PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

ENGINEERING PROPERTIES OF SUBMARINE CLAYS FROM THE PACIFIC

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Information regarding the geotechnical properties of deep sea submarine soils is scarce. A state-of-the-art review of the subject was presented by Noorany and Gizienski (6), and the engineering properties of two deep sea calcareous deposits were given by Noorany (8). The general distribution of the sediments covering the sea floor has been given by Shepard (10), Menard (5), and Keller (3). This paper covers the engineering properties of samples obtained from seven locations on the floor of the Pacific Ocean at water depths ranging from 2350 to 3010 fathoms (14,100 to 18,060 feet). The samples were taken for Kennecott Exploration, Inc., of California using a spade corer (7), a box 10 in. by 12 in. by 24 in., during Legs 9 and 10 of the STYX cruise on R/V Agassiz in the winter of 1968. The locations and the water depths for these samples are given in Table 1. Except for sample 9-3, which was light brown in color and contained some white calcareous particles, the rest were pelagic chocolate brown to dark brown clayey silts and silty clays with water contents ranging from 118 to 388 percent.

Index Properties

The index properties of the sediments are given in Table 2. The water contents listed are representative values--there was a considerable amount of scatter and no definite trend with depth was apparent. G_s denotes specific gravity of solids. The degrees of saturation, S, were calculated from weights and volumes; γ_d denotes dry density in pounds per cubic foot; w_L is liquid limit and I_p is plasticity index. Sample 9-3, which contained some calcareous particles, had 60% material finer than 0.076 millimeter; but, all other samples had 100% particle size finer than 0.076 millimeter. Although hydrometer tests were performed on all samples, an accurate determination of the clay fraction smaller than 2 microns proved very difficult because of a strong tendency to flocculation of the soil particles. Therefore, based on their plasticity characteristics, the sediments were classified according to the Unified System as listed in Table 2.

Samples 9-3, 9-5B, 10-1, and 10-1C, contained manganese nodules varying in size from very small particles up to 2 inch in diameter.

Table 1 - Sample Locations

Sample	Water Depth Fathoms	Location
9-1C	2950	15° 40'S, 172° 00'W; Flank valley of Tonga trench
9-2	2765	11° 55'S, 169° 32'W; Smooth plain
9-3	2350	8° 01'S, 166° 35'W; Near base of seamount
9-5A	2770	8° 36'N, 154° 37'W
9-5B	2750	Seven miles east of 9-5A
10-1	3015	23° 50.4'N, 143° 58'W; Across Molokai Fracture Zone
10-1C	3010	23° 25'N, 144° 04.7'W; Across Molokai Fracture Zone

Table 2 - Index Properties

Sample	w %	G_s	S %	γ_d pcf	w_L	I_p	Unified Classification
9-1C	133	2.73	92	36.5	110	58	MH
9-2	284	2.84	89	15.6	120	47	MH
9-3	148	2.80	100	34.0	79	19	MH
9-5A	247	2.66	96	21.1	210	114	MH
9-5B	388	2.80	99	14.6	273	181	CH
10-1	123	2.83	100	39.4	118	75	CH
10-1C	118	2.82	98	40.1	102	47	MH

Shear Strength

The undrained strength of each sample was determined by laboratory vane shear and unconsolidated-undrained triaxial compression tests. Representative shear strength values, s_u, are listed in Table 3. The strength of these deep sea floor deposits varied from 0.04 Kg/cm^2 (0.57 psi) to 0.13 Kg/cm^2 (1.9 psi). Sensitivities of 2 to 4 indicate "medium sensitivity." However, actual values might be higher since the degree of disturbance caused by sampling was unknown. The measured strength and sensitivity values agree with the available data regarding the strength of deep sea floor clays in the northern Pacific region (3, 6, 9). Two series of consolidated-undrained tests with pore pressure measurements were performed on samples 9-3 and 10-1 using a back pressure of 3.0 Kg/cm^2. The stress-strain-pore water pressure characteristics were typical of normally consolidated soft clays as shown in Fig. 6.

Table 3 - Strength Characteristics

Sample	w %	p'_o Kg/cm^2	s_u Kg/cm^2	Sensitivity	c' Kg/cm^2	ϕ'
9-1C	133	0.014	0.13	2		
9-2	284	0.01	0.05	4		
9-3	148	0.01	0.06	3	0.02	33°
9-5A	247	0.008	0.07	3.5		
9-5B	388	0.006	0.09	4		
10-1	123	0.015	0.04	2	0.02	32°
10-1C	118	0.015	0.04	2.5		

Compressibility

Consolidation tests were performed on 2.5 inch in diameter, 1 inch high samples using a load increment ratio, $\Delta p/p = 1$, starting at a low stress of about 0.02 Kg/cm^2. The duration of each load was usually about 48 hours. Data from consolidation tests are summarized in Table 4. Fig. 1 illustrates typical consolidation test results for one of the samples tested. Fig. 2 shows the data from the same test plotted in terms of compression strain versus consolidation pressure. As proposed by Janbu (2), a compression or deformation modulus, M, can be defined as follows:

$$M = dp'/d\varepsilon \qquad (1)$$

where p' is consolidation stress in one-dimensional compression and ε is strain. The available data (2) indicate that for normally consolidated Norwegian clays, M is a linear function of pressure, i.e.

$$M = mp' \qquad (2)$$

According to Janbu (2), m is less than 10 for soft clays. As listed in Table 4, the m values determined for these deep sea cohesive soils ranged from 5.40 to 8.33.

Figs. 3, 4, 5, 7, 8, 9, and 10, as well as Table 4, show that the samples had generally high void ratios and very high compression index values. However, the relationship between the natural water content and $C_c/(1+e_o)$ conformed to the range known for terrestrial or near shore marine deposits (4) as shown in Fig. 11.

Another interesting point observed from the e-Log p plots as well as Table 4 is that all of the samples tested indicated a "preconsolidation pressure," p_c, much greater than the in situ effective overburden pressure, p'_o. This apparent overconsolidation or "quasi-preconsolidation" is a typical phenomenon in submarine cohesive sediments and appears to be primarily due to prolonged secondary compression and possibly some chemical bonding of particles under extremely low rates of sediment deposition (1, 6). As the typical time-rate of compression curves in Figs. 1 and 3 show, the deep sea sediments tested exhibited pronounced secondary compressions.

Table 4 - Compressibility Characteristics

STYX Sample	p'_o Kg/cm^2	e_o	p_c Kg/cm^2	C_c Kg/cm^2	$C_c/(1+e_o)$	m
9-1C	0.014	3.94	0.60	1.58	0.32	7.9
9-2	0.01	9.10	0.31	3.05	0.30	5.7
9-3	0.01	4.15	0.30	1.35	0.26	6.1
9-5A	0.008	6.90	0.30	2.50	0.32	8.3
9-5B	0.006	10.95	0.33	4.90	0.41	5.4
10-1	0.015	3.50	0.15	0.97	0.21	7.8
10-1C	0.015	3.40	0.15	0.90	0.20	7.2

Summary

The physical properties of seven brown pelagic sediments, sampled in water depths ranging from 4600 to 5920 meters from the floor of the Pacific Ocean, were determined. The samples had high water contents, generally high plasticity characteristics, low strengths, and medium sensitivities. The effective stress parameters, c' and Ø', were typical of normally consolidated soft marine clays. The deep sea samples exhibited some initial resistance against compression; however, their virgin compression behavior was similar to other known plastic cohesive soils.

Acknowledgment

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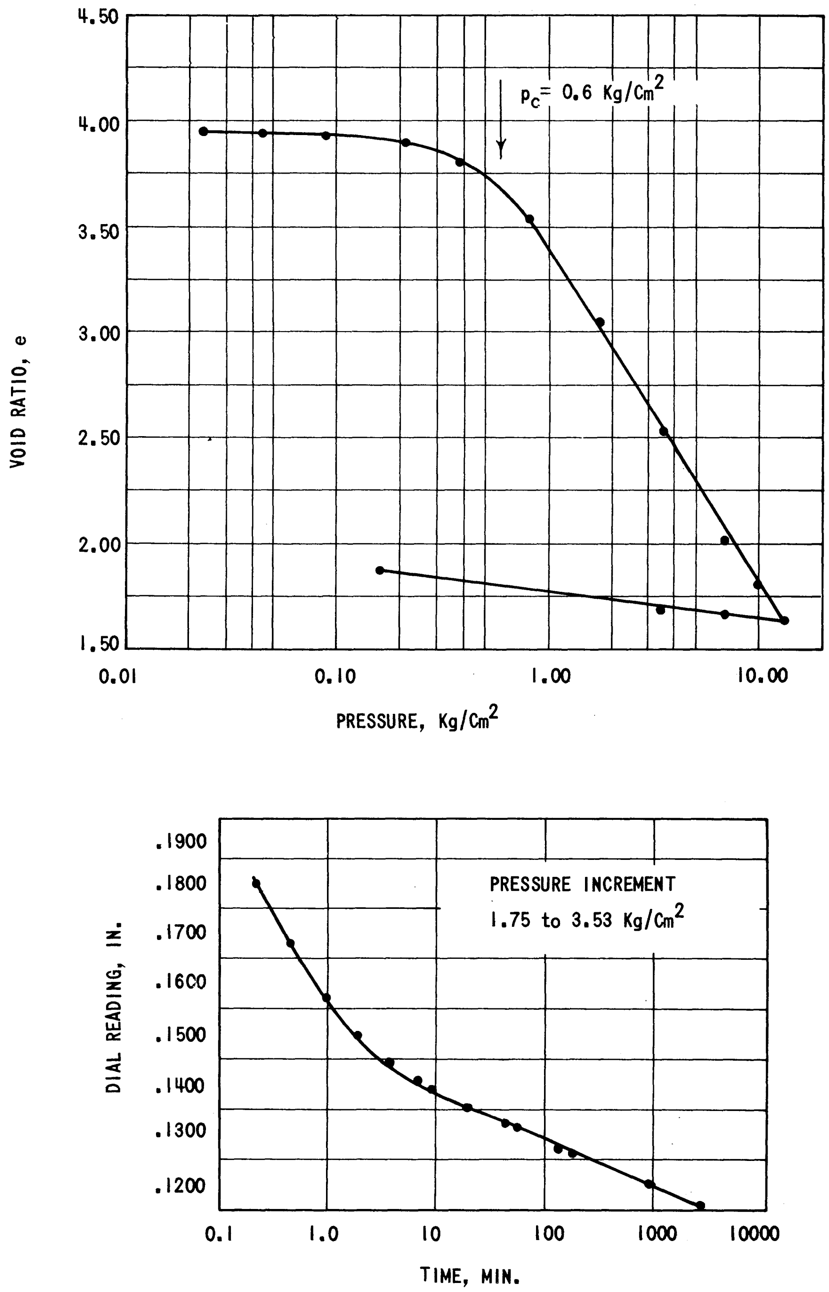
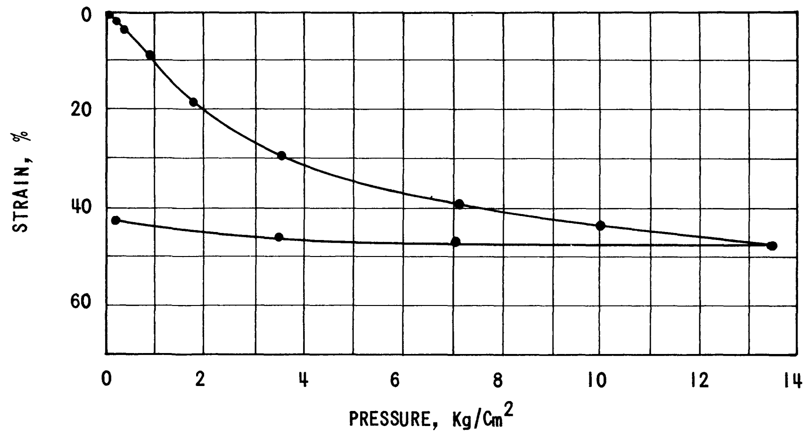
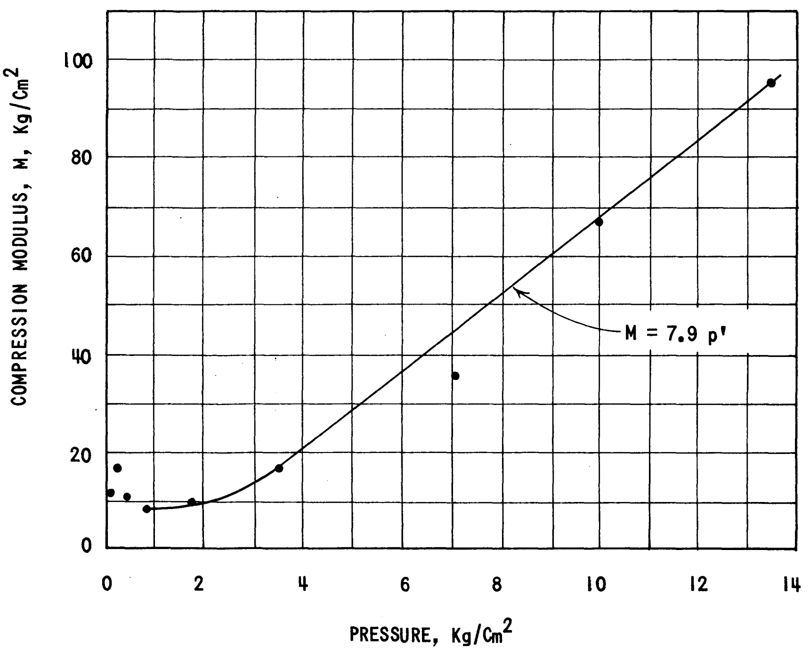


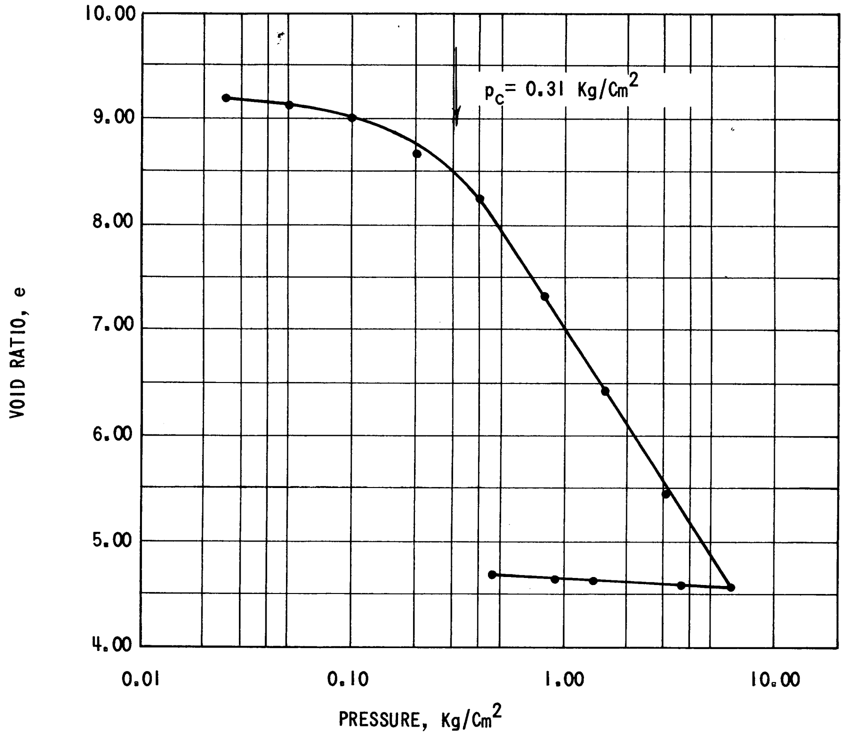
Fig. 1 CONSOLIDATION TEST RESULTS
SAMPLE 9-1C

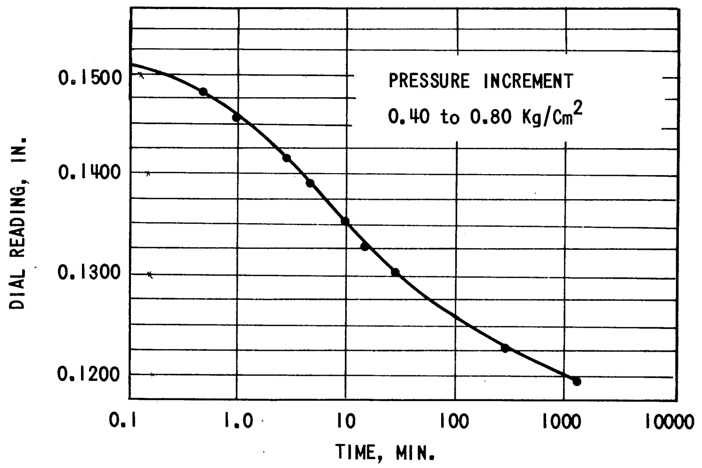




PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS

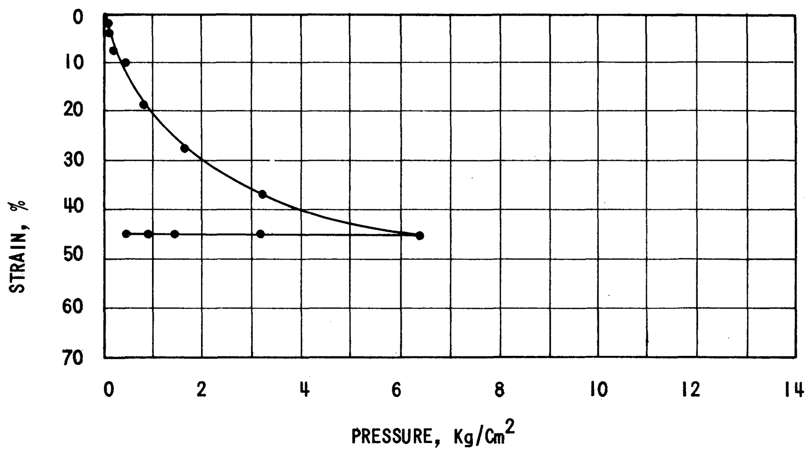
Fig. 2 SAMPLE 9-IC

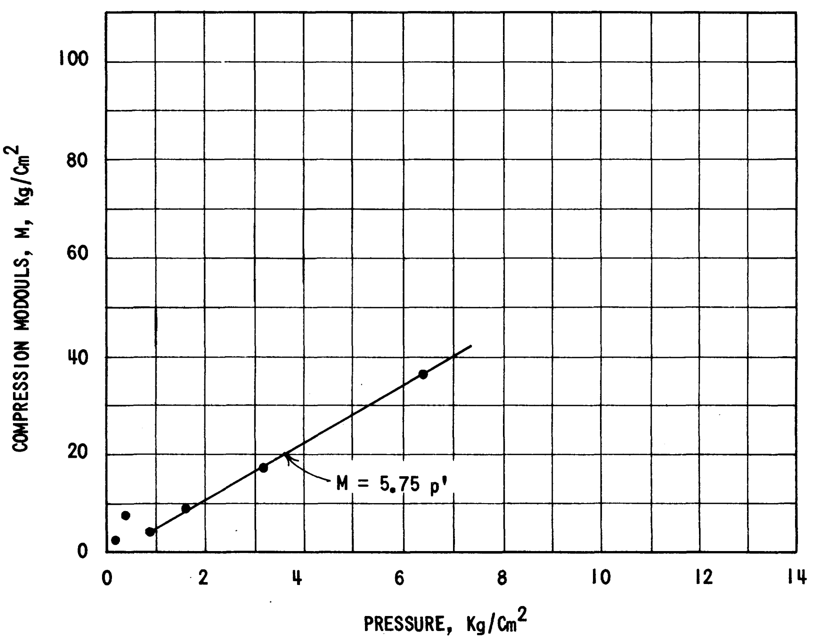




CONSOLIDATION TEST RESULTS
SAMPLE 9-2

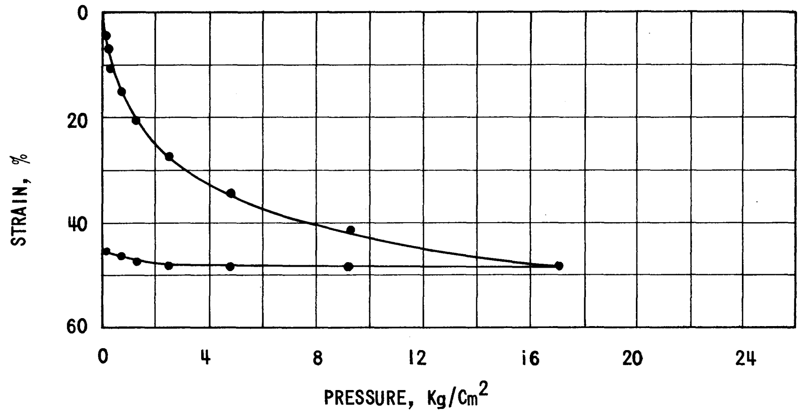
Fig. 3

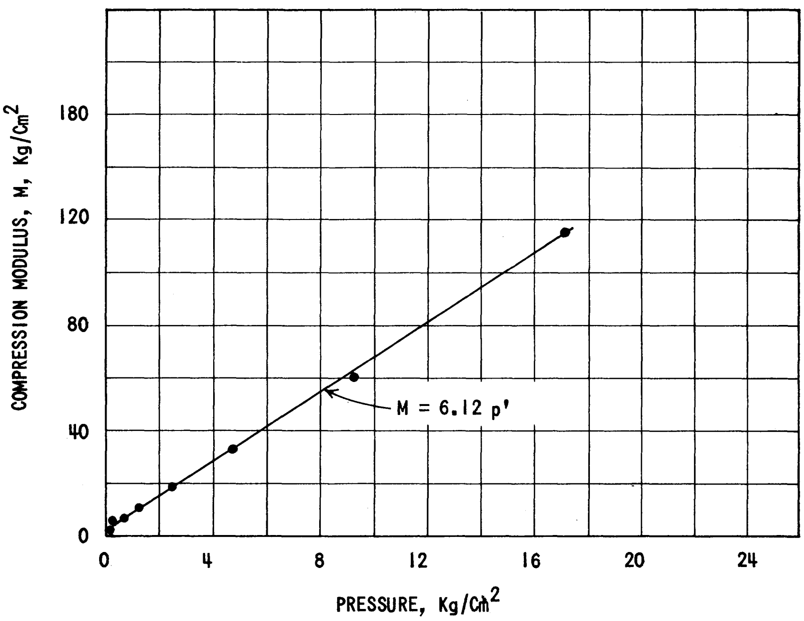




PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS

Fig. 4 SAMPLE 9-2





PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS

SAMPLE 9-3

Fig. 5

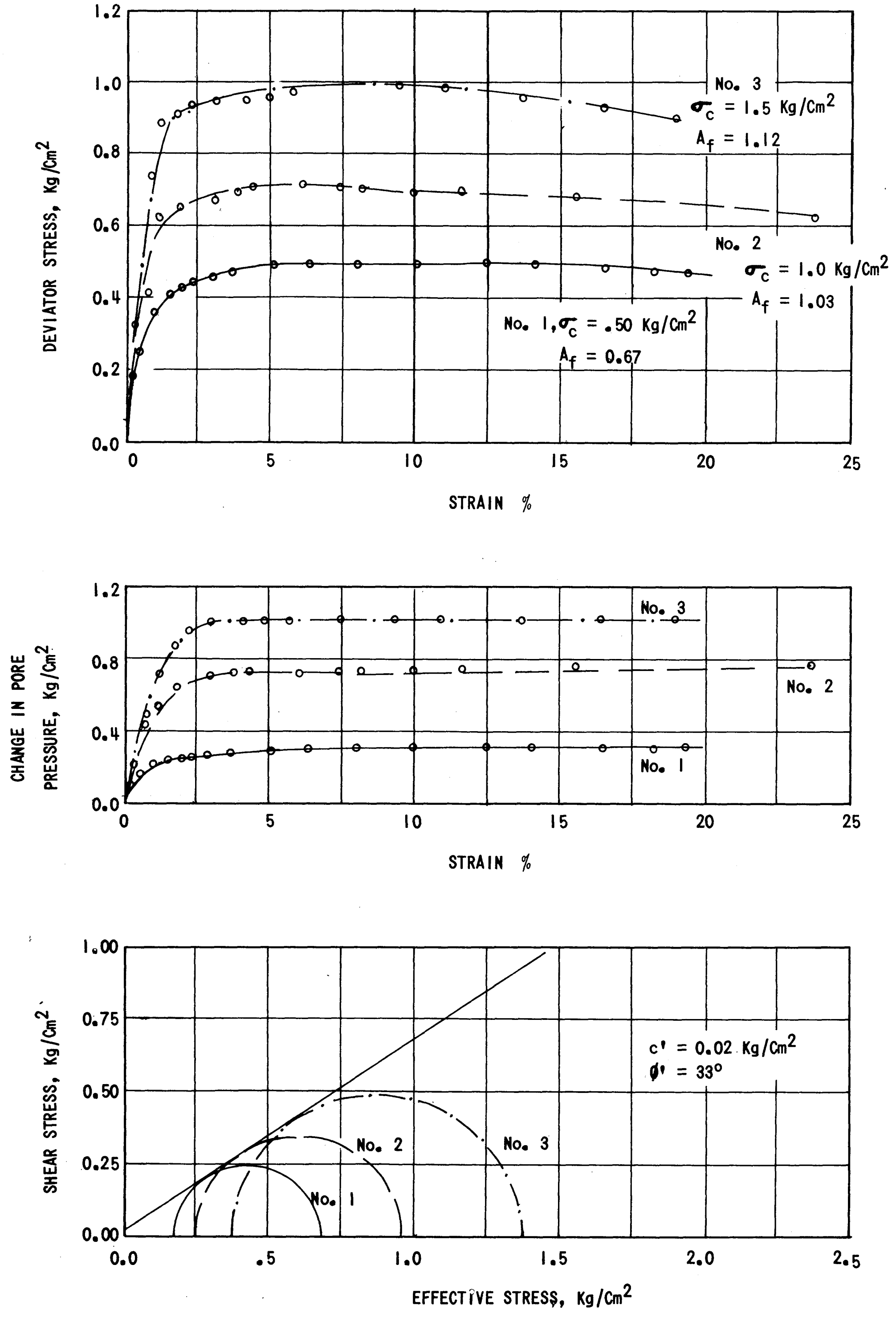
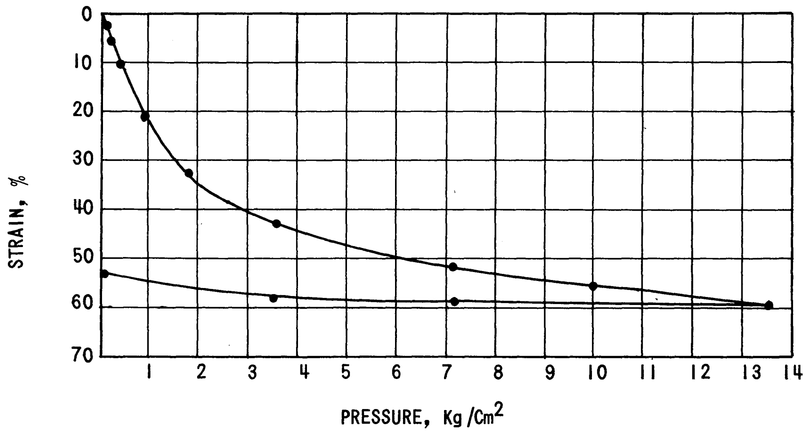


Fig. 6 RESULTS OF CU TRIAXIAL TEST
SAMPLE 9-3



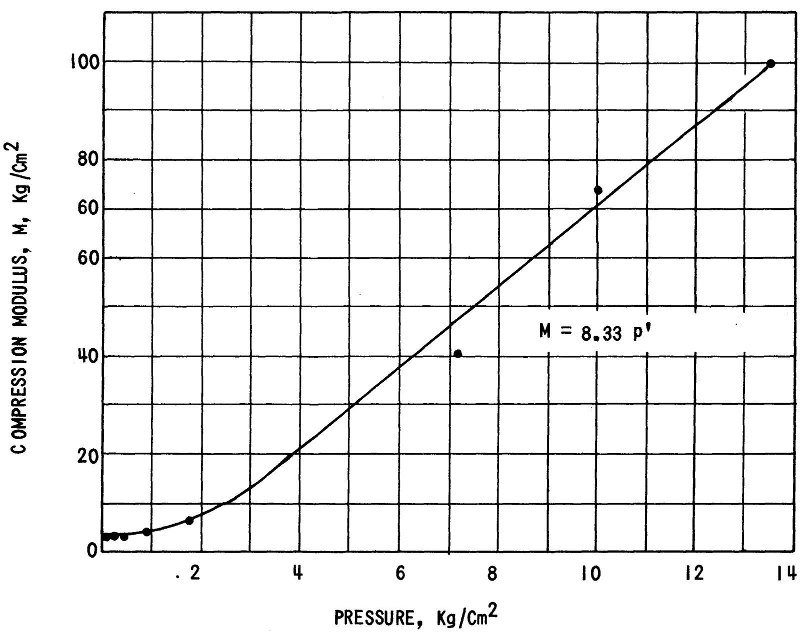
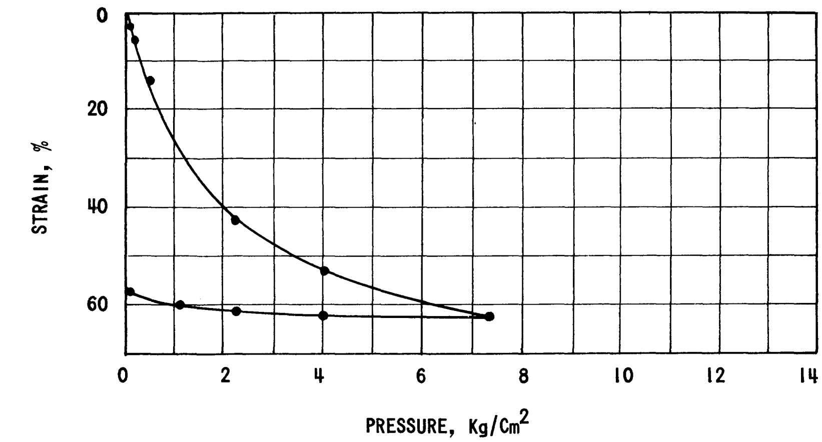
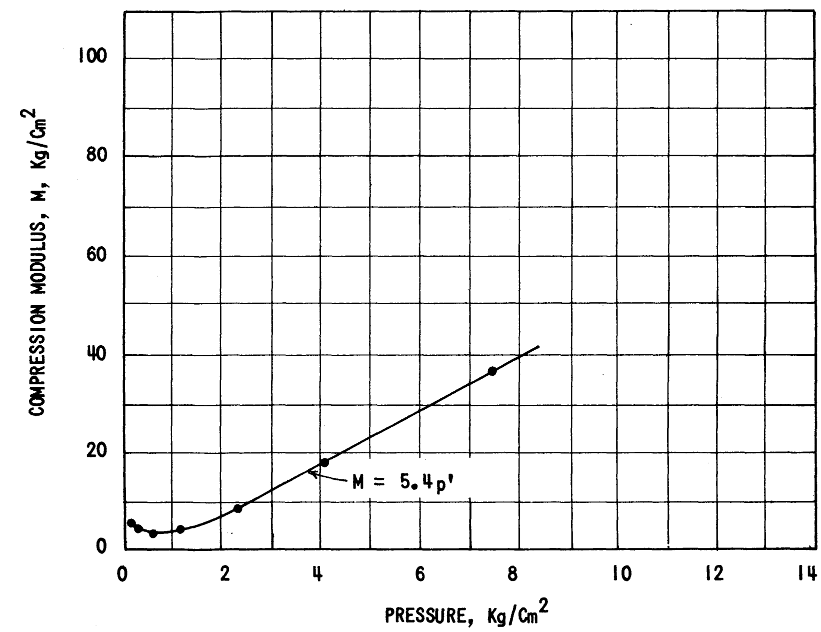


Fig. 7 PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS SAMPLE 9-5A

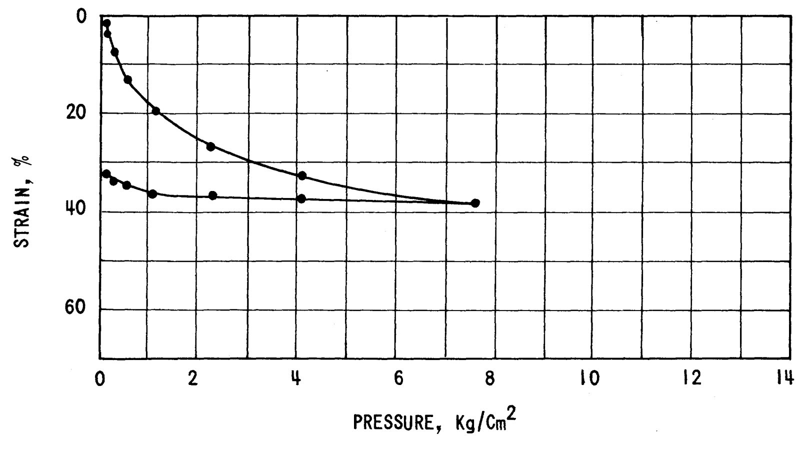


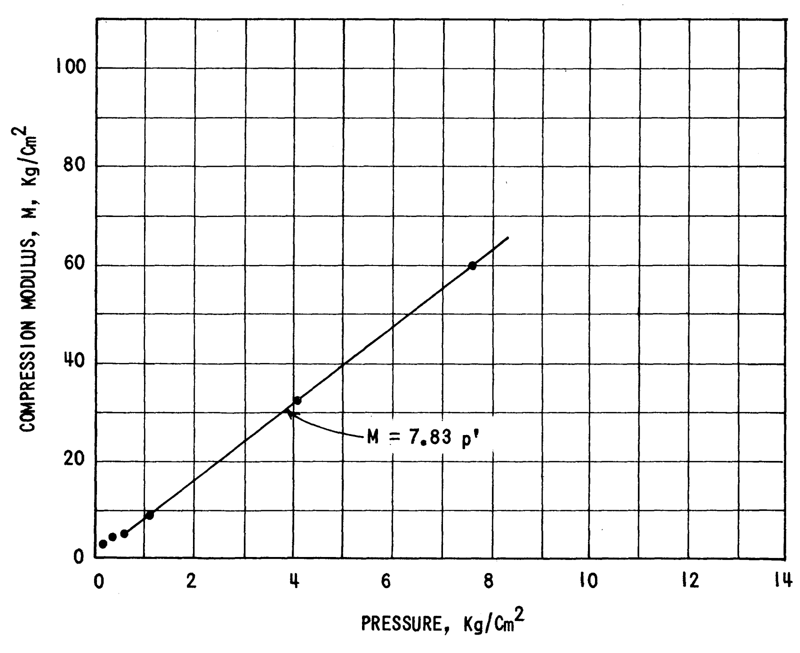


PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS

SAMPLE 9-5B

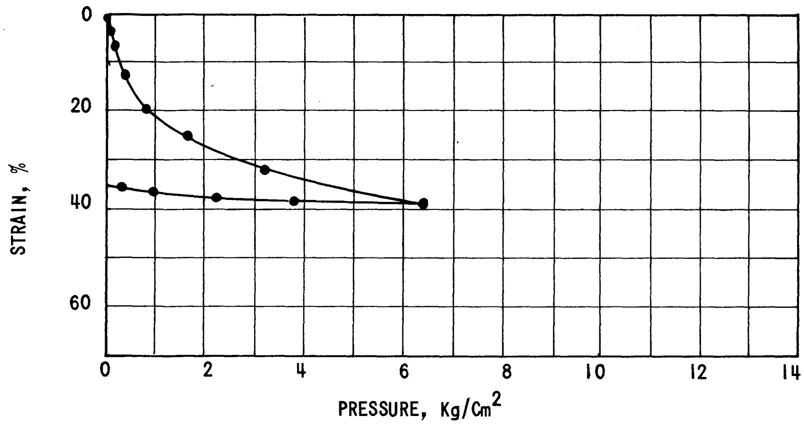
Fig. 8





PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS SAMPLE 10-1

Fig. 9



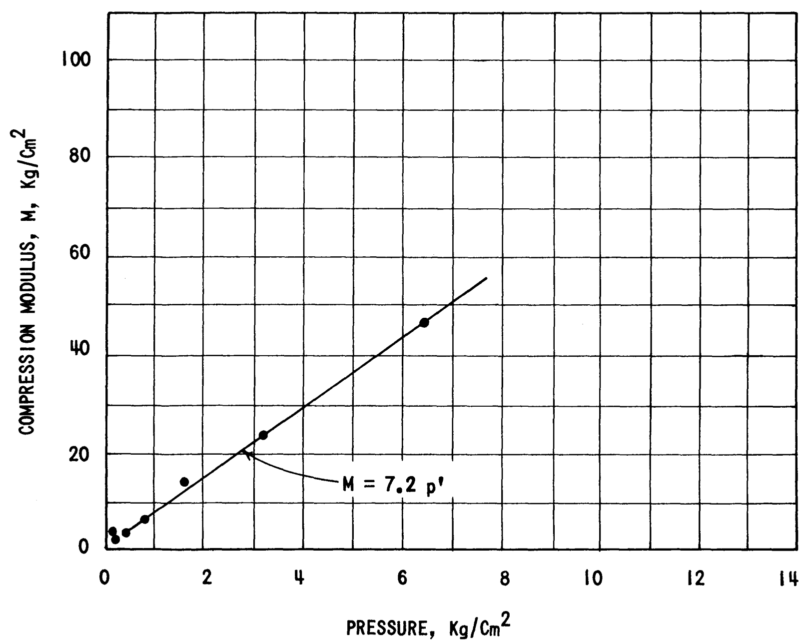
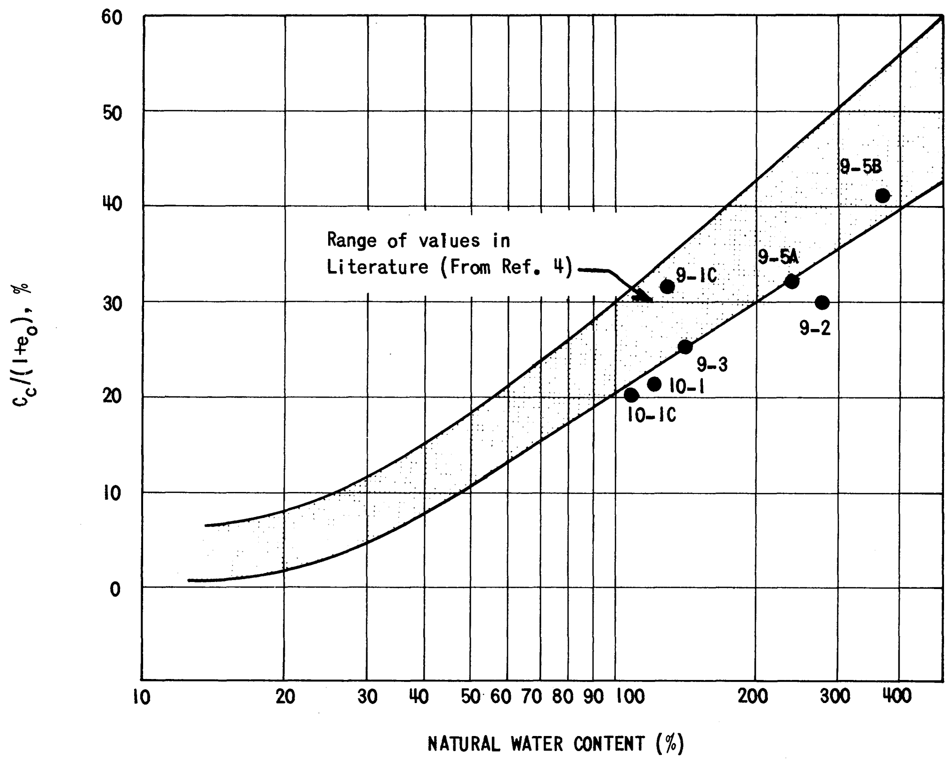


Fig. 10 PRESSURE VERSUS STRAIN, AND PRESSURE VERSUS COMPRESSION MODULUS

SAMPLE 10-1C



RELATIONSHIP BETWEEN w AND $C_c/(1+e_o)$

Fig. 11