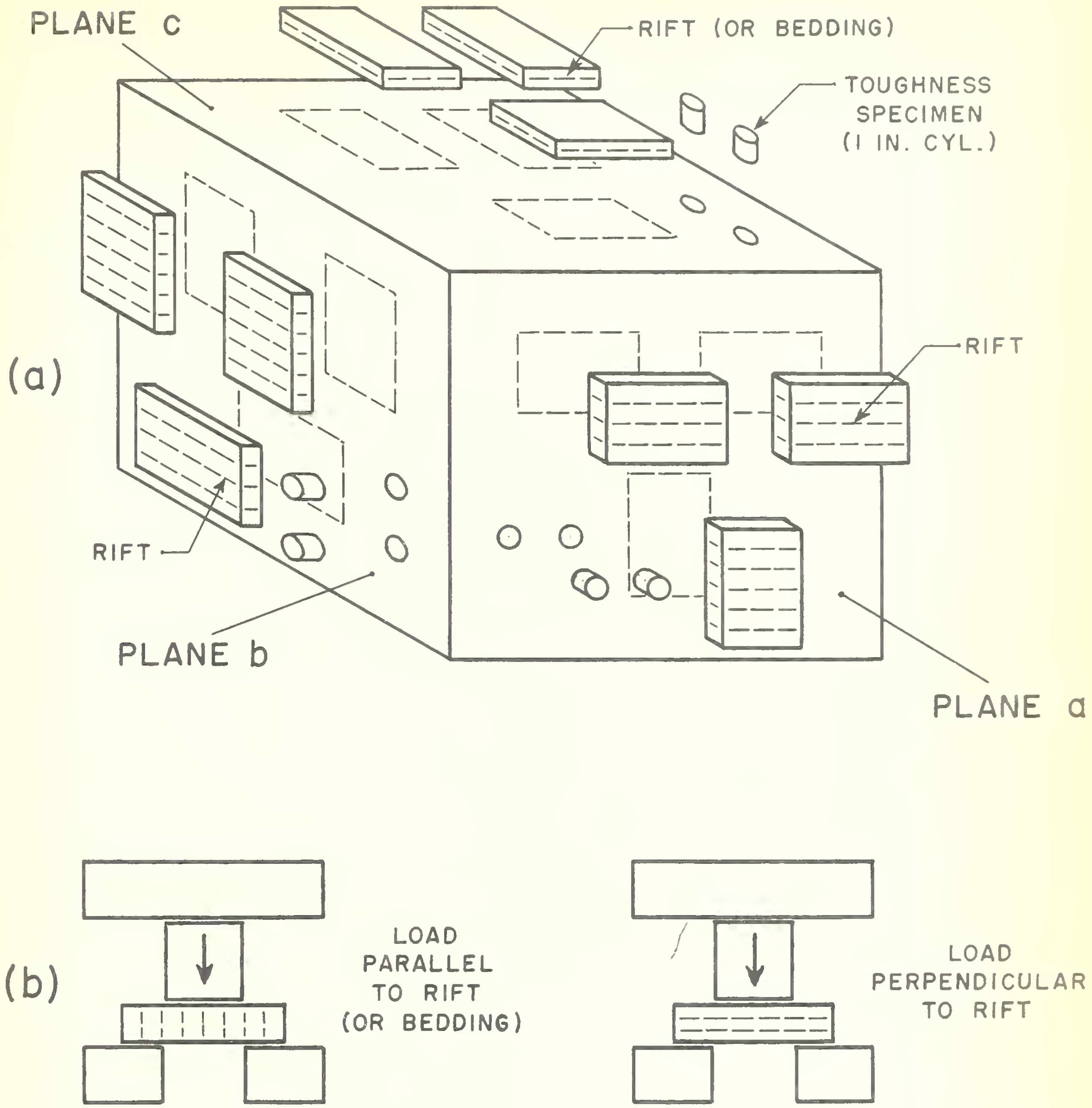

FIGURE 6 (a) DIAGRAM SHOWING HOW SHEARING AND IMPACT TEST SPECIMENS WERE CUT FROM PLANES a, b AND c, AND THEIR RELATIONSHIP TO RIFT DIRECTION OF SAMPLE.

(b) RELATIONSHIP OF RIFT DIRECTION TO DIRECTION OF LOADING IN SHEARING TEST.

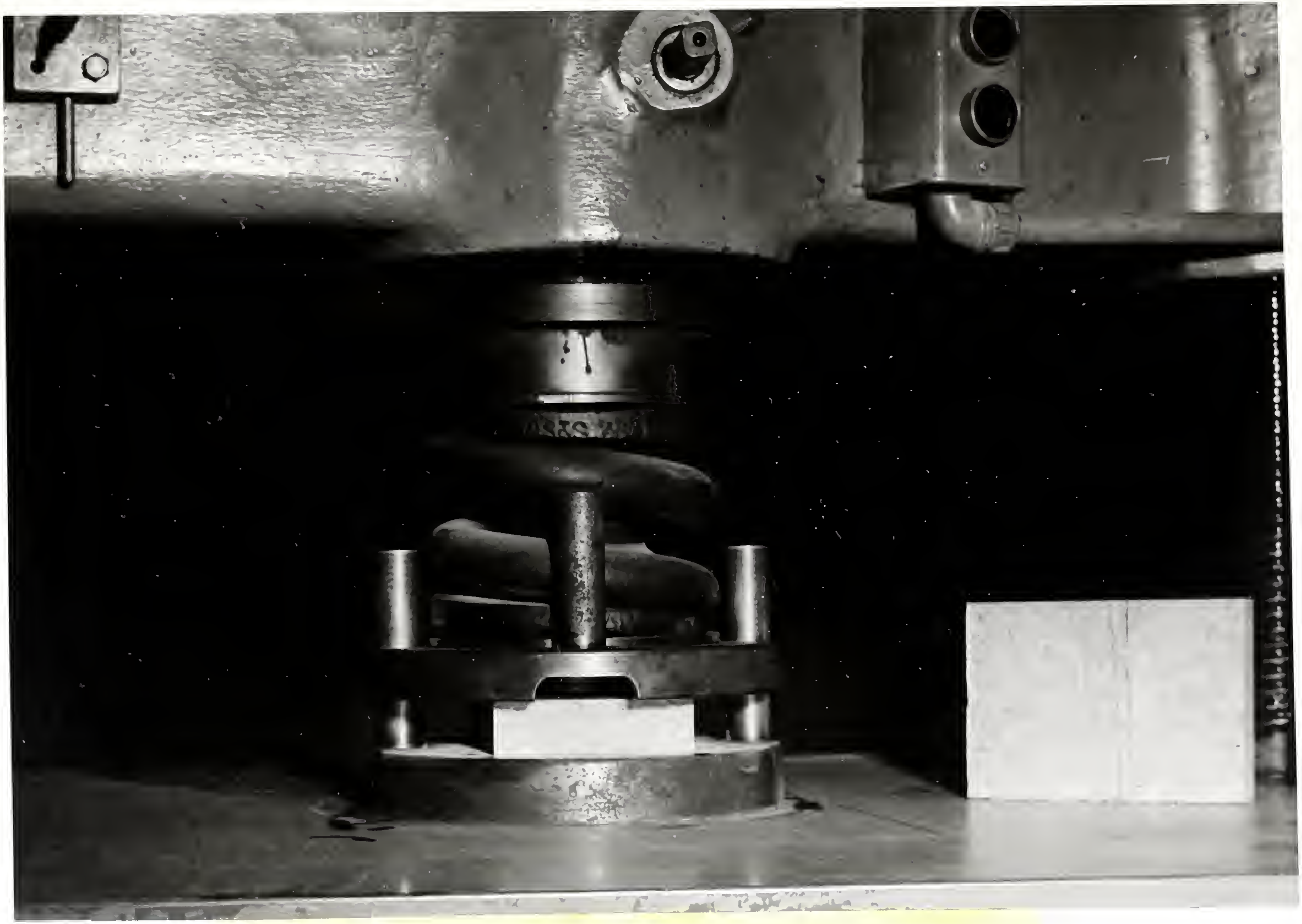

Fig. 7. Punching shear testing device with specimen in position for test.

Fig. 8. True density determination showing operator filling a Le Chatelier flask with powdered sample under test.

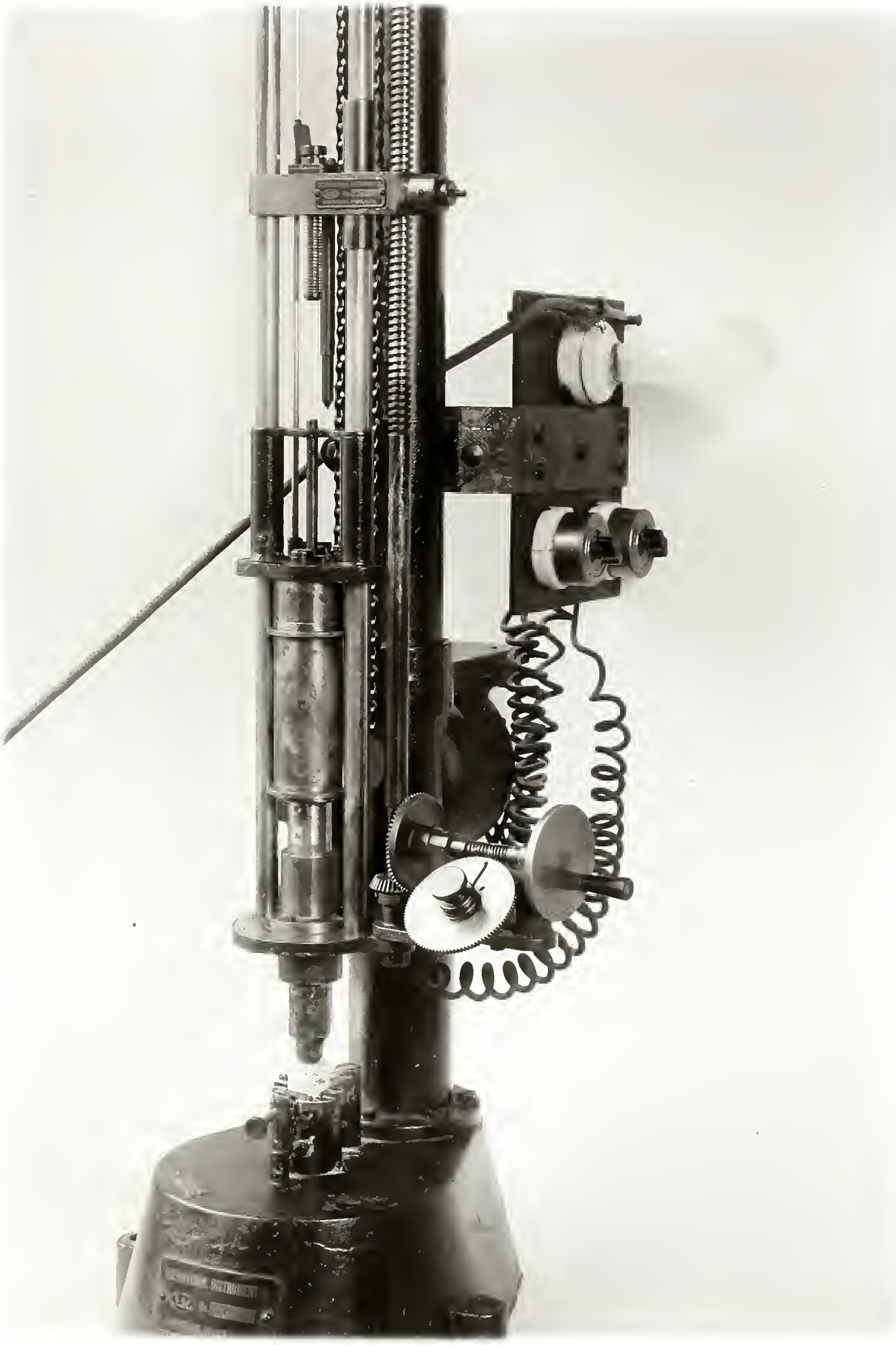

Fig. 9. Page impact toughness tester with cylindrical specimen in position for test.

Fig. 10. Test for determination of modulus of elasticity by static method, showing bonded wire strain gages and strain recorders.

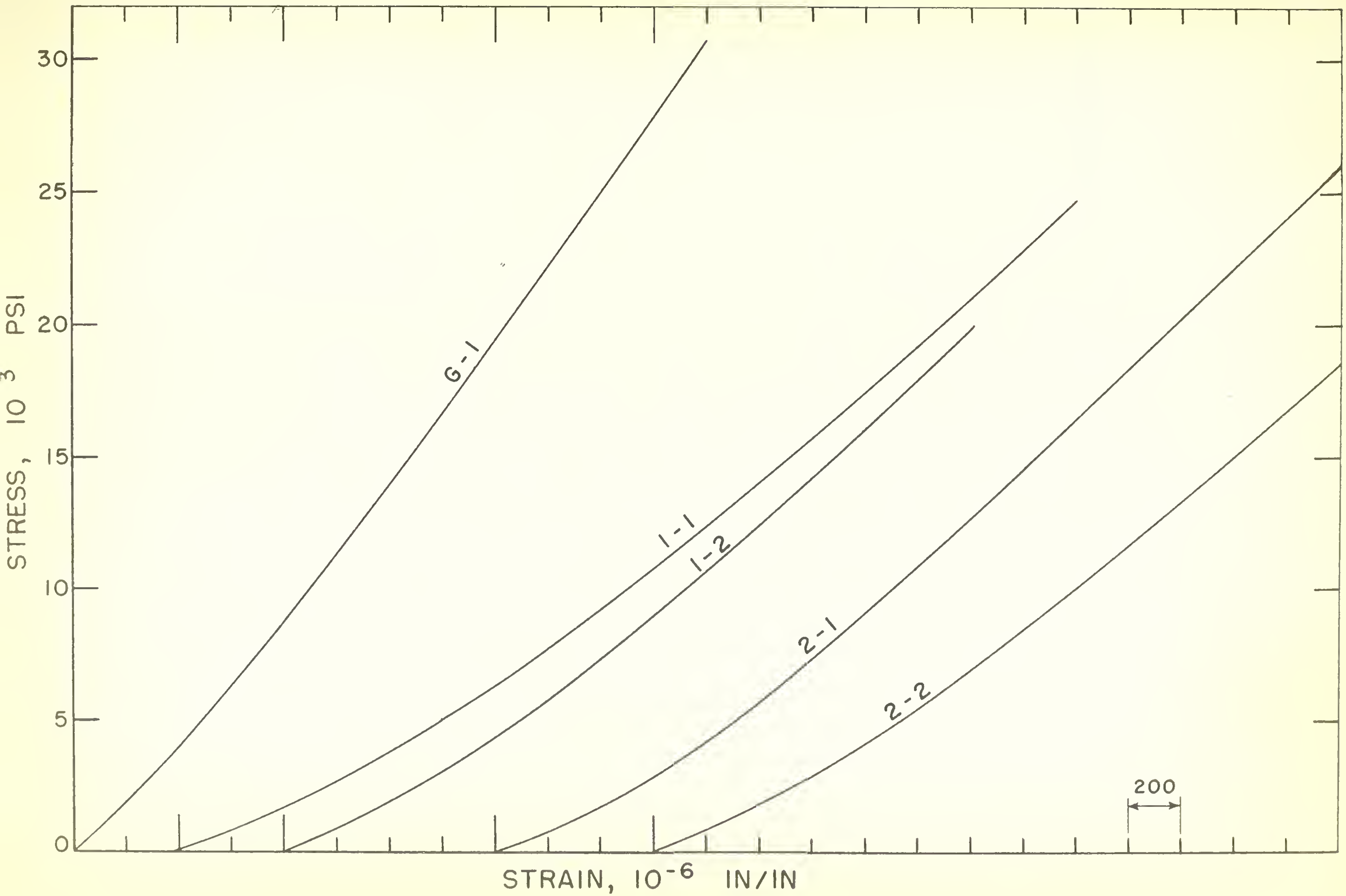

FIGURE 11. COMPRESSIVE TEST, STRESS-STRAIN CURVES

Fig. 12. Equipment used in determination of dynamic elastic properties by sonic resonance method.

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