EPA-600/2-77-139
August 1977

Environmental Protection Technology Series

PHYSICAL AND ENGINEERING PROPERTIES OF HAZARDOUS INDUSTRIAL WASTES AND SLUDGES

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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PHYSICAL AND ENGINEERING PROPERTIES OF HAZARDOUS INDUSTRIAL WASTES AND SLUDGES

by

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Interagency Agreement No. EPA-IAG-D4-0569

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This research was supported by the U.S. Environmental Protection Agency to develop a data base in the event guidelines become necessary for stabilization technology and for potential utilization of sludges in a productive venture.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This report presents the results of a laboratory testing program to investigate the properties of raw and chemically fixed hazardous industrial wastes and flue gas desulfurization (FGD) sludges.

Samples of hazardous wastes and FGD sludges were obtained and divided into several portions. Some portions of each sample were designated for testing to characterize each of the raw sludges. The remaining portions of each sample were chemically fixed at the Waterways Experiment Station by representatives of the respective processors.

Specimens of raw and fixed sludges were subjected to a variety of tests commonly used in soils engineering. The grain-size distributions, Atterberg limits, specific gravities, volume-weight-moisture relationships and permeabilities of raw and fixed sludges were determined. Selected fixed sludges were subjected to appropriate engineering properties (compaction and unconfined compression) tests and durability (wet-dry and freeze-thaw) tests.

Test results show that fixing can cause significant changes in the properties of sludge, that fixed sludges are similar to soil, soil-cement, or low-strength concrete, and that properties are process-dependent. On the basis of test specimen behavior, fixed sludges can be expected to exhibit substantial engineering strength and suitability for landfill and embankment construction, although the durability tests show that weathering can be a problem unless the fixed sludges are protected by an earth cover. No leaching studies were conducted as a part of this phase of the stabilization study. Information and data on leaching are available in the interim report.

This report was submitted in partial fulfillment of Interagency Agreement Number EPA-IAG-D4-0569 by the U. S. Army Engineer Waterways Experiment Station under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period from January 1975 to August 1976.

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CONVERSION FACTORS

All measurements in EPA documents are to be expressed in metric (SI) units. In this report, however, implementing this practice sometimes affects clarity adversely. Factors for converting British units of measurements to SI units are given as follows:

British	Metric
1 in	2.54 cm
1 lb	0.454 kg
1 cu ft	0.0283 cu meter
1 lb/sq in	0.690 N/sq cm
1 lb/cu ft	16.042 kg/cu meter
1 ft-lb/cu ft	47.928 N-m/cu meter

ACKNOWLEDGMENT

The assistance of the firms and companies that provided sludge samples or that performed fixation on these samples is gratefully acknowledged. Without the continued support of these companies, research projects of this nature could not be successfully performed.

The guidance and support of Mr. Robert E. Landreth, Mr. Norbert L. Schomaker, and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency are greatly appreciated.

This project was conducted at the U. S. Army Engineer Waterways Experiment Station under the general supervision of Dr. John Harrison, Chief, Environmental Effects Laboratory (EEL), Mr. Andrew J. Green, Chief, Environmental Engineering Division (EED), EEL, and Mr. Raymond L. Montgomery, Chief, Design and Concept Development Branch, EED. The Soils and Pavements Laboratory performed the laboratory testing under the direction of Mr. G. P. Hale; Directors of WES during the course of this study were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

SECTION 1

INTRODUCTION

BACKGROUND

Pollution control systems are in widespread use to protect the environment from damage resulting from the release of contaminants into the air and water. These systems have become developed to the point where they are now capable of removing most contaminants from liquid industrial waste streams and flue gases before discharge into the environment. The end product of many pollution control systems is a sludge in which pollutants are highly concentrated. These sludges are potentially hazardous because the concentrated pollutants may cause environmental damage upon disposal. To allow the product of pollution control systems to damage the environment would reduce the function of such systems from pollution control to pollution postponement; therefore, the ultimate disposal of hazardous sludges must be accomplished without adverse environmental impact.

Landfilling and ponding are common methods for the ultimate disposal of hazardous waste sludges, but groundwater contamination problems can result. As liquid percolates through the sludge, pollutants may be leached; and if the leachate is allowed to migrate from the sludge into the surrounding environment, the leachate will contaminate the groundwater. Groundwater contamination by leachate can be prevented by lining the disposal site with a material impermeable to leachate, although liners are somewhat expensive and potential difficulties include leakage and deterioration caused by chemical reactions between the liner and the sludge.

Alternatively, pollution of groundwater by leachate can sometimes be lessened or prevented by sludge fixation, retarding pollutant migration from sludges. Chemical fixation alters the chemical and physical properties of hazardous sludges, resulting in the formation of materials which may have any of a wide range of consistencies. While some fixation processes result in the formation of soil-like materials with discrete particles, other processes produce hard and rigid concrete-like materials of significant strength and integrity.

The U. S. Army Engineer Waterways Experiment Station (WES) is investigating the feasibility of using chemical fixation to reduce the pollution potential and to increase the stability and durability of hazardous sludges placed in landfills or used for productive purposes. An interim report[1] of the pollution potential of raw and chemically fixed hazardous industrial wastes and flue gas desulfurization (FGD) sludges has been published by the

U. S. Environmental Protection Agency (EPA), sponsor of the investigation. The interim report presents limited data concerning the physical and engineering properties and the durability of raw and fixed sludges.

PURPOSE

The purpose of this report is to describe laboratory tests appropriate for raw and fixed sludges and to present detailed information concerning the properties of these sludges. Investigation of the test procedures used to determine the sludge properties presented in the interim report revealed that some of the test conditions (notably the temperature used for oven drying) altered the properties of the test specimens during testing, and that incorrect test values had been reported. Consequently, test conditions were modified to preserve the properties of the test specimens, and the sludges were re-tested.

SCOPE

This report is an expansion of Sections III and V of the interim report and provides more detailed descriptions of tests modified for this study and includes additional test results. The report contains the meaningful data presented in the interim report, modified as necessary, and also includes permeability, durability and other test data not previously available.

SECTION 2

CONCLUSIONS

Raw and fixed sludges can be successfully tested by methods currently used in soils engineering. The data resulting from such testing are meaningful and show that raw and fixed sludges exhibit a wide range of properties, many of which are material- and/or process-dependent. Sludges fixed by process B or F resembled cemented soils and could be crushed into individual particles with moderate effort. Sludges fixed by process A, C, E, or G are hard materials resembling soil-cement mixtures or low-strength concrete. Sludge fixed by process D is a hard material covered with 1/4 inch of plastic.

Grain-size analyses indicate that raw sludges have grain-size distributions similar to those of silty soils and that the grain size distributions of sludges are not substantially affected by process B. Attempts to determine the grain size distribution of sludge fixed by process F were only partially successful due to flocculation during the hydrometer analysis. Since raw sludge of the same type was successfully tested, test failure is attributed to the fixing process.

Atterberg limit tests indicate that raw sludges are similar to silts of low plasticity and that fixation generally reduces plasticity. Since raw sludges and sludges fixed by process B exhibit grain size distributions and plasticity properties characteristic of silty soils, the behavior of these sludges is expected to be similar to that of silty soils.

The specific gravities of the raw sludges range generally higher than those of soils. Changes in specific gravity due to fixation are process-dependent.

Moisture-volume-weight relationships for fixed sludges are process-dependent. Three fixed sludges exhibited a marked loss of water after 60°C oven drying, while the majority exhibited little or no loss. Void ratios, porosities, and bulk and dry unit weights for the fixed sludges are generally within the ranges typical of soils.

The compactive effort of the 15-blow compaction test did not increase the dry unit weight of sludges fixed by process B to values significantly higher than those of samples of the same material after air drying. It may be concluded from these data that to achieve significant increases in dry unit weight the application of a compactive effort considerably higher than that of the 15-blow compaction test will be required; this usually requires the use of modern compaction equipment.

Results from the unconfined compression tests indicate that the compressive strengths of fixed sludges are highly dependent on fixation process and sludge type. Sludges fixed by one fixation process exhibited compressive strengths typical of silts and clays. Most of the fixation processes produced fixed sludges having strengths comparable to those of soil-cement mixtures or of low-strength concrete.

Based on the results of unconfined compression testing, the performance of soil-like fixed sludges should be satisfactory in bearing capacity and embankment construction for most landfill applications. Fixed sludges resembling soil cement mixtures or low-strength concretes should perform very well in landfill or embankment construction.

The durability of fixed sludges is a function of the fixation process rather than sludge type. With the exception of sludges fixed by process D or E, fixed sludges are generally unable to withstand 12 durability test cycles. However, since no long-term data concerning the field durability of fixed sludges exist, no prediction of field durability can be made on the basis of laboratory test results. Data from field studies of fixed sludge landfills are needed to develop relationships between laboratory testing and field performance.

SECTION 3

RECOMMENDATIONS

It is recommended that landfills constructed of fixed sludge be carefully monitored to permit correlation with experimental results and to facilitate the prediction of field performance on the basis of laboratory test results.

Some fixed sludges are like soil-cement or concrete, and their potential for use in landfill and embankment construction should be investigated further in hopes of reducing disposal area requirements.

It is recommended that a manual describing recommended test procedures for evaluating the physical and engineering properties and the durability of raw and fixed sludges be prepared. The manual should emphasize evaluation of sludge properties that influence the behavior of landfills of raw or fixed sludge. The manual could be synthesized from the procedures specified by various organizations for use in testing materials other than sludge; the experience of various investigators that have tested sludge could be used as the basis for modification of standard procedures. The manual would serve to consolidate under one cover test procedures for sludge testing, making Corps of Engineers test procedures, which were used during this study, more readily available to the private sector.

SECTION 4

MATERIALS AND METHODS

MATERIALS

Sludges

Sludge samples from five coal-burning electric power generating plants and from five industrial manufacturing plants were obtained and assigned code numbers as shown in Table 1. The sludges were sampled by WES personnel and brought to WES for chemical fixation and laboratory testing.

TABLE 1. SLUDGE CODE NUMBER ASSIGNMENT

Code Number	Sludge
100	FGD, lime process, eastern coal
200	Electroplating
300	Nickel/cadmium battery
400	FGD, limestone process, eastern coal
500	FGD, double alkali process, eastern coal
600	FGD, limestone process, western coal
700	Inorganic pigment
800	Chlorine production, brine sludge
900	Calcium fluoride
1000	FGD, double alkali process, western coal

Note: Information from Reference 1.

Chemical Fixation

The samples of each type of sludge (100, 200, etc.) were divided into several portions. Some portions of each sludge type were designated for testing to characterize each raw sludge. The remaining portions of each sludge type were chemically fixed at the WES by representatives of the respective processors. Each process was assigned a code letter, and Table 2 shows the process(es) used to fix each type of sludge.

Each sludge sample is identified by a code consisting of a letter to represent the fixation process (Table 2) followed by a number to specify the sludge type (Table 1). The identification codes of samples of unfixed (raw) sludge are prefixed by the letter R.

TABLE 2. SLUDGE FIXATION PROCESS ASSIGNMENTS

Sludge type	Fixation processes A	B	C	D	E	F	G
100	X	X			X		
200	X	X	X	X			X
300	X	X					
400	X	X			X		X
500	X	X			X		X
600	X	X			X	X	X
700			X				
800	X	X					
900	X	X					
1000	X	X			X		X

Note: Information from Reference 1.

LABORATORY TESTS

Tests commonly used in determining the properties of soil and/or concrete were performed on the raw and fixed sludges to determine their physical and engineering properties and durability. The use of standard tests and procedures allows the comparison of sludge properties with those of common materials whose properties are described in the literature. The various fixation processes (described in Reference 1) produce sludges of different appearances and characteristics (Figures 1-10); some are similar in appearance to cemented soil and others are hard and brittle, like concrete. One process included coating the sludge with plastic (Figure 2). Procedures used to test raw and fixed sludges were selected on the basis of the appearance of the material (i.e., soil-like, etc.), and the testing schedule is shown in Table 3.

To prevent the alteration of sludge properties during testing and to accommodate non-standard test specimens, standard test procedures were modified as necessary. Specific deviations from standard procedures and the justification for such deviations are presented in appropriate parts of the remainder of this section.

Physical Properties Tests

Grain-size Analysis--

The particle-size distributions of samples of raw and fixed sludges were determined by combined grain-size analysis. A sieve analysis was performed on that fraction of each sludge sample larger than 0.074 mm (#200 sieve); and a hydrometer analysis was performed on the finer fraction. Test procedures are described in Appendix V of Engineer Manual (EM) 1110-2-1906[2] and in American Society for Testing and Materials (ASTM)[3] standard test D422-63.

Samples whose grain size distributions were determined were prepared in

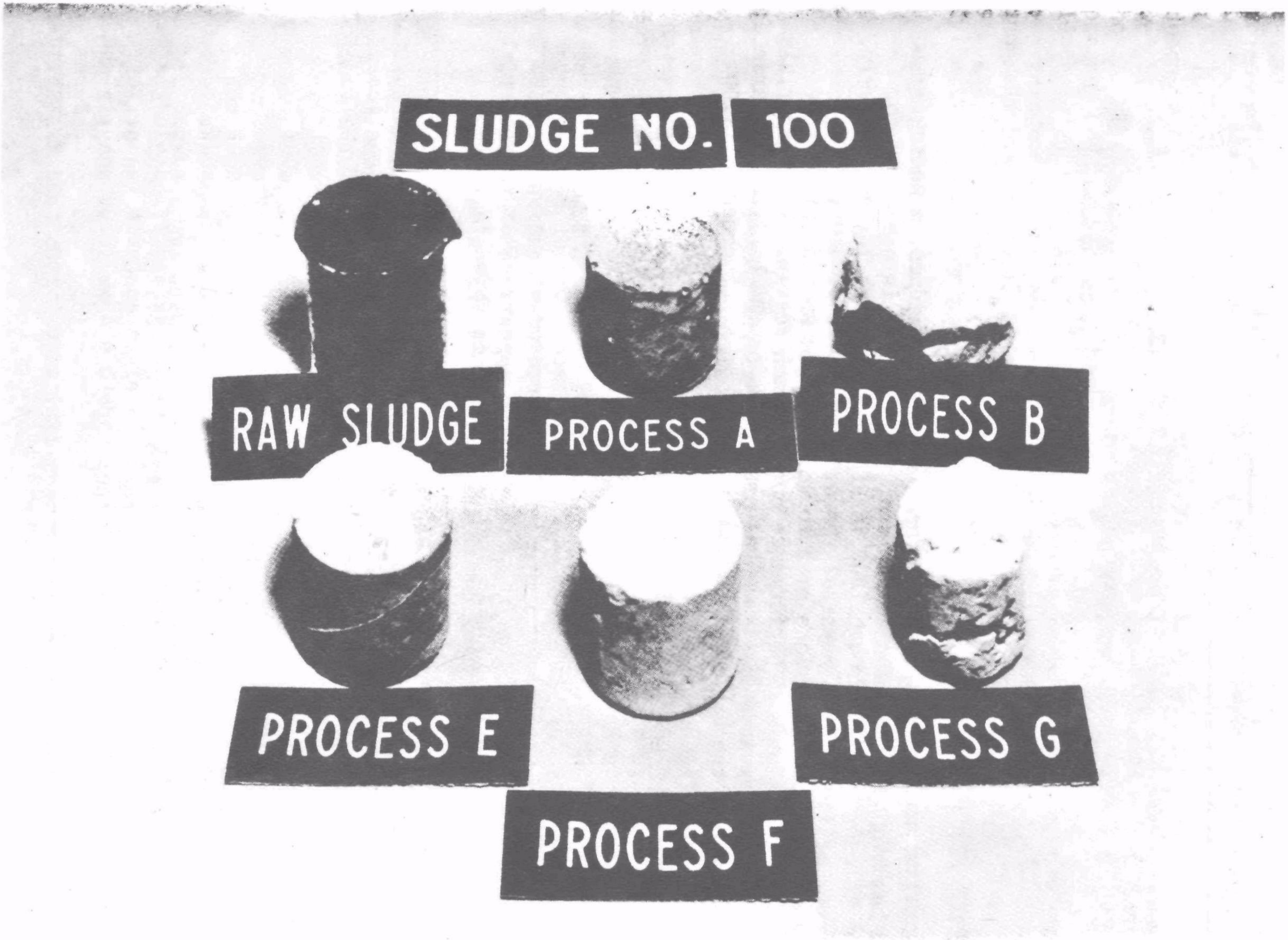

Figure 1. Raw and fixed sludges, Number 100 (from Reference 1).

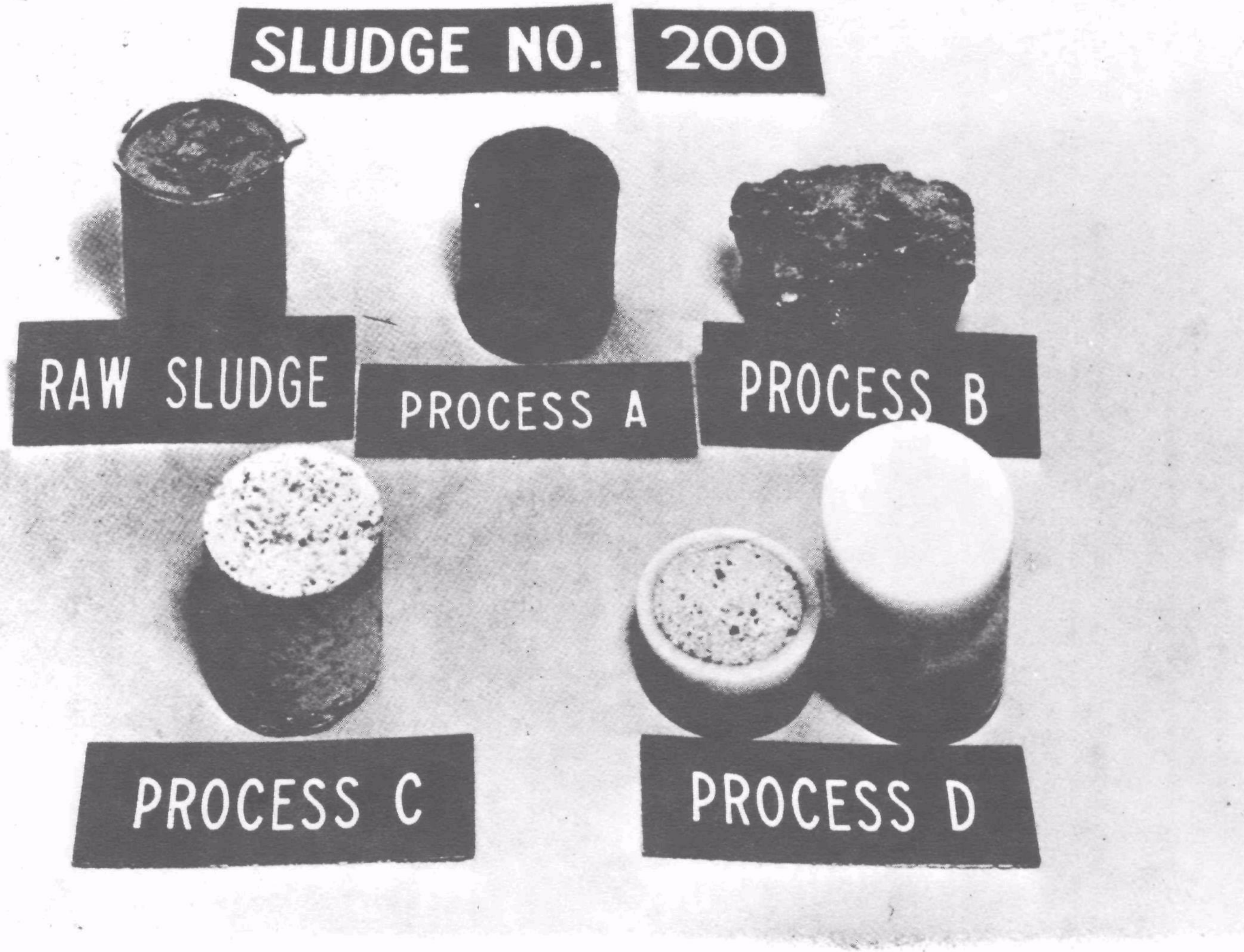

Figure 2. Raw and fixed sludges, Number 200 (from Reference 1).

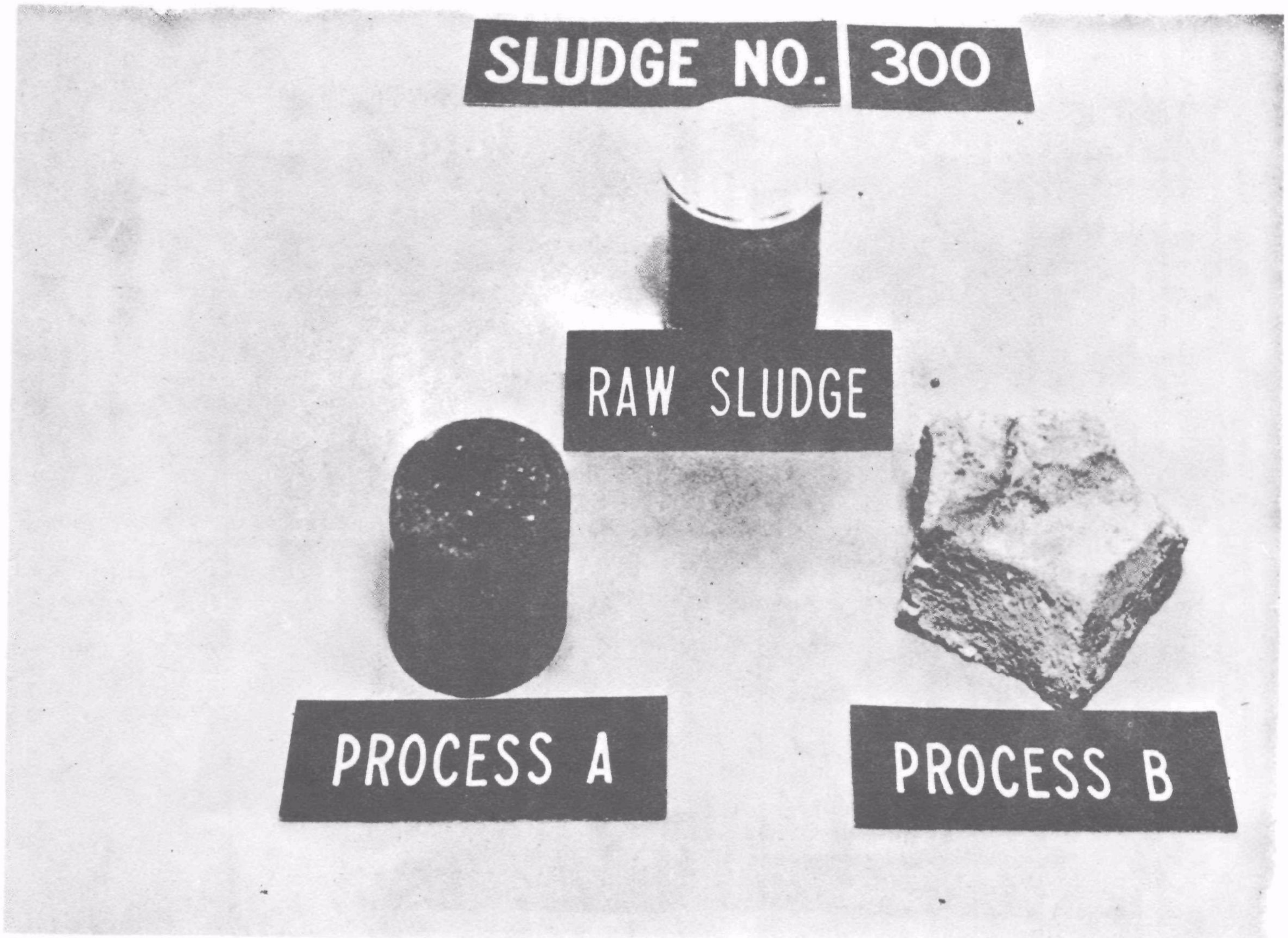

Figure 3. Raw and fixed sludges, Number 300 (from Reference 1).

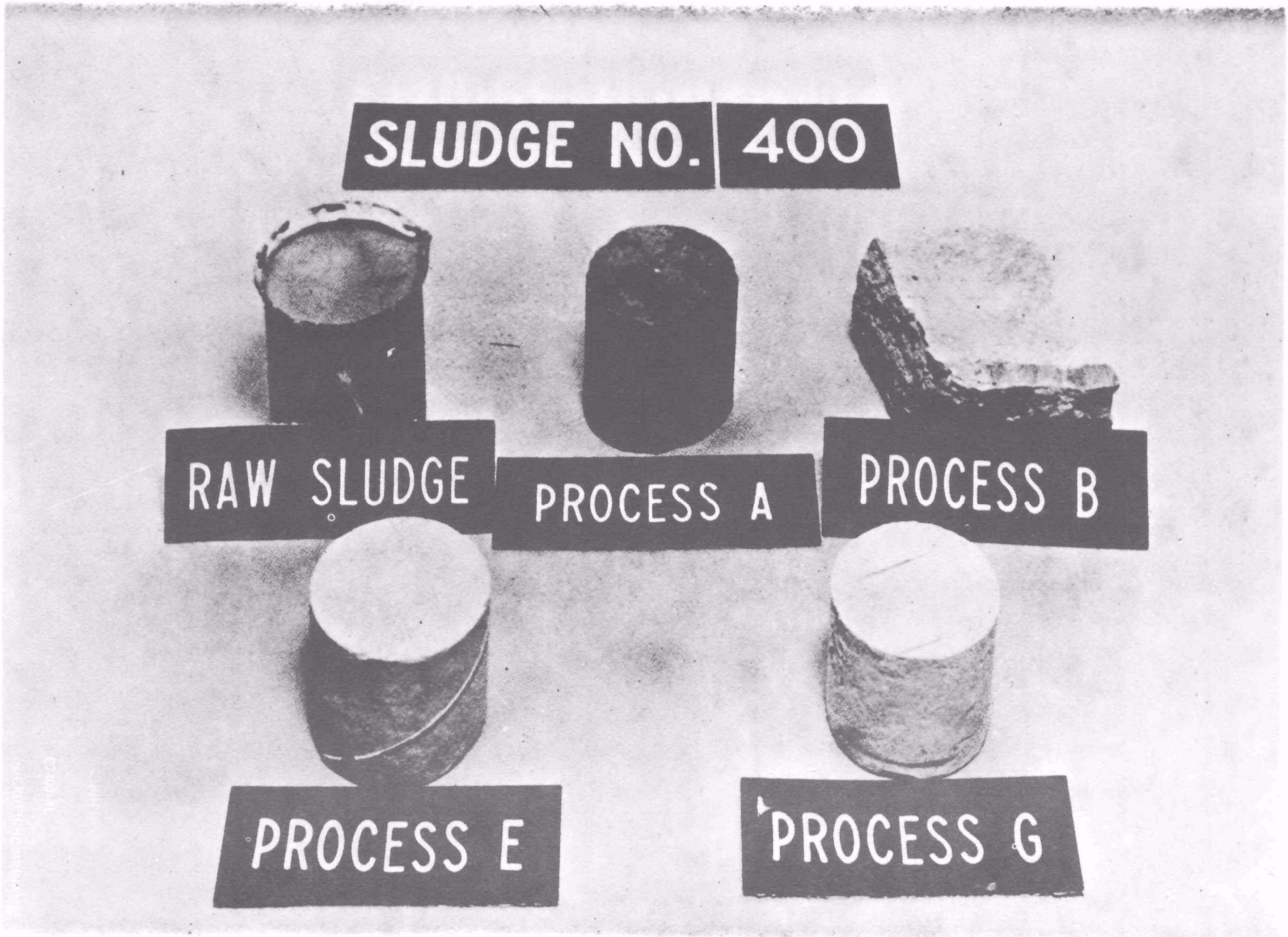

Figure 4. Raw and fixed sludges, Number 400 (from Reference 1).

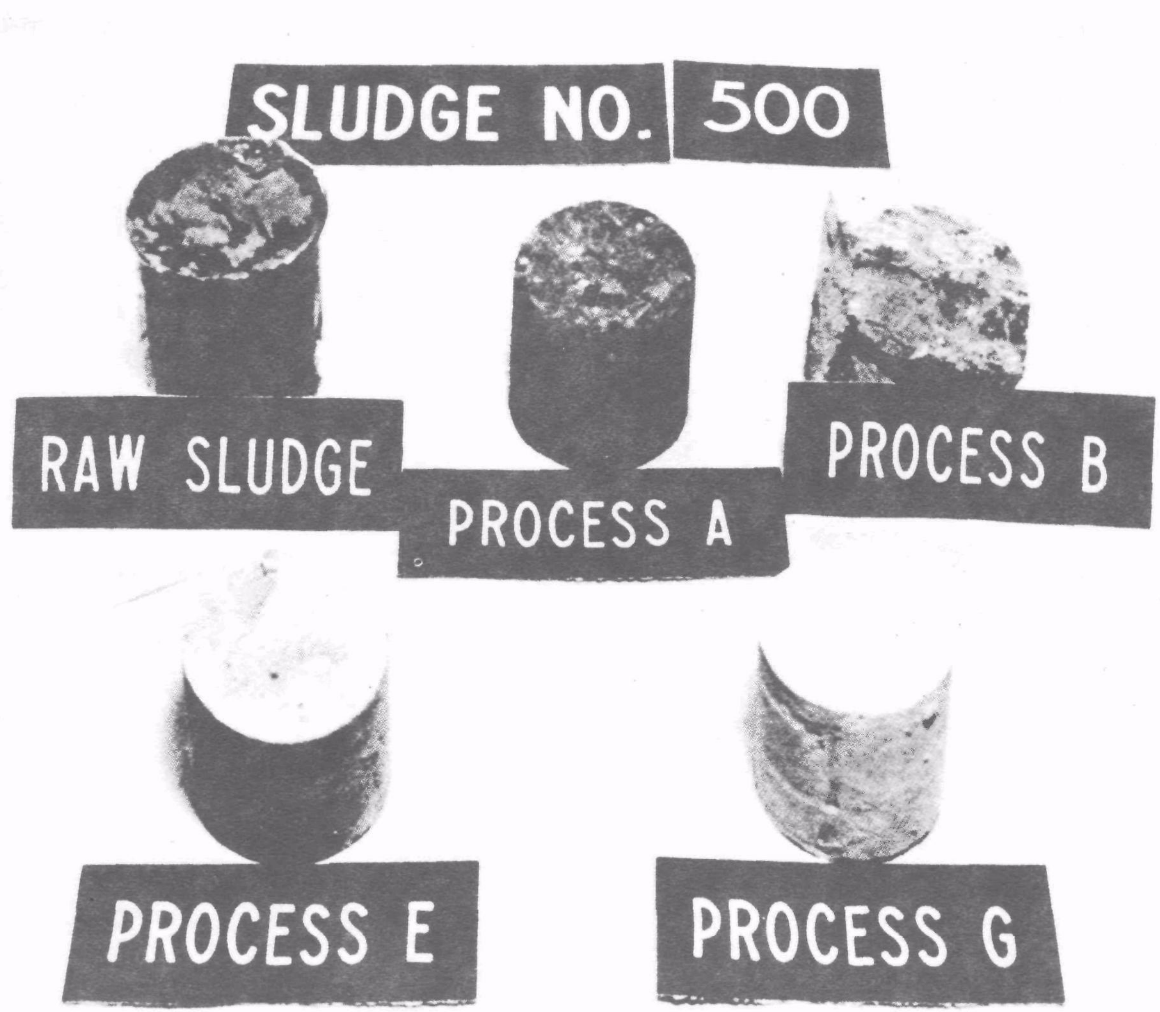

Figure 5. Raw and fixed sludges, Number 500 (from Reference 1).

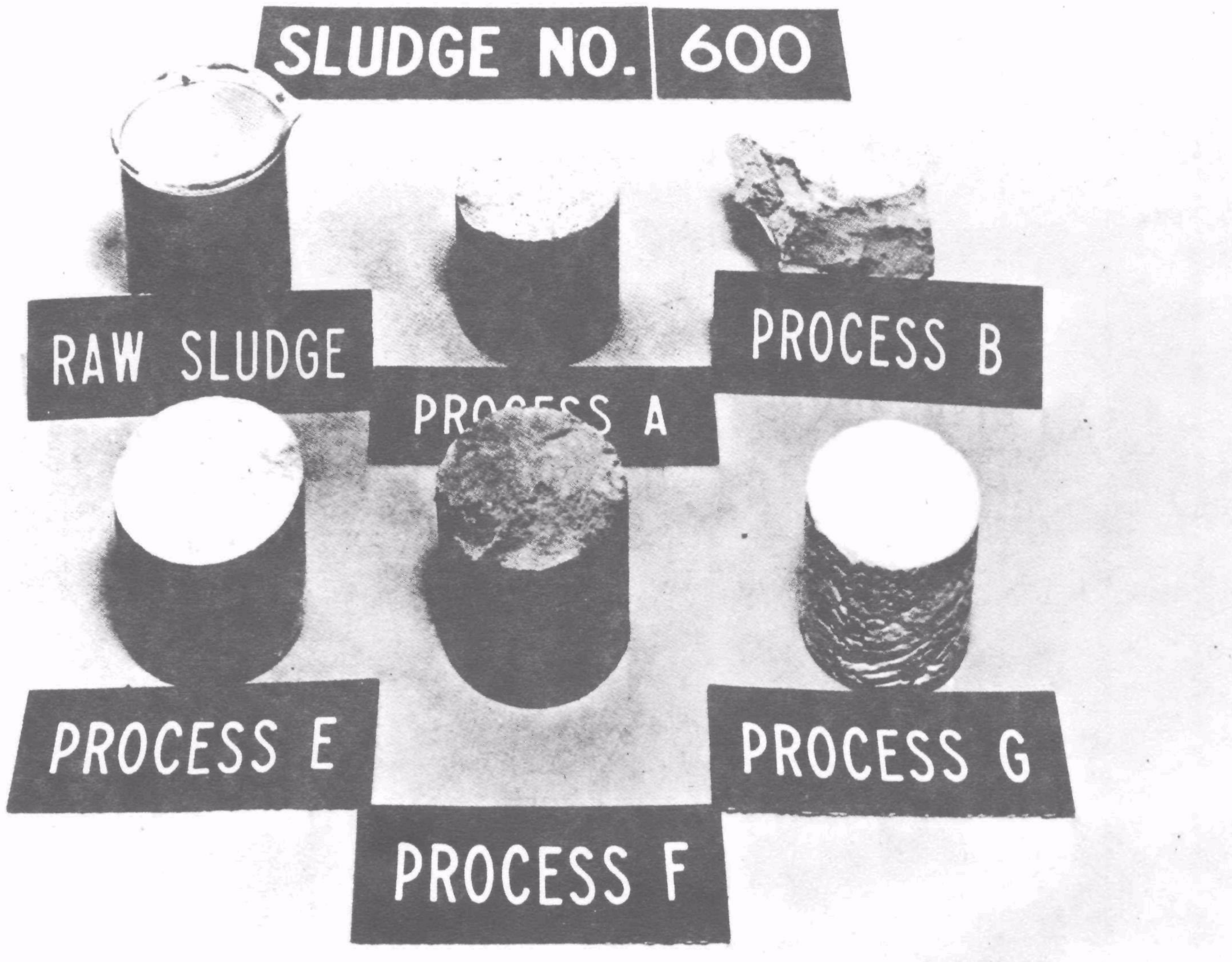

Figure 6. Raw and fixed sludges, Number 600 (from Reference 1).

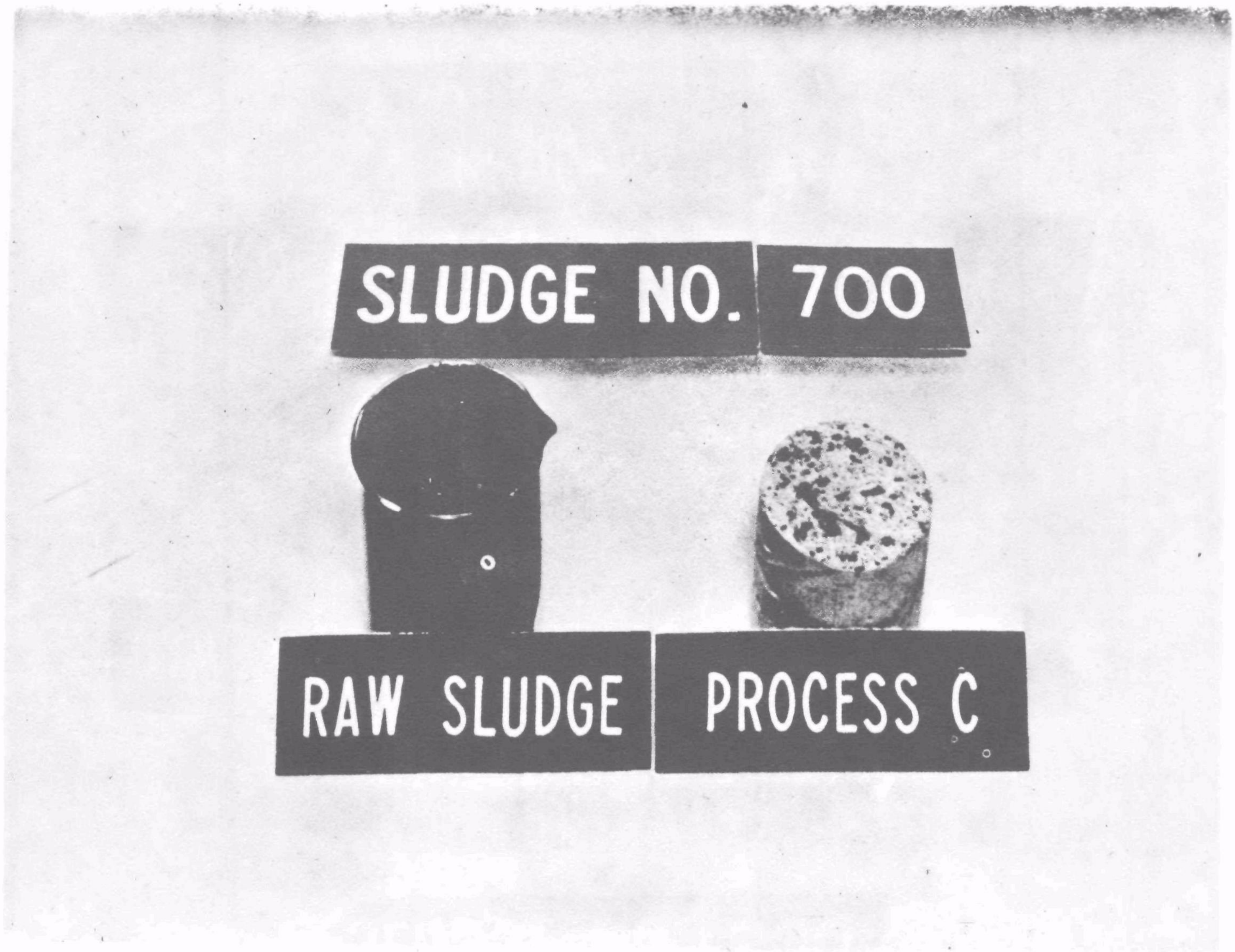

Figure 7. Raw and fixed sludges, Number 700 (from Reference 1).

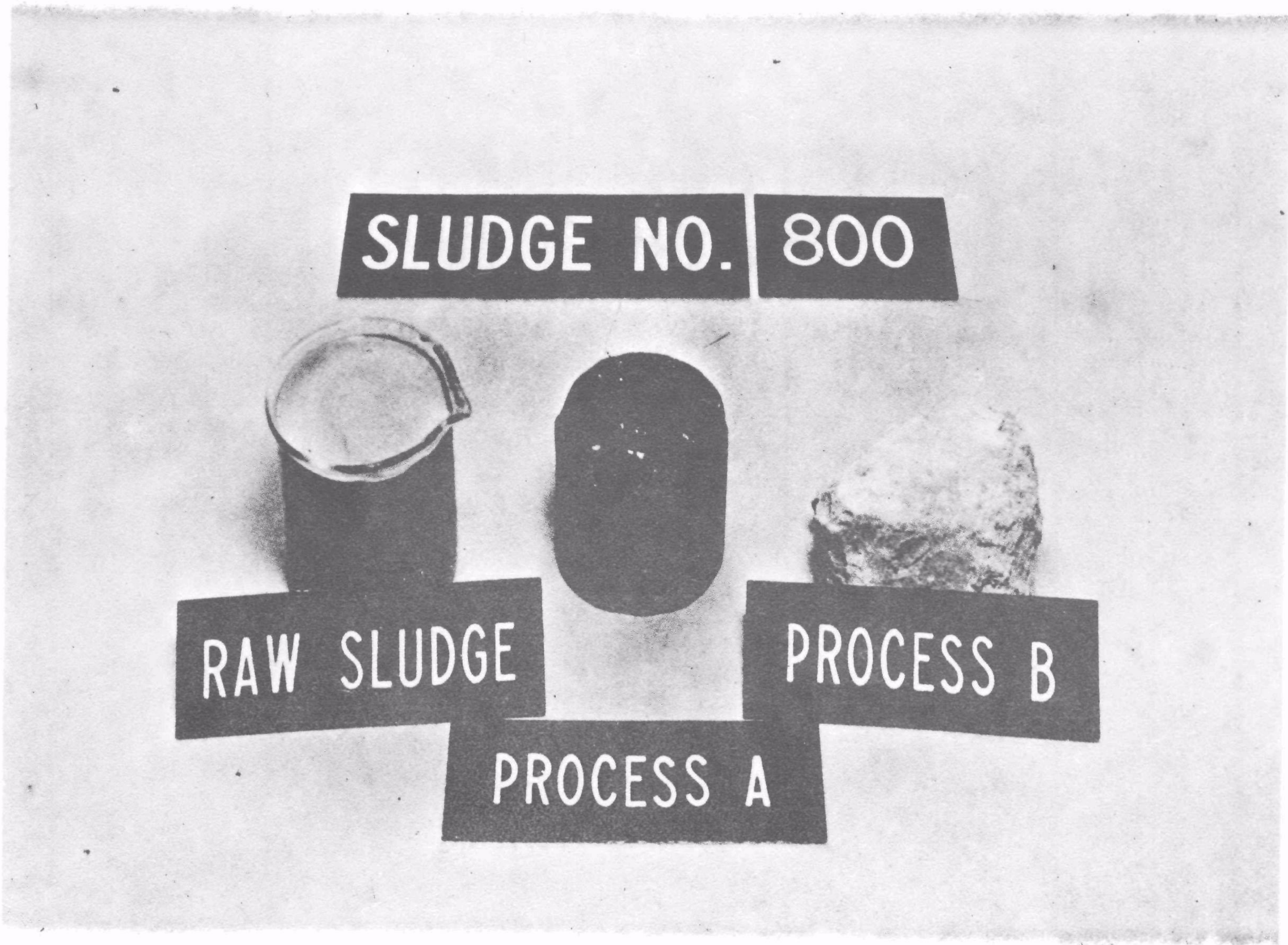

Figure 8. Raw and fixed sludges, Number 800 (from Reference 1).

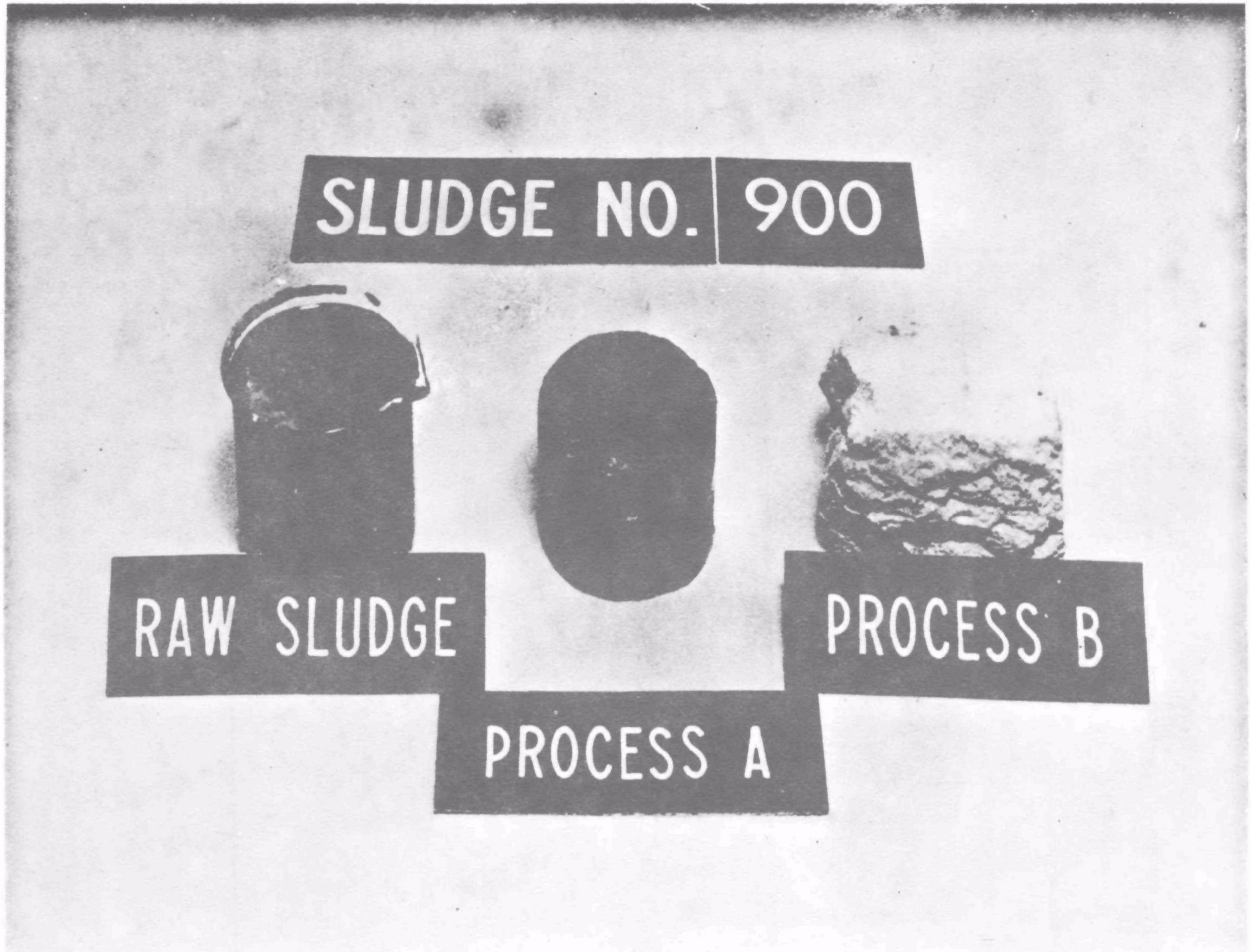

Figure 9. Raw and fixed sludges, Number 900 (from Reference 1).

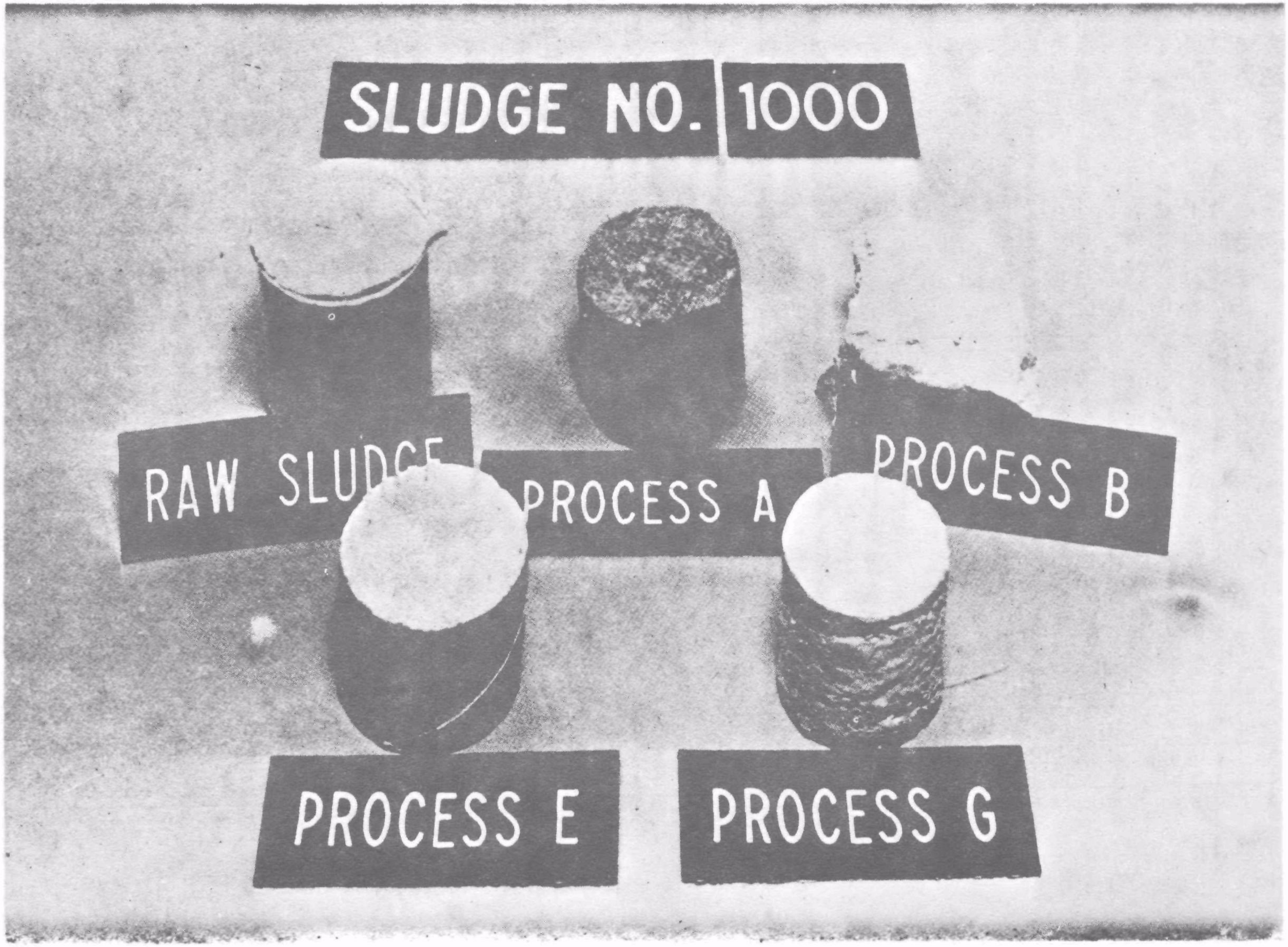

Figure 10. Raw and fixed sludges, Number 1000 (from Reference 1).

TABLE 3. TEST SCHEDULE FOR RAW AND FIXED SLUDGES

Type of Test	ASTM** Method	Raw Sludge	Fixation Processes*						
			A	B	C	D	E	F	G
Grain-size analysis	D422-63	X		X				X	
Specific gravity of solids	D854-58	X	X	X	X	X	X	X	X
Water content	D2216-71	X	X	X	X	X	X	X	X
Bulk and dry unit weight	†	X	X	X	X	X	X	X	X
Porosity and void ratio	†	X	X	X	X	X	X	X	X
Liquid limit	D423-66	X		X					
Plastic limit	D424-59	X		X					
Compaction test (15-blow)	D698-70#			X					
Unconfined compression test	D2166-66		X	X	X	X	X	X	X
Permeability test	†	X	X	X	X	X	X	X	X
Freeze-thaw test	D560-57		X	X	X	X	X	X	X
Wet-dry test	D559-57		X	X	X	X	X	X	X

* The sludge types fixed by each processor are listed in Table 2.

† No ASTM standard method available.

Modified procedure, see text.

** American Society for Testing and Materials.

accordance with the specifications of ASTM D421-58. Figures 1-10 show that the individual particles of the fixed sludges were bound together to form a semi-continuous mass. Using a rubber tipped pestle, the samples were ground into their individual particles in a mortar.

A sieve analysis consists of passing a sample through a set of sieves and weighing the portion of material retained on each sieve. The hydrometer analysis is based on Stoke's Law and involves preparation of a dilute suspension of fine sludge particles in water; measurement of the specific gravity of the suspension at specified time intervals; and correlation of settling velocity, particle diameter, and time to determine grain-size distribution. Dispersing agents were used in the hydrometer analysis to prevent the flocculation of fine particles during the test.

Specific Gravity of Solids--

The specific gravity of solids (G_s) for raw and fixed sludges is defined as the ratio of the unit weight of dry sludge solids to that of water. The test procedure used to determine G_s is given in Appendix IV of EM 1110-2-1906 and in ASTM D854-58. A volumetric flask was used to measure precisely the volume of a suspension of sludge particles in water. Later determination of constituent weights allowed computation of G_s. Tests were originally performed using an oven drying temperature of $110 \pm 5^{\circ}C$. It was later discovered that hydration water was lost at this temperature, significantly affecting G_s values. Consequently, the tests were repeated using an oven drying temperature of $60^{\circ}C$.

Water Content--

The water content (w) of a sludge sample is defined as the ratio of the weight of water to the weight of solids in the sample and is normally expressed as a percentage. This value is termed dry weight basis water content. The values of w of fixed sludges were determined by the method presented in Appendix I of EM 1110-2-1906 and in ASTM D2216-71. A sludge sample of known weight was oven dried at $60^{\circ}C$ and the weight loss upon drying was attributed to loss of interstitial water.

Bulk and Dry Unit Weight--

The bulk unit weight (γ_b) of a sludge sample is defined as the ratio of total weight (solids and water) to total volume. Dry unit weight (γ_d) is defined as the ratio of oven dried ($60^{\circ}C$) weight to total volume. Values are expressed in lb/cu ft*. The standard procedures for both tests are found in Appendix II of EM 1110-2-1906. No ASTM test procedures have been established specifically for determining γ_b or γ_d. Although several ASTM test procedures (e.g., D698-70, D2166-66) include provision for determining the γ_b or γ_d of the test specimen, the method varies from test to test. Volumes were computed using linear measurements of a regularly shaped mass obtained by trimming or cutting.

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*A table of factors for converting British units of measurement to SI units of measurement appears on page x.

Porosity and Void Ratio--

The void ratio (e) of a sludge sample is defined as the ratio of the volume of voids to the volume of solids and is normally expressed as a decimal. Porosity (n) is defined as the ratio of the volume of voids to the total volume and is normally expressed as a percentage. The standard test procedure for determining e and n is found in Appendix II of EM 1110-2-1906. No ASTM standard test procedure exists; e and n are computed from test specimen weight and volume measurements as part of other standard test procedures (e.g., D 2435-70). The volume of solids was computed from the dry weight and G_s, and the total volume was determined during the test to determine γ_d.

The moisture-volume-weight values are related by the following set of equations:

$$e = \frac{V-V_s}{V_s} \quad (1)$$

$$n = \frac{e}{1+e} \times 100\% \quad (2)$$

$$w = \frac{W_w}{W_s} \times 100\% \quad (3)$$

$$G_s = \frac{W_s}{V_s \gamma_w} \quad (4)$$

$$\gamma_d = \frac{W_s}{V} \quad (5)$$

$$\gamma_b = \frac{W}{V} \quad (6)$$

$$S = \frac{V_w}{V-V_s} \times 100\% \quad (7)$$

$$\%\ \text{Solids} = \frac{W_s}{W} \times 100\% \quad (8)$$

where

V = total volume of sample, cu ft

V_s = volume of solids, cu ft

V_w = volume of water, cu ft

W = total weight of sample, lb

W_s = weight of solids, lb

W_w = weight of water, lb

e = void ratio

γ_d = dry unit weight, lb/cu ft

γ_b = bulk unit weight, lb/cu ft

γ_w = unit weight of water, usually taken as 62.4 lb/cu ft

n = porosity, %

w = water content (dry weight basis), %

G_s = specific gravity of solids

S = degree of saturation, %

Values of w determined on a dry weight basis can be converted to a wet weight basis (m) or to percent solids by weight using the following relationships:

$$m = \frac{w}{100+w} \times 100\% \qquad (9)$$

and

$$\%\ \text{solids} = \frac{100}{100+w} \times 100\% \qquad (10)$$

where m = water content (wet weight basis), %

Atterberg Limits--

Atterberg limit tests were performed on samples of raw and fixed sludge to determine the plasticity of the materials. The tests are designed to determine the limiting water contents, termed the plastic limit (PL) and liquid limit (LL), at which the material exhibits plastic and liquid behavior. The plasticity index (PI) or range of plastic behavior is defined as the difference between the LL and PL and is normally expressed as a percentage. Arbitrary tests have been developed to determine the Atterberg limits and are used as standard reference tests for the comparison of soil properties. Test procedures for determining the PL and LL are presented in Appendix III and IIIA of EM 1110-2-1906 and ASTM standard tests D424-59 and D423-66. The PL is defined as the w at which the sludge will start to crumble when rolled into a 1/8 in thread under the palm of the hand. The tests were conducted by taking a small specimen of sludge at a w at which a ball could be shaped easily without sticking to the fingers. The ball was then rolled into a thread on a piece of ground glass. If the thread diameter became 1/8 in without crumbling, the procedure was repeated until drying caused the thread to break at 1/8 in diameter. The w was then determined; a check test was performed; and the average w was taken as the PL.

The LL is defined as the lowest w at which the sludge will flow as a viscous liquid, arbitrarily defined as the w at which two halves of a soil specimen separated by a groove of standard dimensions will close along a distance of 1/2 in under the impact of 25 blows of a standard device. The standard device cited in the definition consists of a brass cup and a cam mechanism, which is used to drop the cup a distance of 10 mm onto a base of a known dynamic resilience. A specimen of sludge was placed in the cup at a w higher than the LL. A standard tool was used to shape a groove of known dimensions through the specimen. The cup was then dropped onto the base a number of times until the groove closed 1/2 in, with the required number of blows recorded. The w of the specimen was then determined. This procedure was repeated several times as the material dried slightly until the number of blows to close the groove exceeded 25. The results were plotted on a graph of w versus number of blows and the w corresponding to 25 blows was termed the LL.

Classification--

Soils engineers use classification systems to group together soils that exhibit similar properties, and use the classification of a soil as an aid to describe the soil properties in a general way. The Unified Soil Classification System (USCS) is a widely used system "based on the identification of soils according to their textural and plasticity qualities and on their grouping with respect to behavior."[4] Using the results of the grain-size analyses and the Atterberg limits, raw and soil-like fixed sludges were classified according to the USCS. Table 4 outlines the procedure used to classify the sludge samples in accordance with the USCS, and Tables 5 and 6 summarize some of the general characteristics of each type of soil. The procedure for classifying soil by the USCS is ASTM standard method D2487-69, and further information concerning the USCS and the properties of soils in each group is available in References 4 through 7.

Engineering Properties Tests

Compaction Test--

The 15-blow compaction test was performed on fixed sludge samples to determine the optimum water content (OMC) for compaction and the unit weights which could be expected from field compaction of the fixed sludge when used as a construction material. The test procedure is presented in Appendix VI of EM 1110-2-1906 and is identical to the procedure of ASTM D698-70, except that 15 (as opposed to 25 or 56) blows are used to compact each layer. A 4 in diameter, 1/30 cu ft cylindrical mold was filled with three equal layers of sludge. Each layer was compacted with 15 uniformly distributed blows using a 5.5 lb hammer with 12 in drop. Following compaction the specimen was weighed and the γ_d and the w were determined. The entire test was then repeated with a small amount of water added to the specimen to increase the w. Results of the test were expressed as a plot of γ_d versus w. The OMC for compaction was considered to be that at which the maximum γ_d was achieved. The 15-blow test described above has a laboratory compactive effort of 7400 ft-lbs/cu ft and simulates conditions encountered when material is placed in a landfill using available equipment such as bulldozers, etc. for compaction, rather than using more sophisticated compaction equipment. Also available is the Standard Proctor test, which has a laboratory compactive effort of 12,400 ft-lbs/cu ft and simulates the compactive effort required for fill placed in roadway subgrades or dams. The Modified Proctor test has a laboratory compactive effort of 56,000 ft-lb/cu ft and is designed to simulate the compactive effort of several passes using modern compaction equipment. Such compaction is necessary in large scale highway construction projects. The 15-blow test was selected for fixed sludge testing because the lower compactive effort is more representative of the field compaction necessary for general landfill applications using fixed sludges.

TABLE 4. THE UNIFIED SOIL CLASSIFICATION SYSTEM

Major Division		Group Symbol	Laboratory Classification Criteria: Finer than 200 Sieve %	Laboratory Classification Criteria: Supplementary Requirements	Soil Description
Coarse-grained (over 50% by weight coarser than No. 200 sieve)	Gravelly soils (over half of coarse fraction larger than No. 4)	GW	0–5*	D_{60}/D_{10} greater than 4, $D_{30}^2/(D_{60} \times D_{10})$ between 1 & 3	Well-graded gravels, sandy gravels
		GP	0–5*	Not meeting above gradation for GW	Gap-graded or uniform gravels, sandy gravels
		GM	12 or more*	PI less than 4 or below A-line	Silty gravels, silty sandy gravels,
		GC	12 or more*	PI over 7 and above A-line	Clayey gravels, clayey sandy gravels
	Sandy soils (over half of coarse fraction finer than No. 4)	SW	0–5*	D_{60}/D_{10} greater than 4, $D_{30}^2/(D_{60} \times D_{10})$ between 1 & 3	Well-graded sands, gravelly sands
		SP	0–5*	Not meeting above gradation requirements	Gap-graded or uniform sands, gravelly sands
		SM	12 or more*	PI less than 4 or below A-line	Silty sands, silty gravelly sands
		SC	12 or more*	PI over 7 and above A-line	Clayey sands, clayey gravelly sands
Fine-grained (over 50% by weight finer than No. 200 sieve)	Low compressibility (liquid limit less than 50)	ML	Plasticity chart		Silts, very fine sands, silty or clayey fine sands, micaceous silts
		CL	Plasticity chart		Low plasticity clays, sandy or silty clays
		OL	Plasticity chart, organic odor or color		Organic silts and clays of low plasticity
	High compressibility (liquid limit more than 50)	MH	Plasticity chart		Micaceous silts, diatomaceous silts, volcanic ash
		CH	Plasticity chart		Highly plastic clays and sandy clays
		OH	Plasticity chart, organic odor or color		Organic silts and clays of high plasticity
Soils with fibrous organic matter		Pt	Fibrous organic matter; will char, burn, or glow		Peat, sandy peats, and clayey peat

* For soils having 5 to 12 per cent passing the No. 200 sieve, use a dual symbol such as GW–GC.

TABLE 5. USCS SOIL TYPES: CHARACTERISTICS PERTINENT TO FOUNDATIONS AND EMBANKMENTS (After Reference 4)

Symbol	Name	Value for embankments	Compaction characteristics*	Value for foundations	Requirements for seepage control
GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Very stable, pervious shells of dikes and dams	Good, tractor, rubber-tired, steel-wheeled roller	Good bearing value	Positive cutoff
GP	Poorly-graded gravel or gravel-sand mixtures, little or no fines	Reasonably stable, pervious shells of dikes and dams	Good, tractor, rubber-tired, steel-wheeled roller	Good bearing value	Positive cutoff
GM	Silty gravels, gravel-sand-silt mixtures	Reasonably stable, not particularly suited to shells, but may be used for impervious cores or blankets	Good, with close control, rubber-tired, sheepsfoot roller	Good bearing value	Toe trench to none
GC	Clayey gravels, gravel-sand-clay mixtures	Fairly stable, may be used for impervious core	Fair, rubber-tired, sheepsfoot roller	Good bearing value	None
SW	Well-graded sands or gravelly sands, little or no fines	Very stable, pervious sections, slope protection required	Good, tractor	Good bearing value	Upstream blanket and toe drainage or wells
SP	Poorly-graded sands or gravelly sands, little or no fines	Reasonably stable, may be used in dike section with flat slopes	Good, tractor	Good to poor bearing value depending on density	Upstream blanket and toe drainage or wells
SM	Silty sands, sand-silt mixtures	Fairly stable, not particularly suited to shells, but may be used for impervious cores or dikes	Good, with close control, rubber-tired, sheepsfoot roller	Good to poor bearing value depending on density	Upstream blanket and toe drainage or wells
SC	Clayey sands, sand-clay mixtures	Fairly stable, use for impervious core for flood control structures	Fair, sheepsfoot roller, rubber-tired roller	Good to poor bearing value	None
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor stability, may be used for embankments with proper control	Good to poor, close control essential, rubber-tired roller, sheepsfoot roller	Very poor, susceptible to liquefaction	Toe trench to none
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Stable, impervious cores and blankets	Fair to good, sheepsfoot roller, rubber-tired roller	Good to poor bearing	None
OL	Organic silts and organic silt-clays of low plasticity	Not suitable for embankments	Fair to poor, sheepsfoot roller	Fair to poor bearing, may have excessive settlements	None
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor stability, core of hydraulic fill dam, not desirable in rolled fill construction	Poor to very poor, sheepsfoot roller	Poor bearing	None
CH	Inorganic clays of high plasticity, fat clays	Fair stability with flat slopes, thin cores, blankets and dike sections	Fair to poor, sheepsfoot roller	Fair to poor bearing	None
OH	Organic clays of medium to high plasticity, organic silts	Not suitable for embankments	Poor to very poor, sheepsfoot roller	Very poor bearing	None
Pt	Peat and other highly organic soils	Not used for construction	Compaction not practical	Remove from foundations	

*The equipment listed will usually produce the desired densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled.

TABLE 6. USCS SOIL TYPES: CHARACTERISTICS PERTINENT TO ROADS AND AIRFIELDS (After Reference 4)

Symbol	Name	Value as subgrade when not subject to frost action	Value as sub-base when not subject to frost action	Value as base when not subject to frost action	Potential frost action	Compressibility and expansion	Drainage characteristics	Compaction equipment*
GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller
GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Good	Fair to good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller
GM	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good to fair	Fair to good	Slight to medium	Slight	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture
GC	Clayey gravels, gravel-sand-clay mixtures	Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller
SW	Well-graded sands or gravelly sands, little or no fines	Good	Fair to good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller
SP	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Fair	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller
SM	Silty sands, sand-silt mixtures	Fair to good	Fair to good	Poor	Slight to high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture
SC	Clayey sands, sand-clay mixtures	Poor to fair	Poor	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor to fair	Not suitable	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired roller, sheepsfoot roller
OL	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired roller, sheepsfoot roller
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber-tired roller
CH	Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller
OH	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller
Pt	Peat and other highly organic soils	Not suitable	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical

*The equipment listed will usually produce the desired densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled.

Unconfined Compression Test--

The unconfined compression test is used to determine the uniaxial, unconfined compressive strength of a cohesive or cemented material. The tests were performed on fixed sludges to determine their relative strength for bearing capacity or embankment construction. A cylindrical specimen of the sludge was prepared and loaded axially until failure. The test load was applied using a controlled rate of strain (1 percent/min), and compressive stresses were recorded as the loading progressed. The peak compressive stress sustained by the specimen was considered the unconfined compressive strength of the material. The undrained shear strength (τ) is approximately one-half the unconfined compressive strength of cohesive soil, and was determined for soil-like samples. Multiple specimens were used for each test and results were averaged to construct a composite stress-strain curve. Young's modulus of elasticity, defined as the slope of the stress-strain curve, was determined from the composite stress-strain curves. The standard test procedure, found in Appendix XI of EM 1110-2-1906 and in ASTM standard method D2166-66, was followed except that a specimen height-to-diameter ratio of 2.0 was used instead of the normal 2.1.

Permeability Tests--

Two types of tests, both applicable for determining the coefficient of permeability (k) of fine-grained soil, were used to determine the k of raw and fixed sludges. A falling head permeability test was used for the raw sludges, while fixed sludges were tested in a triaxial compression chamber with back pressure used to ensure complete saturation. Test descriptions are presented below.

<u>Permeability Test for Raw Sludges</u>--The following permeameter, sample preparation, procedure, and calculations were used to determine the k of samples of raw sludge. The test is a falling head test and is appropriate for testing fine-grained material having k less than 10^{-3} cm/sec.[2]

Permeameter--Figure 11 shows a schematic diagram of the test set-up. The permeameter was constructed of plastic tubing with an inside diameter of 12.7 cm, and ports were provided to allow water to enter into the upper chamber and to exit from the lower chamber. The permeameter was constructed of clear plastic so that the lengths of the samples could be measured during the tests.

Support for the samples was provided by four sheets of filter paper resting on a No. 200 mesh (200 openings per linear inch) wire screen. The filter paper was provided to prevent the migration of fine particles from the sludge. The k of the support system was 1.100 x 10^{-4} cm/sec, greater than the anticipated permeability of the sludges, so that any flow restriction would not influence the determination of the k of the sludges.

The samples were topped with No. 200 mesh wire screen and 5 cm of Ottawa sand to maintain a uniform sludge surface. While the k of the Ottawa sand layer was not quantified, this material was selected because it is known to be several orders of magnitude more permeable than the sludge. The Ottawa sand did not restrict the flow of water to the sludge samples. Prior to beginning

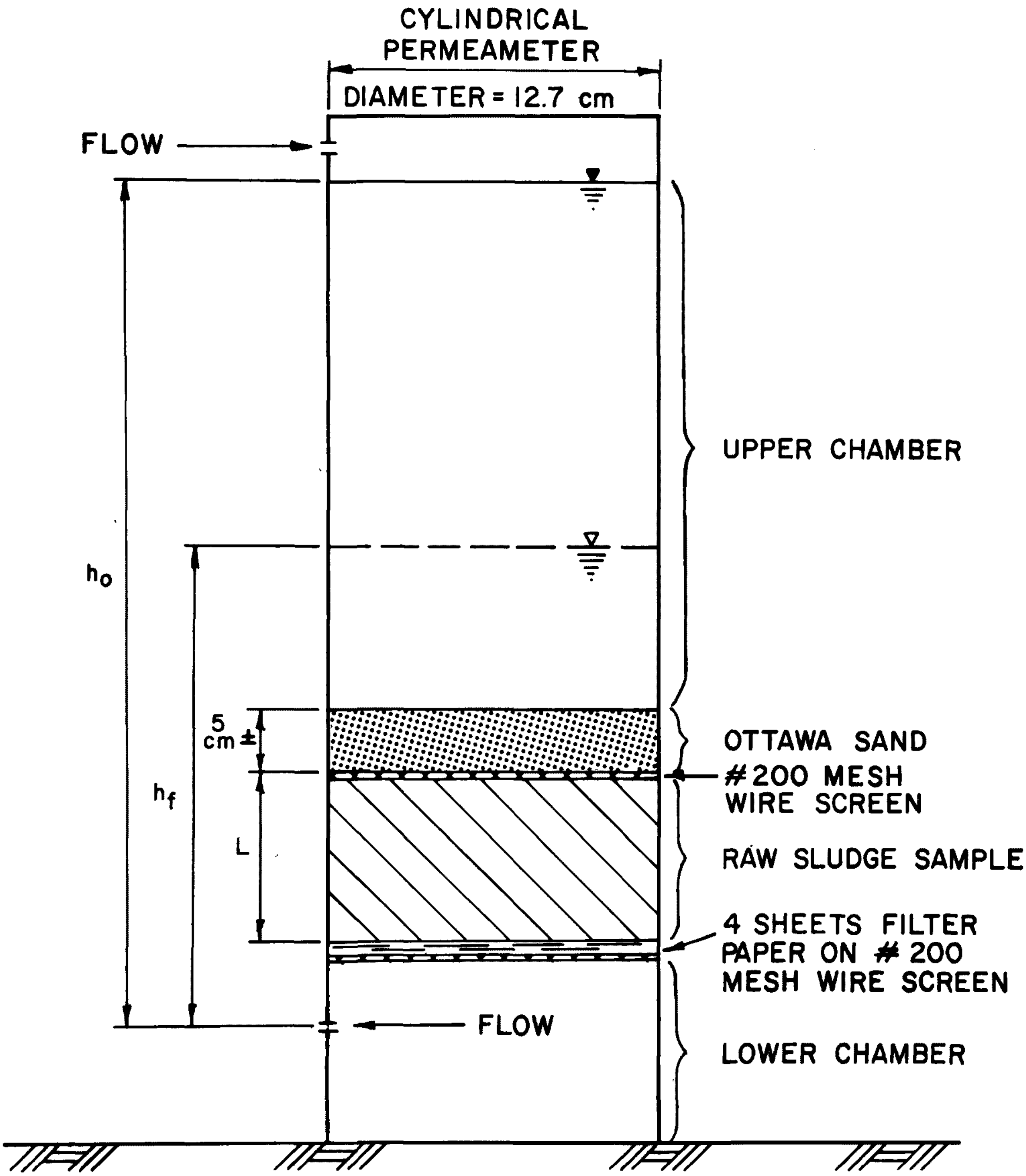


Figure 11. Schematic diagram of falling head permeability test set-up used for raw sludges.

the tests, the lower chamber was filled with deaired distilled water and the 4 sheets of filter paper were saturated.

Sample preparation--A slurry was prepared by mixing sludge with deaired distilled water in a mixer bowl so that the particles in the slurry were completely dispersed. Sludge slurry was then poured into the permeameter until a column 7 to 10 cm in height was obtained. The column was then gently rodded to release entrapped air, thus ensuring complete saturation. The No. 200 screen and the 5 cm of Ottawa sand were placed in the column, completing the sample preparation. The γ_d of slurry placed inside the permeameter was determined so that the γ_d of the sludge sample during the test could be determined.

Test procedure--A small head (h_o) was established by placing deaired distilled water in the upper chamber to a height approximately 20 cm above the Ottawa sand. The head was allowed to fall from h_o to h_f during an arbitrary time (t). During the time allowed for the head to fall, the temperature of the water was determined.

Due to seepage forces caused by the downward flow of water, the sludge column consolidated somewhat during the test. It was necessary, therefore, to continue the flow for a time sufficient for the sludge to stabilize. The flow rate of water through the sludge sample was measured repeatedly until the flow became steady. When the flow was steady, the length (L) of the sludge sample was measured.

When the procedure had been completed, the permeameter tube was vibrated externally to cause further densification (increase in unit weight) of the sludge. The test procedure was then repeated so that the k of the sludge at the higher unit weight could be determined. The length of the densified sludge sample was measured as before for γ_d determination.

Calculations--The γ_d of the sludge sample was determined by using the following formula:

$$\gamma_d = \frac{(0.000035)W_s}{V} \quad (11)$$

where

γ_d = dry unit weight, lb/cu ft

0.000035 = factor to convert lb/cm^3 to lb/cu ft

W_s = weight of dry sludge particles in permeameter, lb

V = volume of sludge sample in permeameter during time (t) for head to fall from h_o to h_f, cu ft

The k of the sludge sample was determined by using the following formula:

$$k_{20} = 2.303 \frac{L\ R_t}{t} \log_{10} \frac{h_o}{h_f} \quad (12)$$

where

k_{20} = coefficient of permeability for water at 20°C, cm/sec

2.303 = factor for converting logarithms from natural base to base 10.

L = length of sample at time of test, cm

R_t = Viscosity correction factor, determined by dividing the viscosity of water at the test temperature by the viscosity of water at 20°C

t = time for head to fall from h_o to h_f, sec

h_o = head at start of test, cm

h_f = head at finish of test, cm

Permeability test for fixed sludges--Accurate determinations of the k of porous materials can be obtained only by testing samples that are completely saturated. The complete saturation of cohesive soils, concrete, and other materials with low permeability is difficult to ensure; and for this reason the application of pressure is used to saturate samples as much as possible. During this study samples of fixed sludge were tested using a falling head permeability test conducted in a triaxial compression chamber with back pressure to increase saturation. The difference between the chamber pressure and the back pressure was 10 lb/sq in.

The test procedure itself is complex and requires considerable care and experience. The exact test procedure, including sample preparation, equipment and calculations is fully described in Reference 2. The only deviation from the procedure cited therein was specimen diameter. Standard specimen diameter is 2.8 in, but the specimens tested were 3 in in diameter. The ASTM has not published a standard method suitable for determining the permeability of fixed sludge.

Durability Tests

Samples of fixed sludge were subjected to freeze-thaw tests and to wet-dry tests to evaluate the resistance of these fixed sludges to natural weathering stresses. The 2 tests are standard ASTM tests used to estimate the durability of soil-cement mixtures.

Freeze-Thaw Test--

Properly cured fixed sludge samples were subjected to the standard freezing and thawing test of compacted soil-cement mixtures, ASTM test D560-57. This test calls for cylindrical samples to be subjected to 12 test cycles, each consisting of freezing for 24 hours, thawing for 23 hours, and 2 firm strokes on all surface areas with a wire scratch brush. Performance is evaluated by determining the weight loss after 12 cycles or the number of cycles to cause disintegration, whichever occurs first.

The procedure specified in ASTM D560-57 was followed except that test specimens were 3 in in diameter and 4 to 6 in in height, rather than 4 in in diameter and 4.5 in in height. Specimens for all properties tests were 3 in in diameter to accomodate WES specifications for leaching column tests.

Wet-Dry Test--

The wet-dry test is similar to the freeze-thaw test. Cured cylinders of fixed sludge were subjected to 12 test cycles, each consisting of 5 hours of submergence in water, 42 hours of oven drying, and 2 firm strokes on all surface areas with a wire scratch brush. Test results are presented as weight loss after 12 cycles or the number of cycles causing sample disintegration, whichever occurs first. A detailed test procedure is given in ASTM D559-57, which is the standard wetting and drying test of compacted soil-cement mixtures. As in the case of the freeze-thaw test, specimens were 3 in in diameter and 4 to 6 in in height, rather than 4 in in diameter and 4.5 in in height.

SECTION 5

PROPERTIES OF RAW AND FIXED SLUDGES

PHYSICAL PROPERTIES

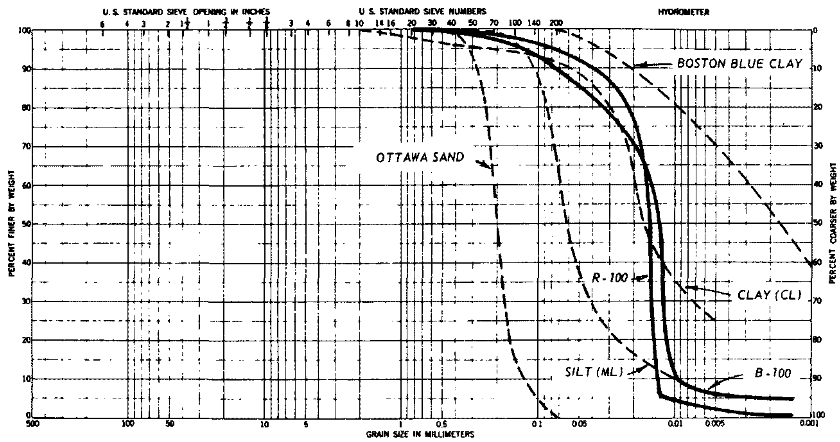
Grain-size Analysis

Results from the combined sieve and hydrometer analyses were used to determine the grain-size distributions of 9 raw sludges, 9 sludges fixed by process B, and 1 sludge fixed by process F. No other fixed sludges exhibited soil-like characteristics; therefore no other fixed sludges were tested. The grain-size distributions are presented in Figures 12, 13, and 14 as grain size in mm versus percent finer by weight. Results of testing raw and fixed samples of the respective sludge types are presented on the same figure, and some typical grain-size distributions for common soils are included for comparison.

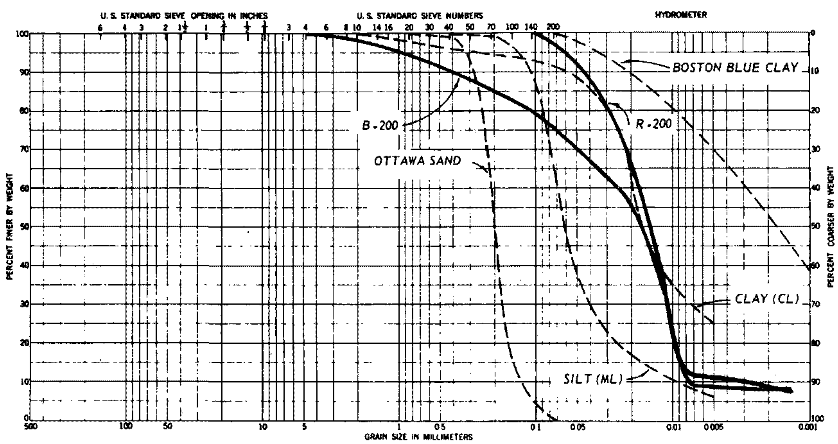
Median grain sizes as determined by the grain size analyses ranged between 0.0076 and 0.125 mm. The sludges are generally well-graded with a smooth distribution of grain sizes. A high percentage of the particles of raw sludges and sludges fixed by process B pass the #200 sieve (.074mm), usually indicative of low permeability, low strength, and high compressibility.[5,6]

Comparison of the grain-size distributions of raw sludges with corresponding sludges fixed by process B shows that fixation had only a slight effect on the distribution of particle sizes. There was essentially no change in gradation for sludge 800; the fixation process resulted in a generally finer gradation for sludges 100, 400, 500, and 600; and sludges 200, 300, 900, and 1000 exhibited generally coarser gradations after fixation. It was anticipated that a particular fixation process would have a consistent effect on the grain-size distribution of the various sludges; however, effects on gradation were not uniform for all sludges fixed by process B. Differences in gradation can be partially attributed to the imprecision inherent in the sample preparation procedure. Grinding in a mortar using a rubber coated pestle may not separate all agglomerated particles and may break some individual particles into smaller particles. In general, sludges fixed with process B exhibited gradations in the same ranges as the corresponding raw sludges and very similar to those of silty soils.

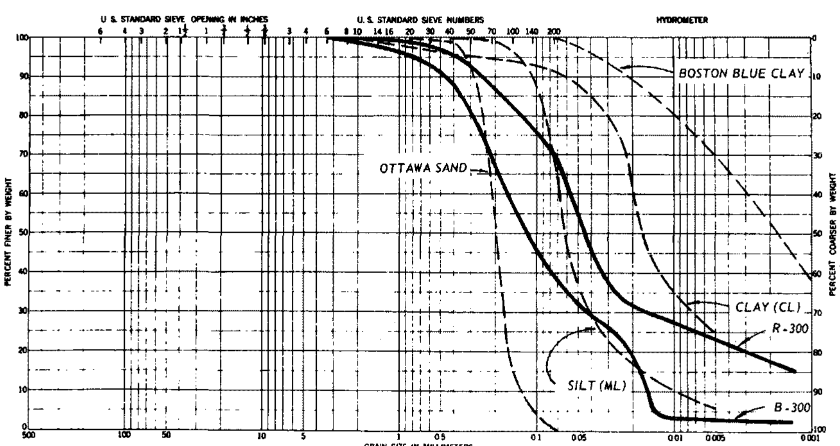
Grain-size analyses for sludge 600 fixed by process F were only partially successful due to flocculation of the sludge suspension during the hydrometer analysis. Several attempts were made to run the test using the deflocculants tetraphosphate and sodium oxalate; however, in all cases flocculation occurred after four minutes at a grain size of 0.02 mm. Flocculation of fixed sludge F-600 was apparently caused by the chemical fixing agent, since the raw type



SLUDGE 100



SLUDGE 200



SLUDGE 300

Figure 12. Grain-size distributions, raw and fixed sludges.

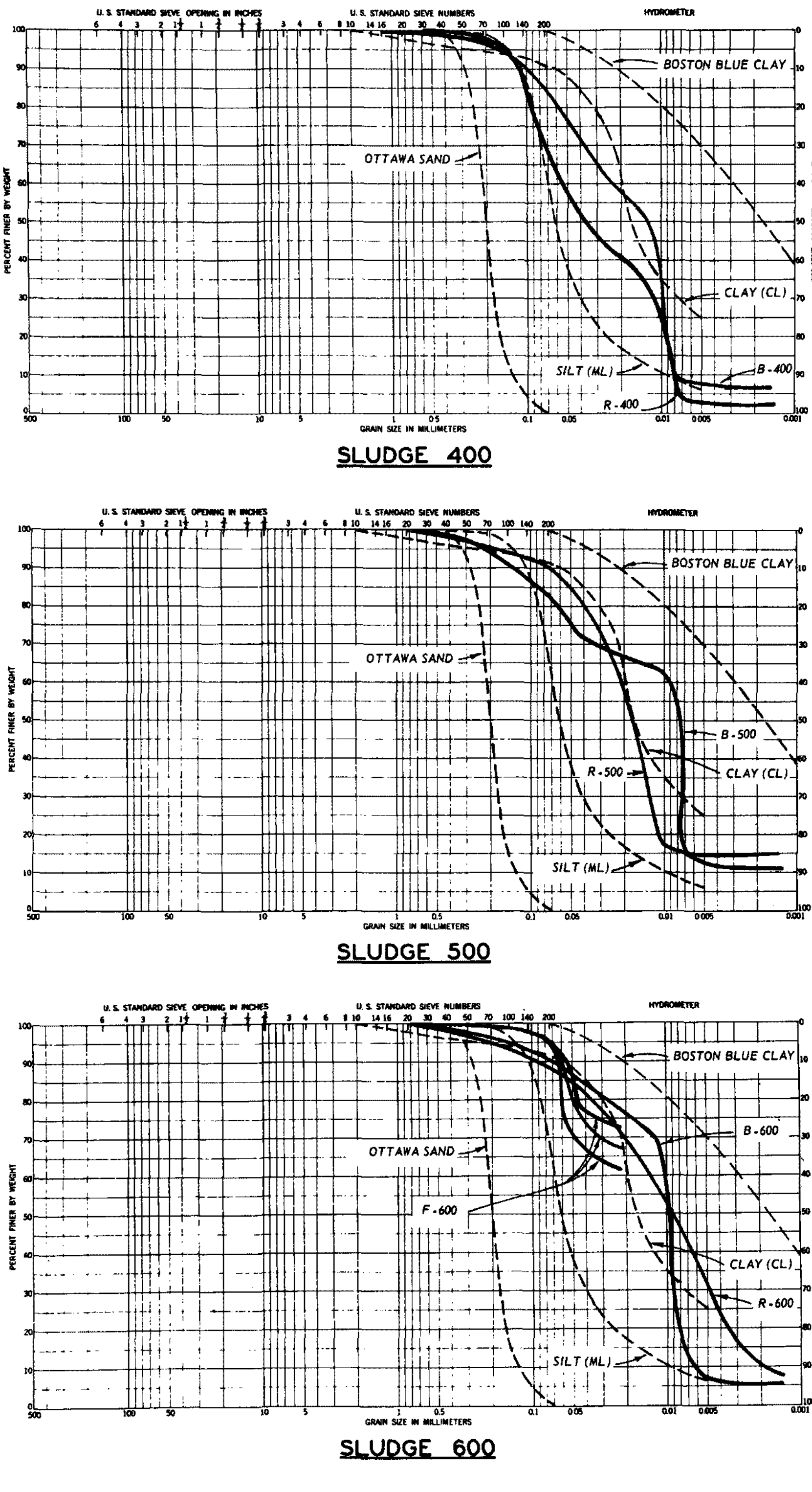
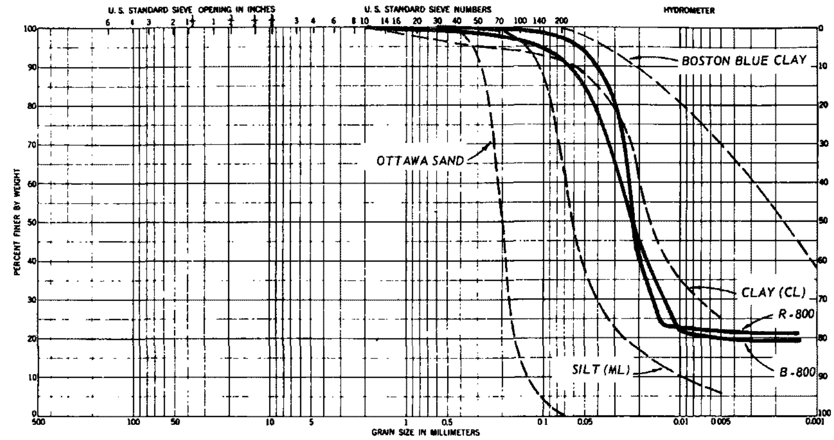
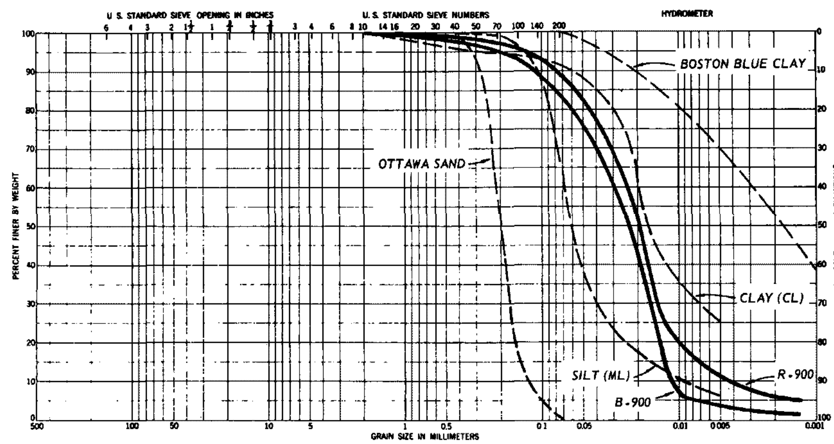


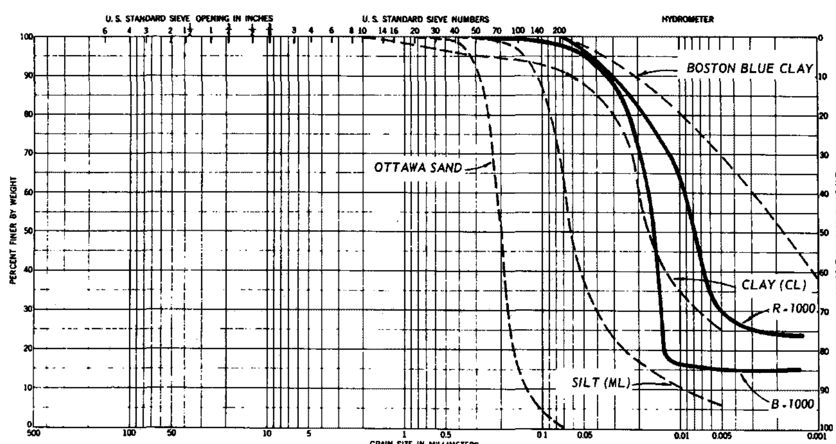
Figure 13. Grain-size distributions, raw and fixed sludges.



SLUDGE 800



SLUDGE 900



SLUDGE 1000

Figure 14. Grain-size distributions, raw and fixed sludges.

600 sludge was successfully tested. Results of these tests are presented in Figure 13.

Atterberg Limits

The Atterberg limits of eight raw sludges and seven fixed sludges (process B) were determined. Values for the liquid limit (LL), the plastic limit (PL), and the plasticity index (PI) are listed in Table 7. The fixation process increased the LL and the PI of the sludge in some cases and decreased the values in other cases. The data are plotted on a standard plasticity chart in Figure 15. For all sludges the points plotted below the A-line, the arbitrary boundary between silts and inorganic clays. However, fixed sludges tended to appear further below the A-line than did the raw sludges, indicating a general decrease in plasticity due to the fixation process.

Classification

Because raw sludges and sludges fixed by process B are soil-like in texture, these sludges were classified according to the USCS; but the classification of these sludges does not indicate that they are soils. The sludges were classified as ML, MH or SM, all silty soils (see Table 7), and exhibited properties similar to these soil types. General statements concerning the properties of these soil types and of their behavior under a variety of field conditions have been formulated on the basis of extensive experience and are summarized in Tables 5 and 6.

Specific Gravity

The specific gravities of raw and fixed sludges are presented in Table 8. A total of 42 tests were conducted on samples of raw and fixed sludges. Values of specific gravity (G_s) were within the range of common minerals and soils as shown in Figure 16.

Values of G_s for the raw sludges varied from 2.41 to 3.96, a range extending somewhat higher than that of soils. In general, the various fixation processes caused only slight changes in G_s. Process A resulted in either lower or unchanged G_s values for all sludges. Processes B, E, F, and G caused slight changes, resulting in values both higher and lower than the G_s values of the corresponding raw sludges. Process C reduced the G_s of raw sludges 200 and 700 significantly. Values were 34 or 51 percent lower respectively than those of the corresponding raw sludges. From these comparisons it seems that changes in G_s do not seem to be dependent on the type of sludge processed, although sludges 500 and 1000 experienced decreases in G_s for all fixation processes tested.

The G_s of fixed sludge D-200 reported in Table 8 is the bulk specific gravity (G_b), determined by dividing the total weight of the plastic cylinder containing the sludge by the weight of an equal volume of water. Since the volume of the sludge mass includes void spaces, G_b is not comparable to G_s. In addition, the value for G_b of the test specimen of fixed sludge D-200 is indicative of sludge D-200 only when the process involves the same relative proportions of sludge and plastic as the test specimen. A variation of either

TABLE 7. PHYSICAL PROPERTIES OF RAW SLUDGES AND SLUDGES FIXED BY PROCESS B

Sludge	D_{50} mm	LL %	PL %	PI %	USCS* classification
R-100	0.016	42	36	6	ML
R-200	0.015	107	58	49	MH
R-300	0.044	50	37	13	MH
R-400	0.029	51	38	13	MH
R-500	0.016	95	67	28	MH
R-600	0.009	NP	NP	NP	ML
R-700	0.016	201	109	92	MH
R-800	0.022	37	30	7	ML
R-900	0.020	NP	NP	NP	ML
R-1000	0.0076	44	37	7	ML
B-100	0.014	NP	NP	NP	ML
B-200	0.015	98	76	22	MH
B-300	0.125	NP	NP	NP	SM
B-400	0.012	100	85	15	MH
B-500	0.0074	80	70	10	MH
B-600	0.011	108	100	8	MH
B-800	0.022	38	33	5	ML
B-900	0.023	51	47	4	MH
B-1000	0.016	64	57	7	MH

D_{50} = median grain size

LL = liquid limit

PL = plastic limit

PI = plasticity index

NP = non-plastic

* = Use of the USCS indicates only that sludges have properties similar to those of soils and does not mean that sludges are silts, sandy silts, etc. See Tables 4-6 for description of soils in each classification.

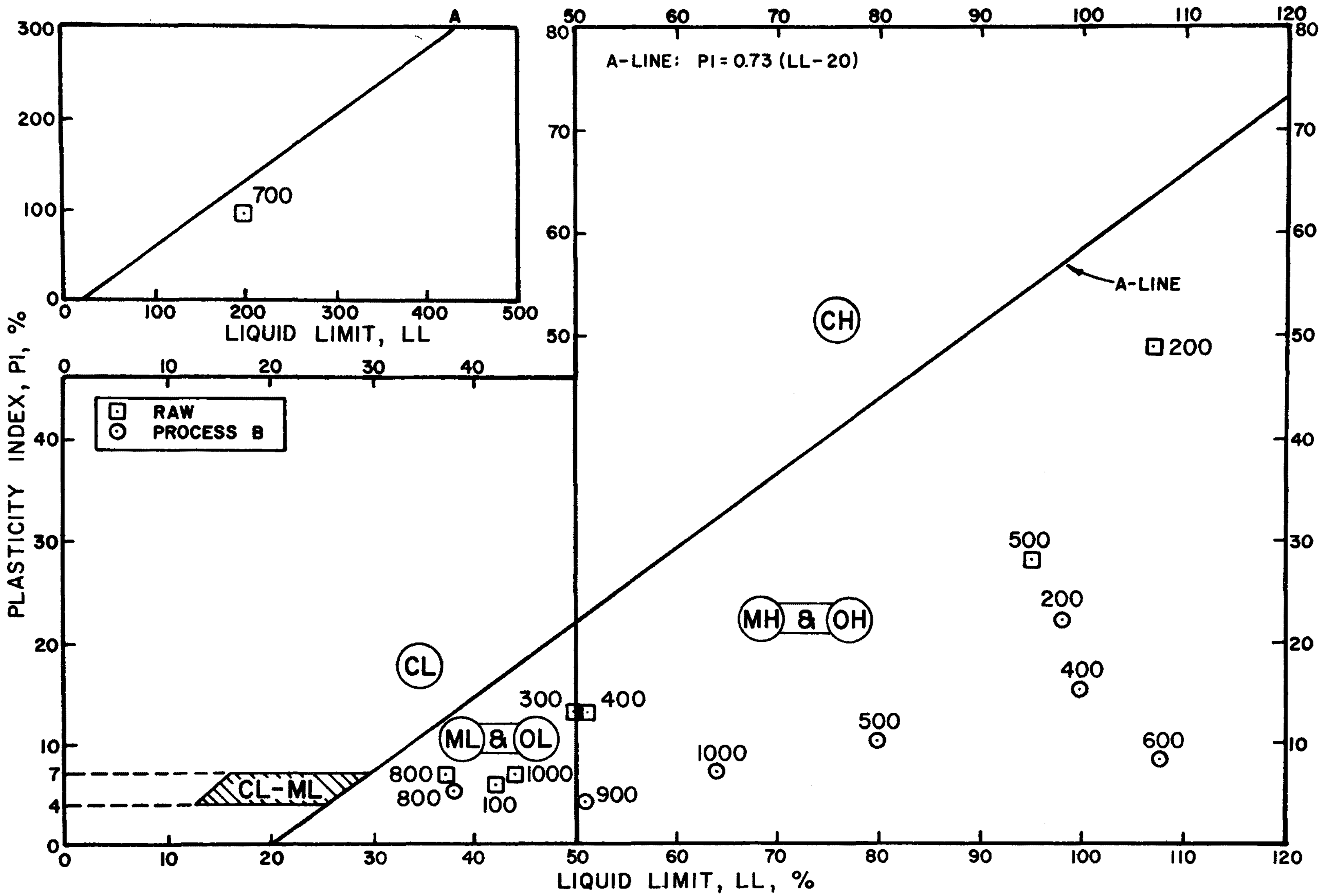


Figure 15. Plasticity chart for raw sludges and sludges fixed by process B (see Table 4).

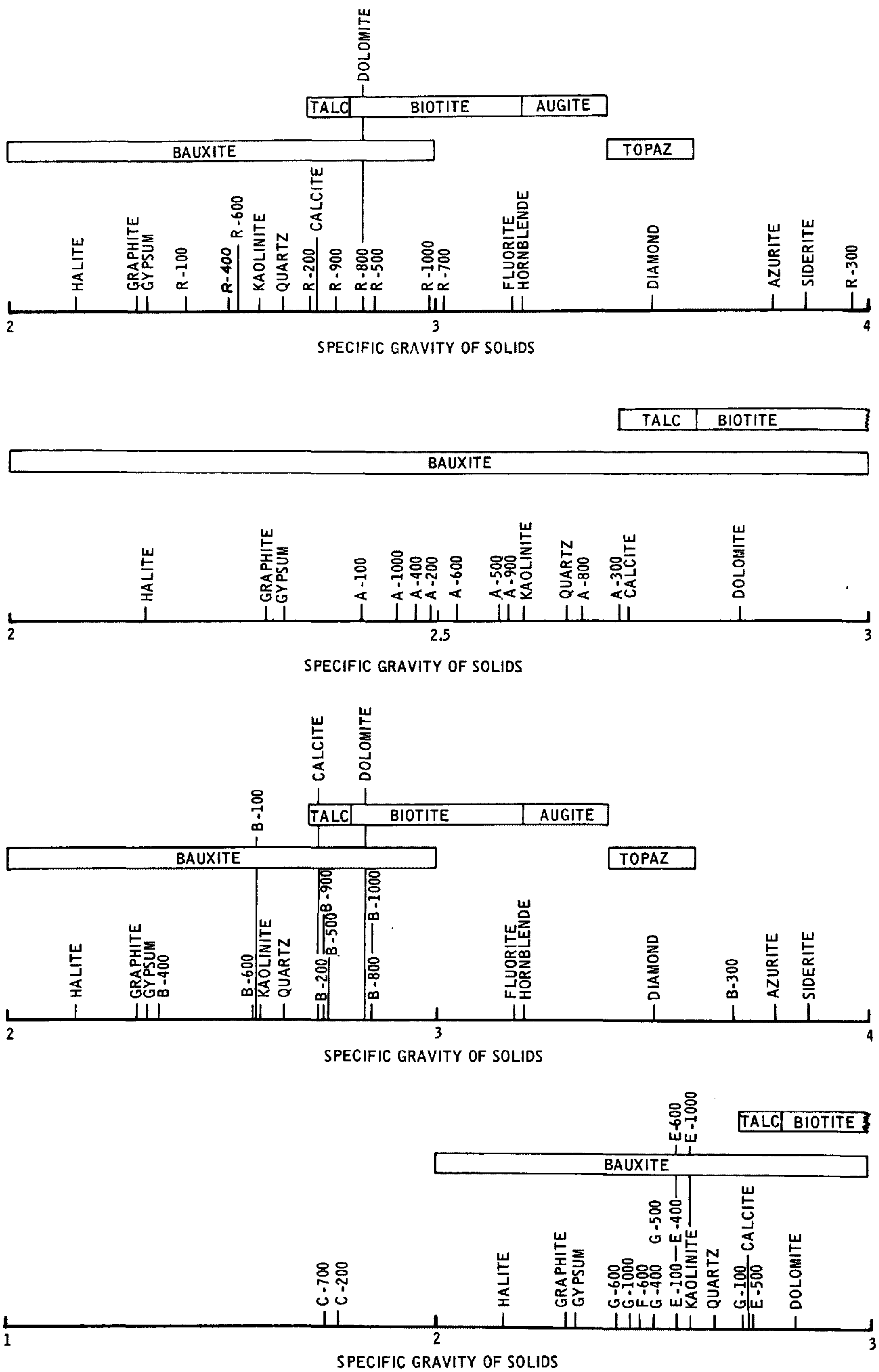


Figure 16. Specific gravities of common minerals compared to those of raw and fixed sludges.

TABLE 8. COMPARISON OF SPECIFIC GRAVITIES OF RAW AND FIXED SLUDGES†

Sludge	Specific Gravity							
	Raw	Fixation Process						
		A	B	C	D	E	F	G
100	2.41	2.41	2.58			2.54		2.70
200	2.70	2.49	2.73	1.77	1.18*			
300	3.96	2.71	3.68					
400	2.51	2.47	2.35			2.55		2.49
500	2.85	2.57	2.74			2.72		2.50
600	2.53	2.52	2.57			2.57	2.46	2.41
700	3.09			1.74				
800	2.82	2.67	2.84					
900	2.76	2.58	2.73					
1000	2.99	2.45	2.84			2.61		2.44

Note: Blank spaces indicate processors did not fix that sludge. See Table 2.

* Bulk specific gravity of entire cylinder of fixed sludge, including plastic coating and voids within sludge structure.

† This Table presents corrections to data presented in Tables 13 and 14 of Reference 1.

the specimen volume or the thickness of the plastic coating will result in different values of G_b, due to the dissimilarity of the sludge and the plastic.

Moisture-Volume-Weight Relationships

Water Content--

The water contents (w) of samples of fixed sludge were determined and are listed in Table 9. These data indicate that the relative amount of available interstitial water after fixation is greatly process-dependent. Sludges fixed by process B exhibited values of w comparable to those of natural soils. Processes A, C, E, F, and G produced fixed sludges with a wide range of properties. These fixed sludges were plastic or rubber-like masses or hard materials resembling concrete. The conventional w determination has little meaning for such materials. The w of the sludge portion of sample D-200 is unknown because the plastic coating on the sample prevents the escape of any water from within the sludge mass.

Void Ratio and Porosity--

Values for the void ratio (e) and the porosity (n) of the fixed sludges are presented in Table 9. The results are also presented in a comparison graph in Figure 17. The data indicate that the e and n of the fixed sludges are process-dependent. Processes A, C, E, and F resulted in fixed sludges whose e values vary between 0.601 and 1.418, corresponding to n values between 37.5 percent and 58.7 percent. These values are comparable to those of fine sands, silts, and silty clays. Processes B and G resulted in fixed sludges whose e values range between 1.617 and 3.857, corresponding to n values between 61.8 percent and 79.4 percent. These values are in the range of values typical of soils with significant amounts of small clay particles. The e and n of fixed sludge D-200 were not determined because the value of G_s was not known. Values of e and n for the sludge mass inside the plastic coating would be meaningless because they would not be representative of the fixed sludge as a whole, which includes the plastic coating.

Bulk and Dry Unit Weight--

The bulk and oven-dry unit weights (γ_b and γ_d, respectively) of the fixed sludges were determined and are presented in Table 9. Processes A and B yielded materials whose γ_b values are in the range typical of soils and whose γ_b and γ_d values differ, as would those of soils. The remaining processes resulted in materials having smaller differences between γ_b and γ_d in some cases showing very little difference. This is again indicative of process-dependence. The laboratory values of γ_b and γ_d for sludge fixed by process D were of course identical because the plastic coating prevented water from escaping from within the sludge mass.

ENGINEERING PROPERTIES

Compaction

TABLE 9. PHYSICAL PROPERTIES OF FIXED SLUDGES*

Sludge	Specific** gravity	Water content %	Void ratio	Porosity %	Bulk† unit weight lb/ft^3	Dry unit weight lb/ft^3
A-100	2.41	23.8	0.860	46.2	100.1	80.9
A-200	2.49	29.7	1.008	50.2	100.4	77.4
A-300	2.71	20.6	0.963	49.0	103.9	86.2
A-400	2.47	24.2	0.768	43.4	108.3	87.2
A-500	2.57	41.4	1.377	57.9	95.5	67.5
A-600	2.52	15.6	0.663	39.9	109.3	94.6
A-800	2.67	15.8	0.881	46.8	102.6	88.6
A-900	2.58	20.9	1.418	58.7	85.9	66.6
A-1000	2.45	23.7	0.958	48.9	96.6	78.1
B-100	2.58	77.5	2.711	73.1	77.0	43.4
B-200	2.73	83.6	2.595	72.2	87.1	47.4
B-300	3.68	97.2	3.857	79.4	93.2	47.3
B-400	2.35	69.5	1.794	64.2	89.0	52.5
B-500	2.74	67.3	2.150	68.3	90.8	54.3
B-600	2.57	88.9	2.811	73.8	79.6	42.1
B-800	2.84	30.3	1.181	54.1	105.9	81.3
B-900	2.73	63.3	2.225	69.0	86.2	52.8
B-1000	2.84	70.9	2.717	73.1	81.5	47.7
C-200	1.77	43.2	1.097	52.3	75.4	52.7
C-700	1.74	45.6	1.409	58.5	65.7	45.1
D-200	1.18††				73.6	73.6
E-100	2.54	6.4	0.671	40.2	101.1	94.9
E-400	2.55	8.7	1.072	52.2	82.7	76.1
E-500	2.72	6.5	0.822	45.1	99.3	93.2
E-600	2.57	10.7	0.601	37.5	110.9	100.2
E-1000	2.61	0.7	0.987	49.7	82.7	82.0
F-600	2.46	3.7	0.996	49.1	81.0	78.1
G-100	2.70					
G-400	2.49	10.7	1.737	63.5	62.7	56.8
G-500	2.50	7.6	2.198	68.7	52.5	48.8
G-600	2.41	13.3	1.991	66.6	56.9	50.3
G-1000	2.44	17.0	1.617	61.8	68.1	58.2

* Tests conducted using 60°C oven for drying; this Table presents corrections to data presented in Tables 13 and 14 of Reference 1.

** Value determined using one sample, all others are average for three samples.

† Sample air-dried prior to determination of unit weight.

†† Bulk specific gravity of entire cylinder of fixed sludge including plastic coating and voids within sludge structure.

NOTE: The water content, void ratio and porosity of sample D-200 could not be determined because the sample was sealed in plastic.

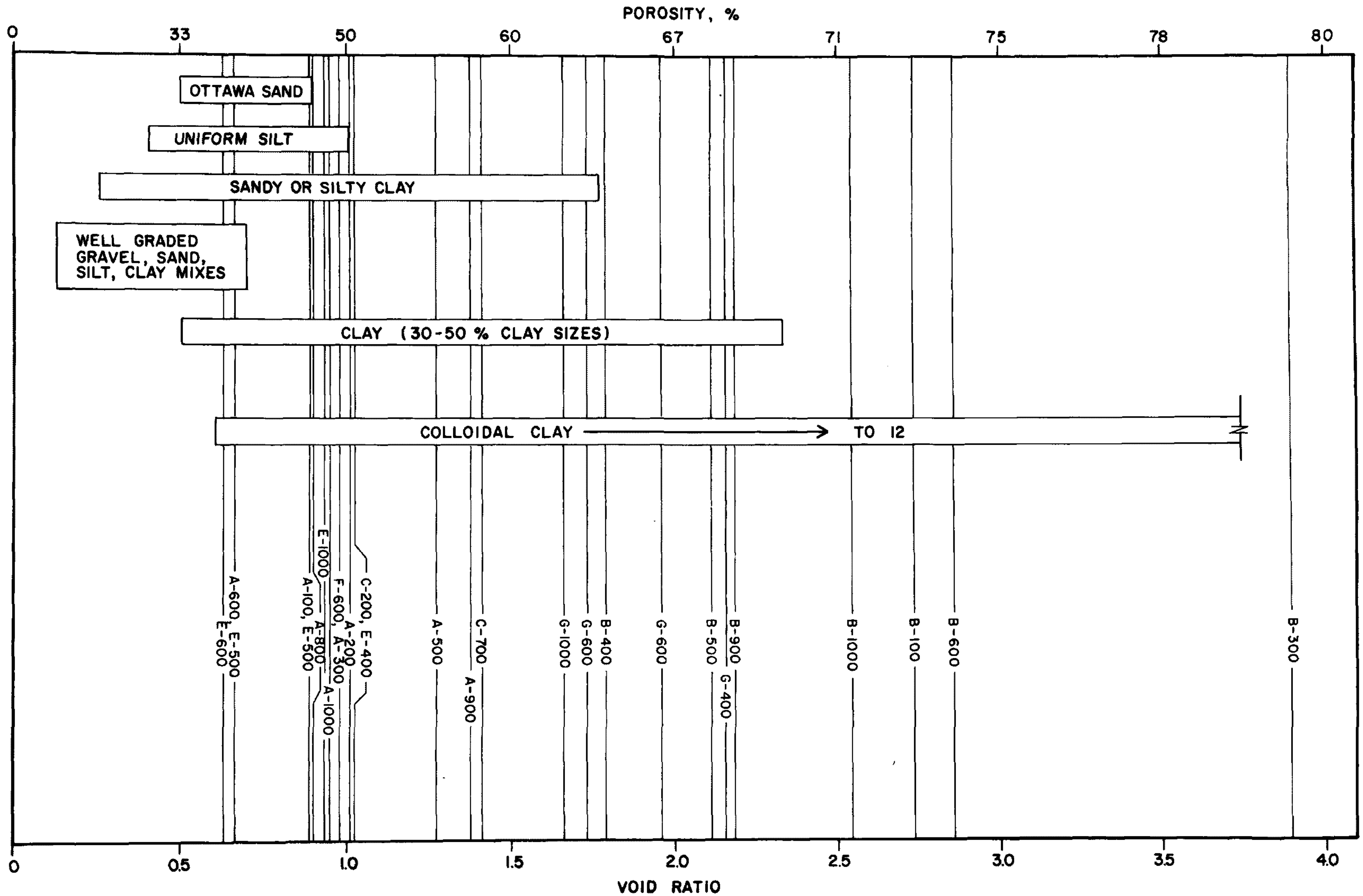


Figure 17. Void ratio and porosity of common soils compared to those of fixed sludges.

The 15-blow compaction test was conducted on nine sludge samples fixed by process B to determine the moisture-density relationships of the fixed sludges and test results are presented in Figure 18. Values of the optimum water content (OMC) at which maximum γ_d was achieved are listed in Table 10. These data reveal that the OMC for the compaction of sludges fixed by this process depended upon the type of sludge fixed. Optimum water contents ranged from 37.0 to 89.5 percent. These values are high when compared to values typical of soils.

Unconfined Compression

Unconfined compression tests were run on a total of 30 samples of fixed sludge. Multiple specimens were used in nearly all tests with a separate axial stress-strain curve generated for each specimen. Composite stress-strain curves were constructed from each test report and were used to determine the modulus of elasticity (E) of each of the fixed sludges. The composite stress-strain curves are presented in Figures 19 and 20. Photographs of some of the test specimens are shown in Figures 20-27.

The unconfined compressive strength test data (Table 11) reveal that the behavior of fixed sludges in compression was highly process- and material-dependent. The compressive strengths of sludges fixed by process B ranged from 3.98 to 22.28 lb/sq in and are comparable to those of cohesive or cemented soils. Sludges fixed by process A exhibited generally higher unconfined compressive strengths and more closely resembled low-strength soil-cement mixtures. Processes C, E, F, and G produced fixed sludges that resemble low-strength concretes with one fixed sludge having a compressive strength in excess of 4,000 lb/sq in. The reported compressive strength of the sample of fixed sludge D-200 is considered academic because application of the data to a field situation would require that the sludge be placed as cylinders of the same proportions as the test specimen. Since the properties of the sludge and of the plastic are dissimilar, variation of the test specimen construction will have a great effect on the compressive strength.

Values for Young's modulus of elasticity (E), the ratio of stress to strain, were taken as the slope of the straight line portion of the composite stress-strain curves, and are presented in Table 11. Sludges fixed by process B showed values of E comparable to those of cohesive or cemented soils, while values for samples fixed by other processes were from one to two orders of magnitude higher. A comparison of these moduli with those of some common materials is shown in Figure 28.

Knowledge of the unconfined compressive strength of a fixed sludge is required for evaluation to be made of its bearing capacity and of its performance as an embankment construction material. For soils, these evaluations are based in part on shear strength (τ). The normal procedure for estimating the τ of soils from unconfined compression test data is to assume that τ is equal to one-half the unconfined compressive strength. These values are presented for sludges fixed by process B in Table 11. Only the B-300 sludge exhibited a comparatively low τ value. Terzaghi[6] formulated a system for categorizing the consistency of clay by unconfined compressive strength. This system is shown in Table 12 and shows that sludges fixed by

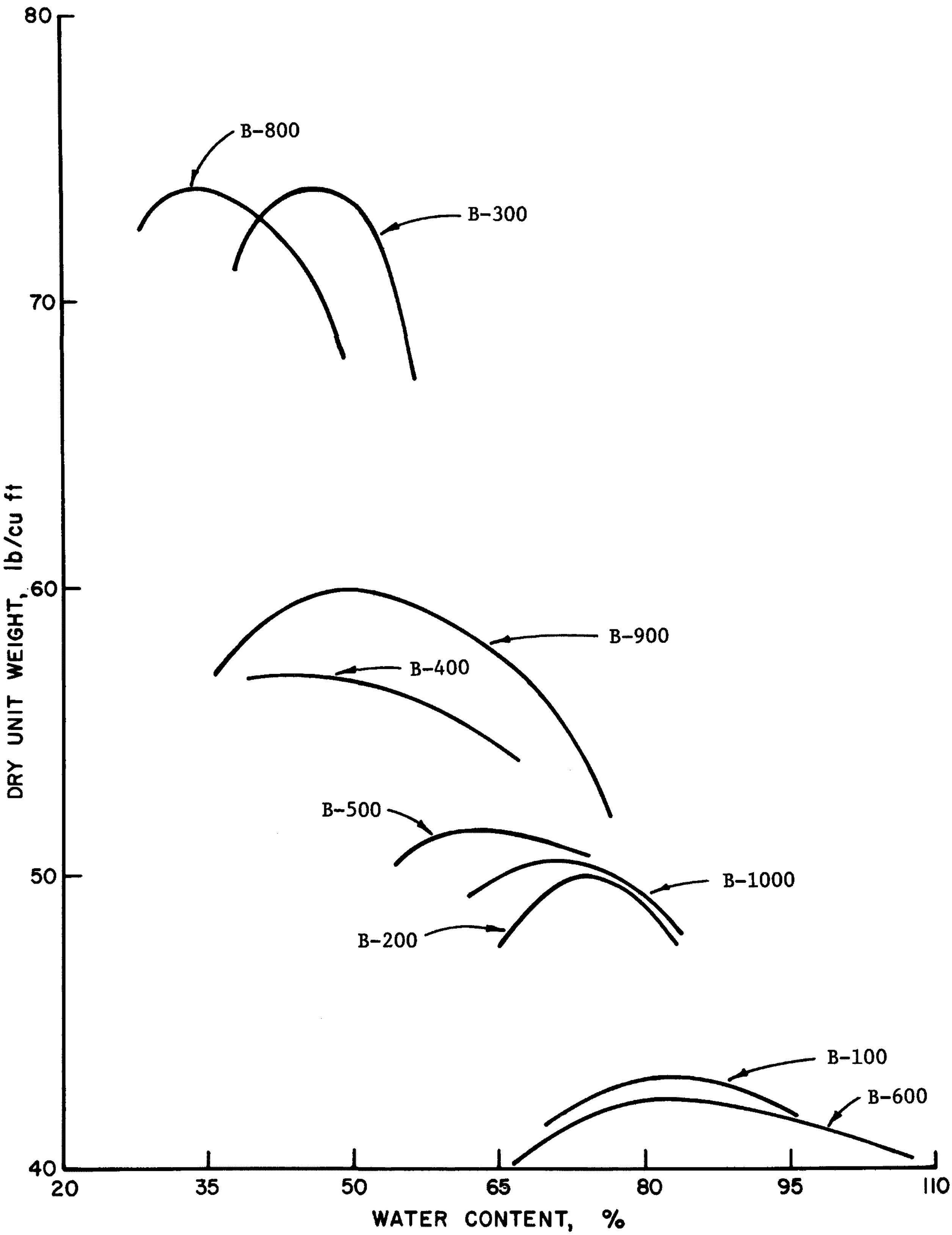


Figure 18. Compaction curves for sludges fixed by process B.

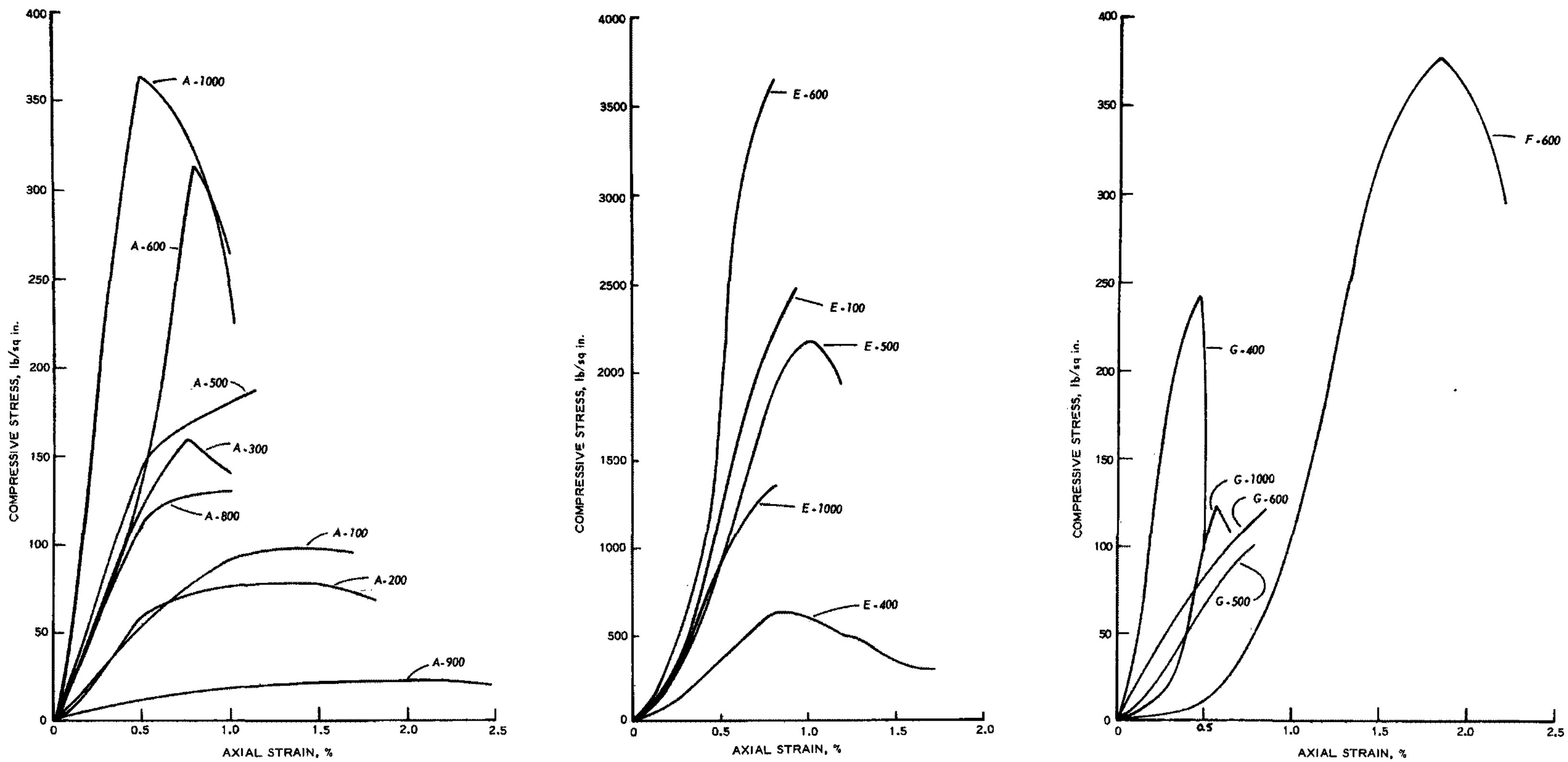


Figure 19. Composite stress-strain curves for fixed sludges.

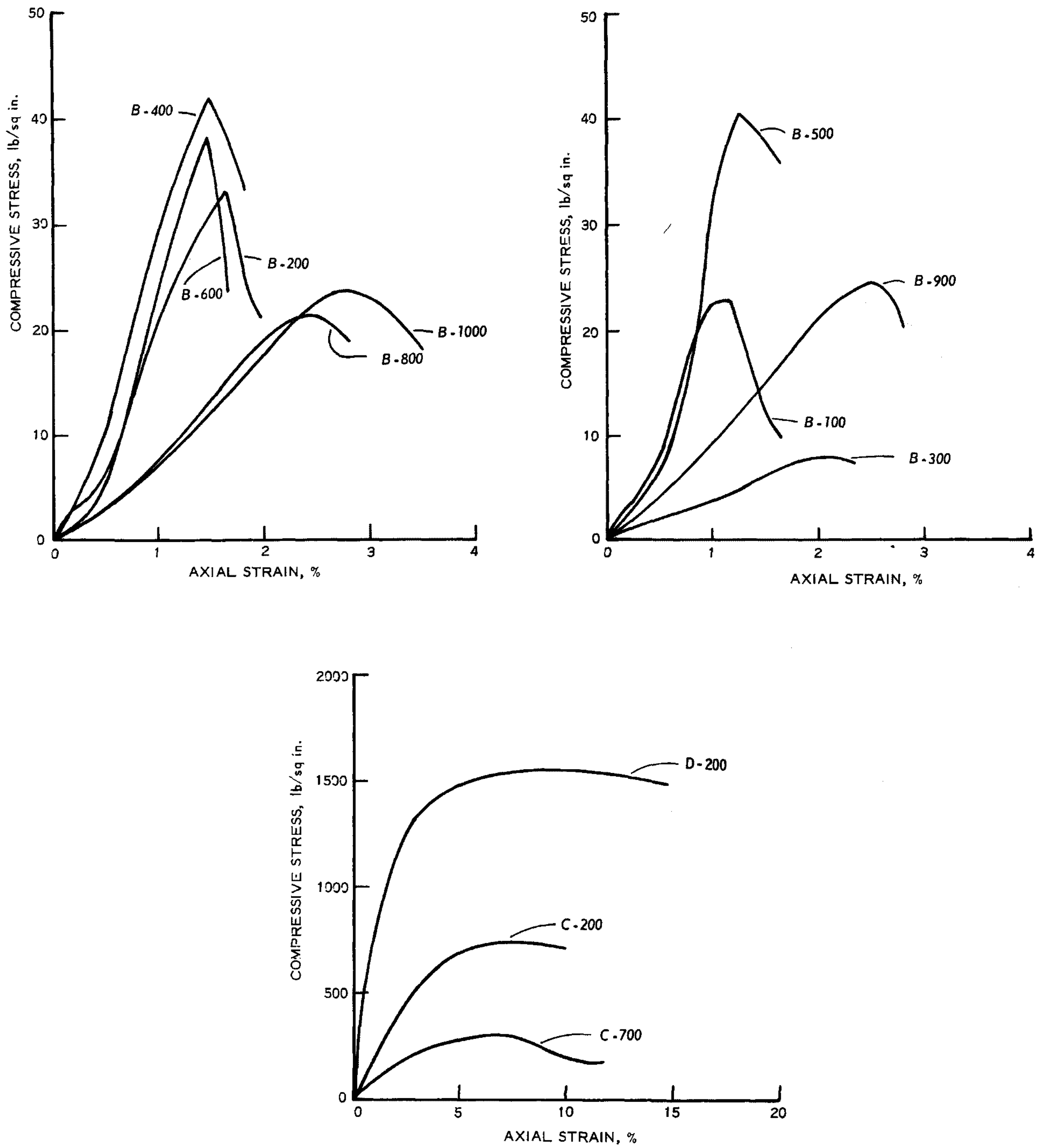


Figure 20. Composite stress-strain curves for fixed sludges.

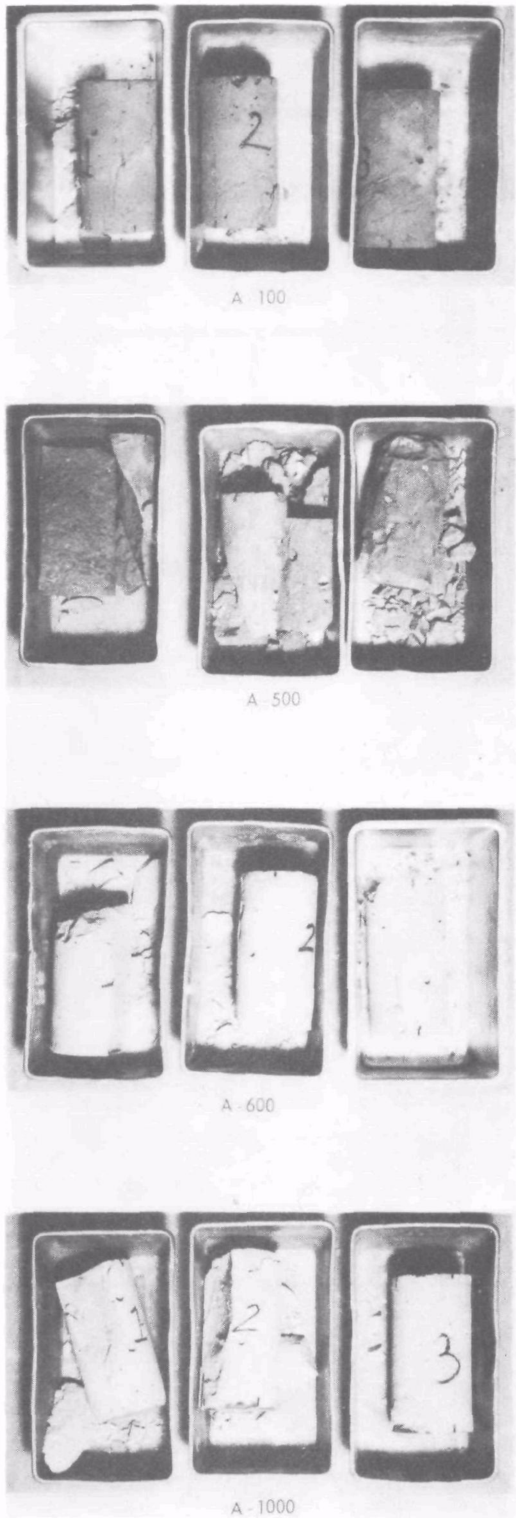
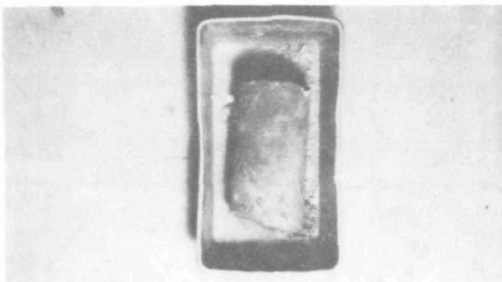
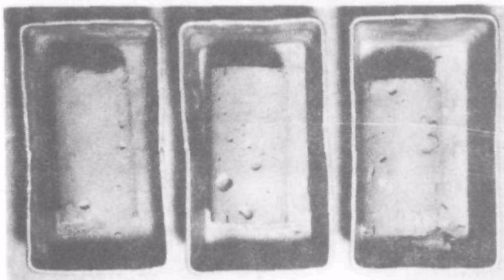


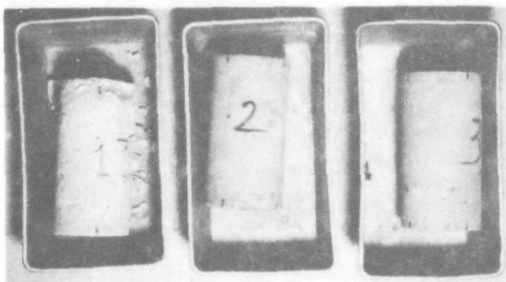
Figure 21. Photographs of specimens after unconfined compression test, FGD sludge fixed by process A.



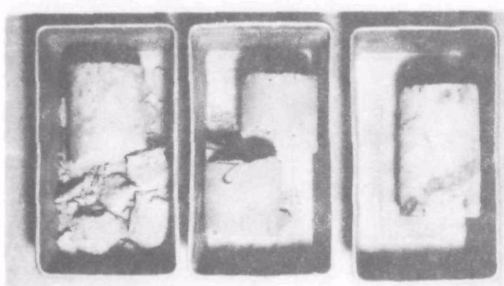
A-200



A-300



A-800



A-900

Figure 22. Photographs of specimens after unconfined compression test, industrial sludge fixed by process A.

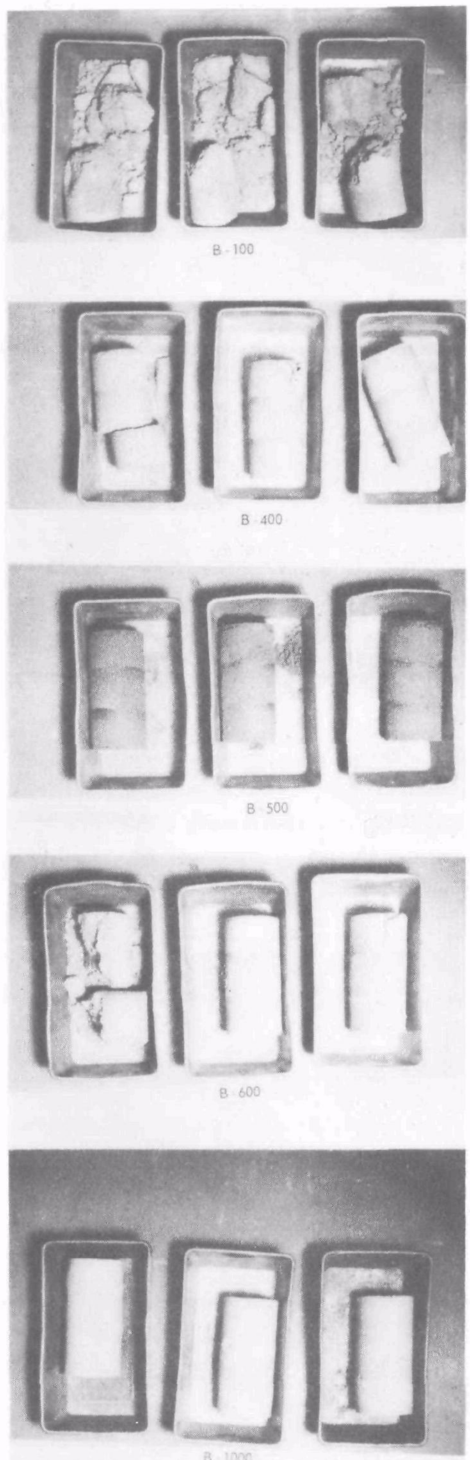


Figure 23. Photographs of specimens after unconfined compression test, FGD sludge fixed by process B.

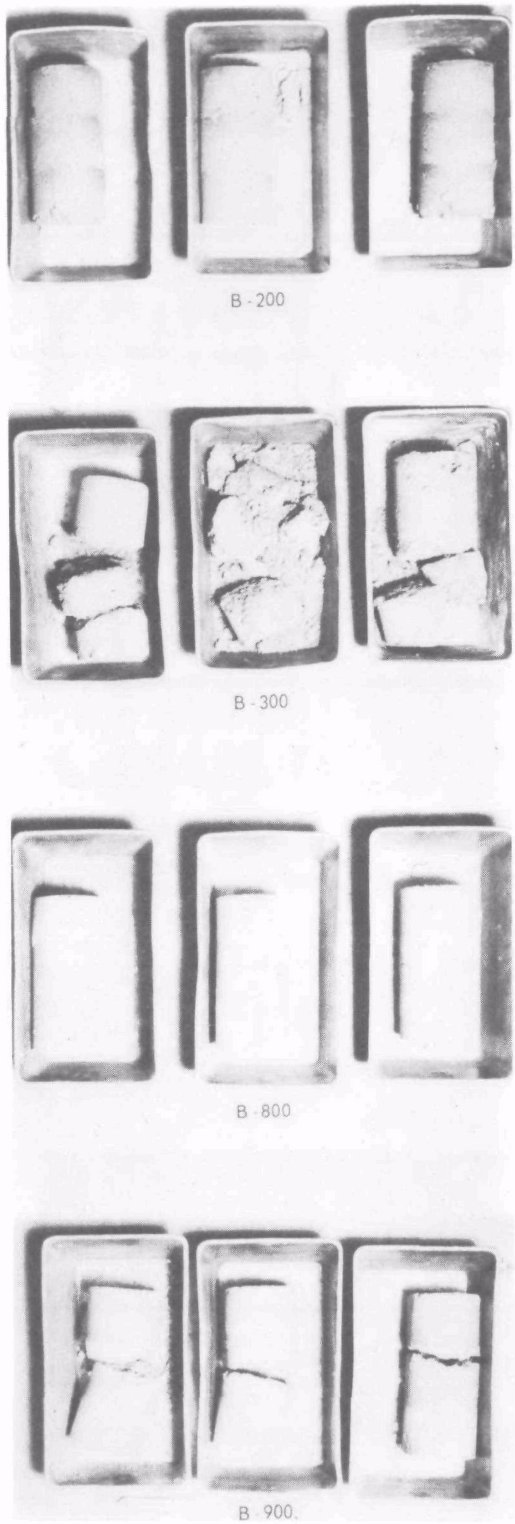


Figure 24. Photographs of specimens after unconfined compression test, industrial sludge fixed by process B.

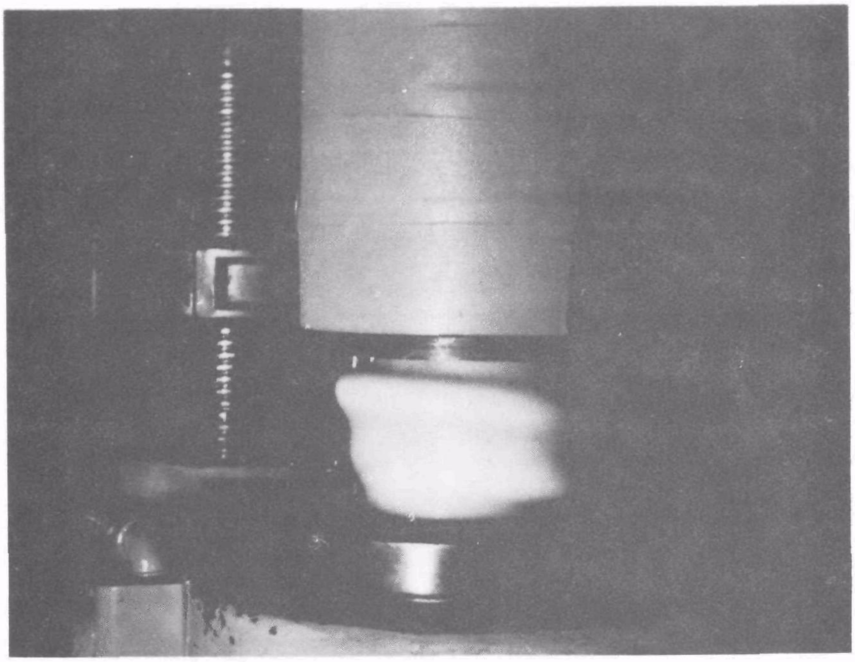
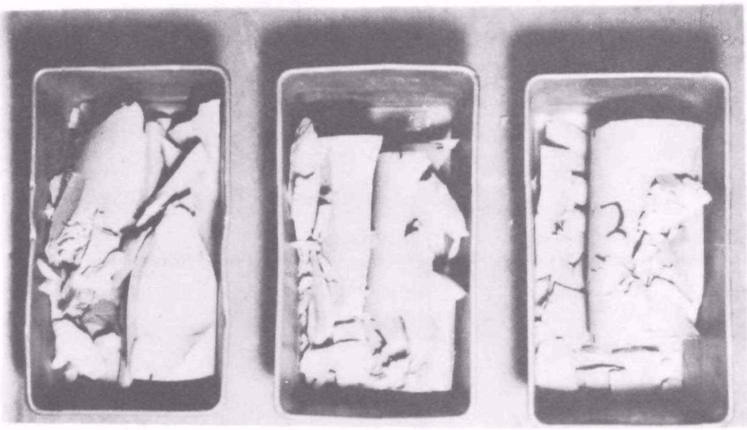


Figure 25. Photograph of specimen during unconfined compression test, industrial sludge (200) fixed by process D.



E-600

Figure 26. Photograph of specimens after unconfined compression test, FGD sludge fixed by process E.

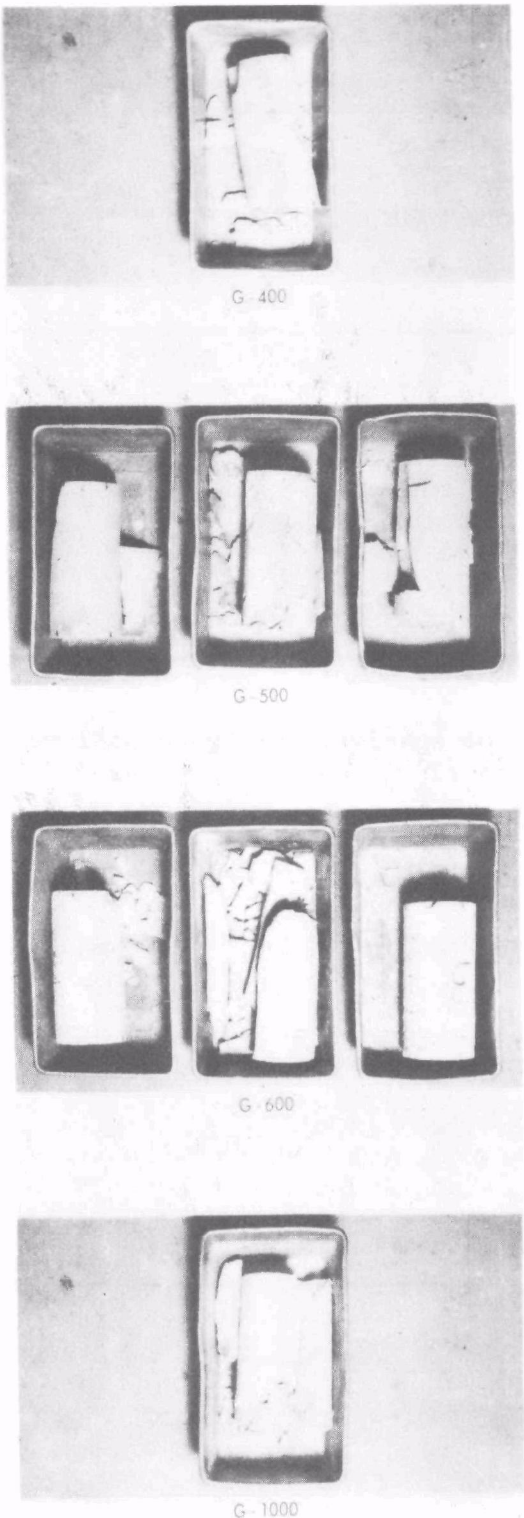


Figure 27. Photographs of specimens after unconfined compression test, FGD sludge fixed by process G.

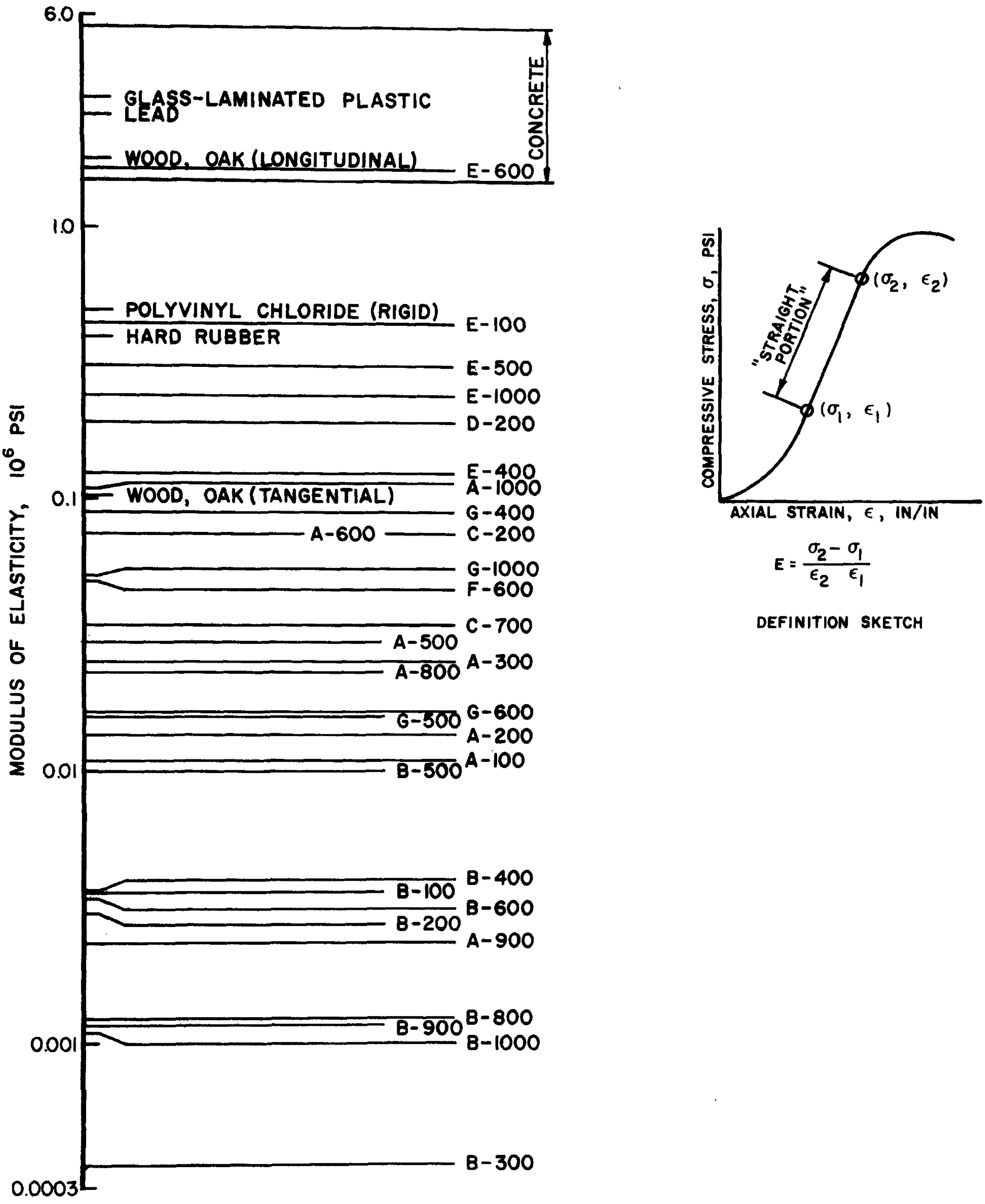


Figure 28. Elasticities of common materials compared to those of fixed sludges.

TABLE 10. CHANGES IN DRY UNIT WEIGHT AFTER COMPACTION OF SLUDGES FIXED BY PROCESS B†

Sludge	Dry unit weight* Without compaction lb/ft^3	Maximum after compaction** lb/ft^3	Change due to compaction lb/ft^3	Optimum water content %
B-100	43.4	42.9	-0.5	82.5
B-200	47.4	50.2	+2.8	73.0
B-300	47.3	76.0	+28.7	46.0
B-400	52.5	56.9	+4.4	47.0
B-500	54.3	51.5	-2.8	65.0
B-600	42.1	41.9	-0.2	89.5
B-800	81.3	74.1	-7.2	37.0
B-900	52.8	60.0	+7.2	50.5
B-1000	47.7	50.5	+2.8	73.5

* Drying performed in 60°C oven.

** 15-blow compaction test, 7400 ft-lb/cu ft compactive effort.

† This Table presents corrections to data presented in Tables 13 and 14 of Reference 1.

TABLE 11. SUMMARY OF UNCONFINED COMPRESSION TEST DATA

Sludge	Initial dry unit weight lb/cu ft	Undrained shear strength* lb/sq in	Unconfined compressive strength lb/sq in	Modulus of elasticity lb/sq in
A-100	80.9		100.28	1.10×10^4
A-200	77.4		77.39	1.45×10^4
A-300	86.2		169.14	2.55×10^4
A-500	67.6		188.32	3.03×10^4
A-600	94.6		403.08	7.50×10^4
A-800	88.6		133.73	2.30×10^4
A-900	71.1		26.28	2.34×10^3
A-1000	78.1		337.40	1.10×10^5
B-100	41.7	11.85	23.71	3.57×10^3
B-200	60.5	16.23	32.47	3.03×10^3
B-300	74.6	3.98	7.96	3.61×10^2
B-400	65.4	22.28	44.59	3.64×10^3
B-500	58.3	21.37	42.74	1.00×10^4
B-600	44.2	17.66	35.32	3.39×10^3
B-800	83.9	10.82	21.64	1.23×10^3
B-900	62.2	12.34	24.68	1.16×10^3
B-1000	53.5	11.62	23.23	1.10×10^3
C-200	52.7		747.33	7.69×10^4
C-700	45.1		308.66	3.46×10^4
D-200†	69.1		1542	1.92×10^5
E-100	95.0		2574	4.50×10^5
E-400	82.7		719.33	1.26×10^5
E-500	93.3		2200.67	3.10×10^5
E-600	100.3		4486.70	1.67×10^6
E-1000	82.7		1374	2.45×10^5
F-600	69.6		395.66	5.00×10^4
G-400	56.8		242.56	9.10×10^4
G-500	48.8		86.36	1.59×10^4
G-600	50.3		126.07	1.64×10^4
G-1000	58.2		144.25	5.28×10^4

* Taken as one-half unconfined compressive strength. Significant for soil-like sludges only. Blank spaces indicate non-soil-like sludges.

† Results meaningful only for material of same construction as test specimen. Larger or smaller samples require individual testing.

process B ranged from medium to hard in consistency. In general, all fixed sludges should perform satisfactorily as embankment construction material, and bearing capacities should prove adequate for most general landfill applications (see Section 6).

TABLE 12, CONSISTENCY OF CLAY IN TERMS OF UNCONFINED COMPRESSIVE STRENGTH (FROM REFERENCE 6)

Consistency	Unconfined compressive strength lb/sq in
Very soft	< 3.5
Soft	3.5-7
Medium	7-14
Stiff	14-28
Hard	28-56
Very hard	> 56

Permeability

Using the test procedures cited in Section 4, the coefficients of permeability (k) of raw and fixed sludges were determined. Table 13 presents the data from the permeability testing of raw sludges and shows that k ranged from 1.257×10^{-6} to 1.033×10^{-4} cm/sec. Table 14 lists the physical properties and values of k of the samples of fixed sludges. Values ranged from 4.540×10^{-11} to 7.935×10^{-4} cm/sec, a great variation. Raw sludges can be described as having low permeability, while most fixed sludges have low to very low permeability. A few fixed sludges were practically impermeable ($k \leq 10^{-7}$ cm/sec) and one (D-200), because of the plastic coating, was absolutely impermeable to water; and no permeability tests of this fixed sludge were run. In the following paragraphs the influence of e and γ_d on the permeability of raw and fixed sludges are discussed, as is the dependence of permeability on the fixation process. Also, the values of k of fixed sludges are compared with those of soil and concrete.

The discussion of permeability presented below is predicated on the assumption that the sludge test specimens are representative of anticipated field conditions. The most significant considerations are of the effects of discontinuities and incomplete saturation. If the sludge is placed as a mass of chunks or becomes cracked, the permeability will be greatly affected. The other consideration is the degree of saturation of the material. The fixed sludge samples could not be completely saturated during the test procedure, which included 10 lb/sq in differential pressure. Complete saturation of fixed sludge requires an extremely large hydraulic head and/or an exceedingly long period of time, and might never be accomplished in the field. Complete saturation would be expected to result in a slight increase in permeability.

Influence of Dry Unit Weight and Void Ratio--

The permeability of porous media is known to be influenced by the size of the pore spaces through which liquid can flow.[5,6,8] Two parameters, γ_d

TABLE 13. SUMMARY OF PERMEABILITY TEST DATA FOR RAW SLUDGES

Sludge	Percent solids %	Water content*† %	Dry unit weight* lb/cu ft	Void ratio	Coefficient of permeability # cm/sec
R-100	54.8	82.5	58.8	1.559	3.610×10^{-5}
	63.1	58.6	64.4	1.336	1.070×10^{-5}
R-200	33.8	194.9	28.1	4.998	3.152×10^{-5}
	39.5	153.0	36.1	4.334	1.257×10^{-6}
R-300	43.1	132.3	43.9	4.631	5.761×10^{-6}
	46.1	116.8	54.9	3.503	1.318×10^{-6}
R-400	51.1	95.7	57.9	1.706	9.498×10^{-5}
	59.8	67.0	70.1	1.235	7.784×10^{-6}
R-500	59.2	145.6	30.3	4.872	4.373×10^{-5}
	45.0	121.6	36.0	3.942	2.505×10^{-5}
R-600	69.9	43.0	86.9	0.818	2.013×10^{-5}
	77.5	29.4	103.6	0.525	1.439×10^{-5}
R-700	36.9	171.4	27.7	5.964	6.557×10^{-6}
	45.5	119.2	33.5	4.758	3.391×10^{-6}
R-800	60.2	119.2	64.0	1.751	1.033×10^{-4}**
	62.5	60.3	73.2	1.405	8.165×10^{-5}
R-900	43.9	128.2	46.8	2.682	3.524×10^{-5}
	50.3	98.7	53.1	2.245	2.834×10^{-5}
R-1000	40.5	146.5	43.2	3.321	8.461×10^{-5}
	42.4	136.1	48.9	2.817	6.536×10^{-5}

* All drying done in 60°C oven. Note two sets of data for each sludge. Samples were tested, densified, retested. See Section 4.

† Dry weight basis.

\# Corrected for water at 20°C.

** Value questionable because flow restriction caused by sample support system may have influenced flow through sample.

TABLE 14. SUMMARY OF PERMEABILITY TEST DATA FOR FIXED SLUDGES

Sludge	Percent solids %	Water content*† %	Dry unit weight* lb/cu ft	Void ratio	Coefficient of permeability # cm/sec
A-100	78.1	28.3	76.9	0.956	2.057×10^{-6}
A-200	71.4	40.6	73.2	1.124	4.039×10^{-7}
A-300	82.0	22.4	84.3	1.007	1.913×10^{-6}
A-500	67.6	47.8	62.3	1.575	1.124×10^{-7}
A-600	86.2	16.1	92.5	0.701	4.308×10^{-7}
A-800	77.0	30.2	82.4	1.023	8.525×10^{-7}
A-900	83.3	19.5	68.0	1.369	3.847×10^{-5}
A-1000	78.1	27.8	73.7	1.075	8.953×10^{-7}
B-100	82.0	21.9	60.0	1.684	1.590×10^{-4}**
B-200	64.6	55.6	52.9	2.215	1.117×10^{-5}
B-300	69.5	43.7	73.7	2.117	1.893×10^{-4}***
B-400	82.6	21.2	63.7	1.303	1.082×10^{-5}
B-500	65.4	52.7	54.2	2.156	4.563×10^{-5}
B-600	59.2	68.8	44.4	2.613	3.968×10^{-5}
B-800	71.4	39.9	71.4	1.483	3.617×10^{-5}
B-900	66.7	49.8	61.5	1.771	8.735×10^{-6}
B-1000	58.1	71.9	45.1	2.931	6.625×10^{-5}
C-200	65.7	52.1	38.4	1.877	1.148×10^{-4}**
C-700	60.6	64.7	36.5	1.926	1.602×10^{-4}**
D-200	100.0	0.0	73.6		Impervious††
E-100	77.0	30.9	81.0	0.958	7.935×10^{-4}**
E-400	91.0	11.3	72.5	1.196	2.518×10^{-6}
E-500	75.2	33.4	77.9	1.180	4.540×10^{-11}
E-600	80.0	24.7	88.3	0.881	3.571×10^{-8}
E-1000	90.1	10.4	77.3	1.108	7.328×10^{-7}
F-600	97.0	3.7	78.1	0.966	5.007×10^{-6}
G-400	93.5	7.7	53.1	1.927	5.241×10^{-5}
G-500	98.4	2.9	50.6	2.084	1.388×10^{-4}**
G-600	91.7	9.1	53.0	1.837	1.224×10^{-4}**
G-1000	63.7	56.8	54.0	1.821	4.047×10^{-5}

* All drying done in 60°C oven.

† Dry weight basis.

Corrected for water at 20°C.

†† Sample D-200 encapsulated in impervious plastic.

** Value questionable because flow restriction caused by sample support may have influenced flow through sample.

and e, are used to describe the pore size of the sludges. Increasing values of γ_d are indicative of pore volume reduction, and therefore of decreasing k, while increasing values of e show increasing pore volume and increasing k.

Raw sludges--Figures 29a and 29b show the relations between e and k, and between γ_d and k, respectively, for samples of raw sludge. These plots show that decreasing pore volume, as indicated by increasing γ_d and decreasing e, was indicative of decreasing k. Figure 29b also shows that the values of k of the raw sludges are comparable to those of loess and silty sand, although the values of γ_d of these soils are higher than those of most raw sludges. The figure also suggests that compaction of the raw sludges to 100 lb/cu ft could reduce k to values near those of the sandy silt, although insufficient data exist to make a confident prediction.

Fixed sludges--Figures 30a and 30b show the relations of e and γ_d with k for sludges fixed by process A or B. The figures show that the samples of sludge fixed by process A were generally more dense and less permeable than were the sludges fixed by process B. The values of k for sludges fixed by process A ranged from 1.124×10^{-7} to 3.847×10^{-5} cm/sec, while k ranged from 8.735×10^{-6} to 1.893×10^{-4} cm/sec for sludges fixed by process B. Collectively, the sludges fixed by process A or B generally are less permeable with smaller pore size. Separately, however, neither process exhibited such a trend.

Figures 31a and 31b show the relations of e and γ_d with k for sludges fixed by process C, E, F, or G. Since only a few samples of sludge fixed by each of these processes were tested, no process-dependence is well-defined. The values of k for the two samples of sludge fixed by process C were 1.148×10^{-4} and 1.602×10^{-4} cm/sec. The range of k for sludges fixed by process E was 4.54×10^{-11} to 7.935×10^{-4}, and for sludges fixed by process G, k ranged from 4.047×10^{-5} to 1.388×10^{-4} cm/sec. Single samples of sludge were fixed by process D or F. Fixed sludge sample D-200 was impermeable (k = 0), and the k of sludge F-600 was 5.007×10^{-6}.

Taken collectively the fixed sludges exhibit some evidence of the influence of pore size on permeability at values of k greater than about 10^{-6} cm/sec. As was the case with the total group of sludges fixed by process A or B, decreasing pore sizes generally correlated with lower values of k. There are insufficient data to assess the influence of pore size on k for each fixing process, but sludges fixed by process E are noteworthy.

Sludges fixed by process E exhibited a wide range of k, with no noticeable influence by either γ_d or e. The permeability of sludge E-500 ($k = 4.54 \times 10^{-11}$ cm/sec) is comparable to that of concrete, whose k is typically on the order of 10^{-12} cm/sec. Sludge 500 was the least permeable of the sludges fixed by process A, as well; but since the permeabilities of R-500 and B-500 were not the lowest in their respective categories, the occurrence of sludge 500 as the least permeable of the fixed sludges is process-dependent and is of little practical significance.

DURABILITY

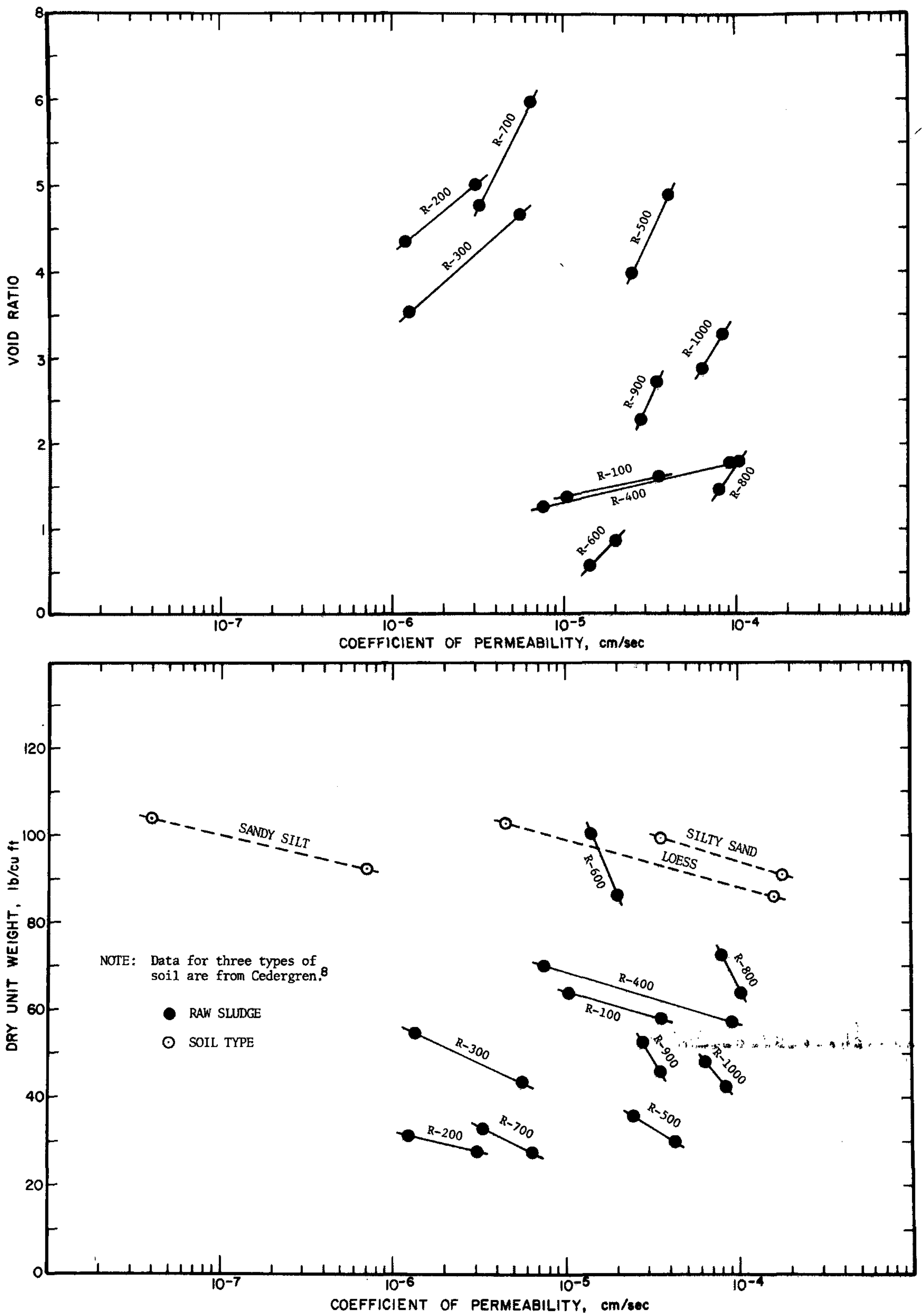


Figure 29. Influence of pore size on the permeability of raw sludges.

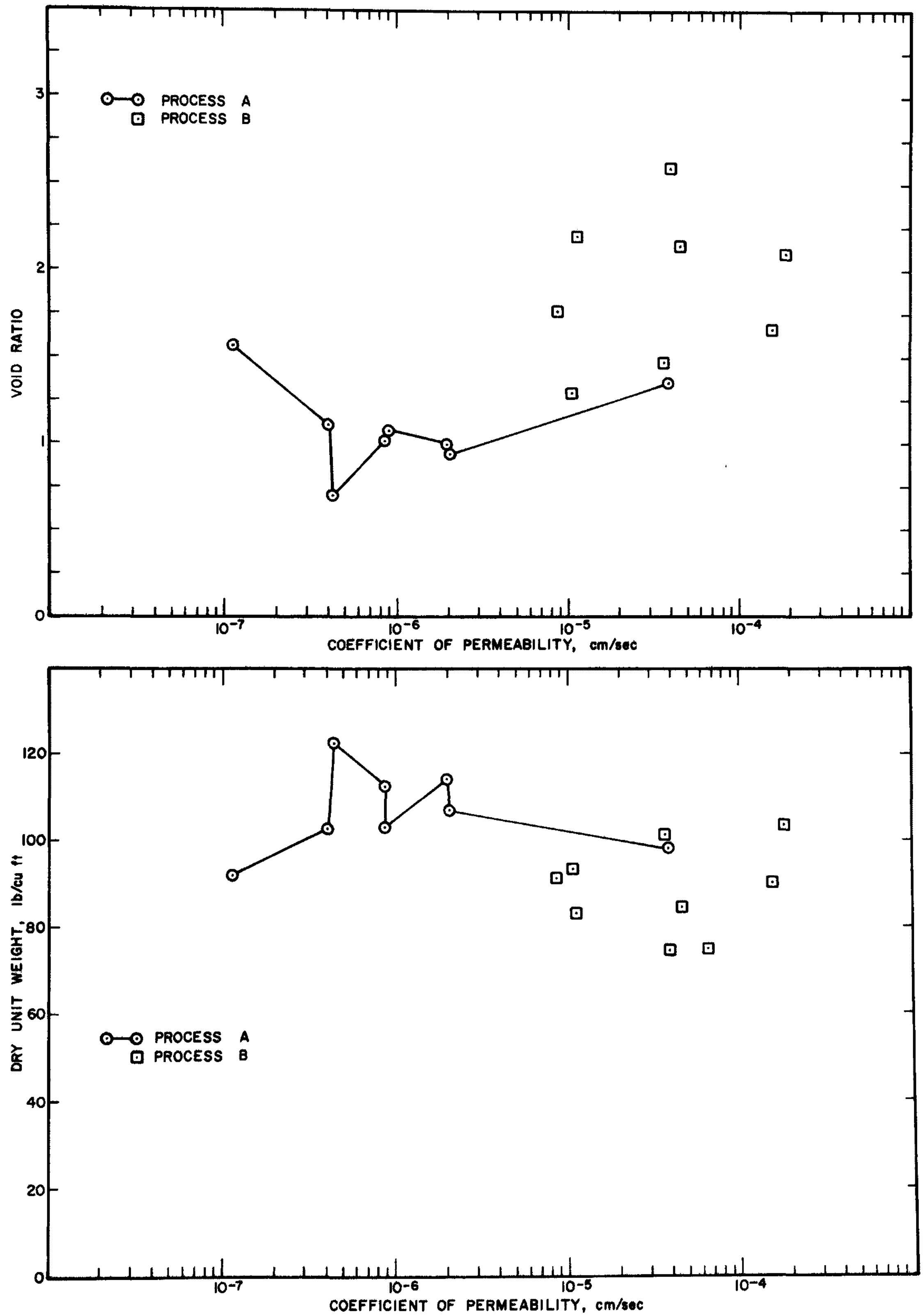


Figure 30. Influence of pore size on the permeability of sludges fixed by process A or B.

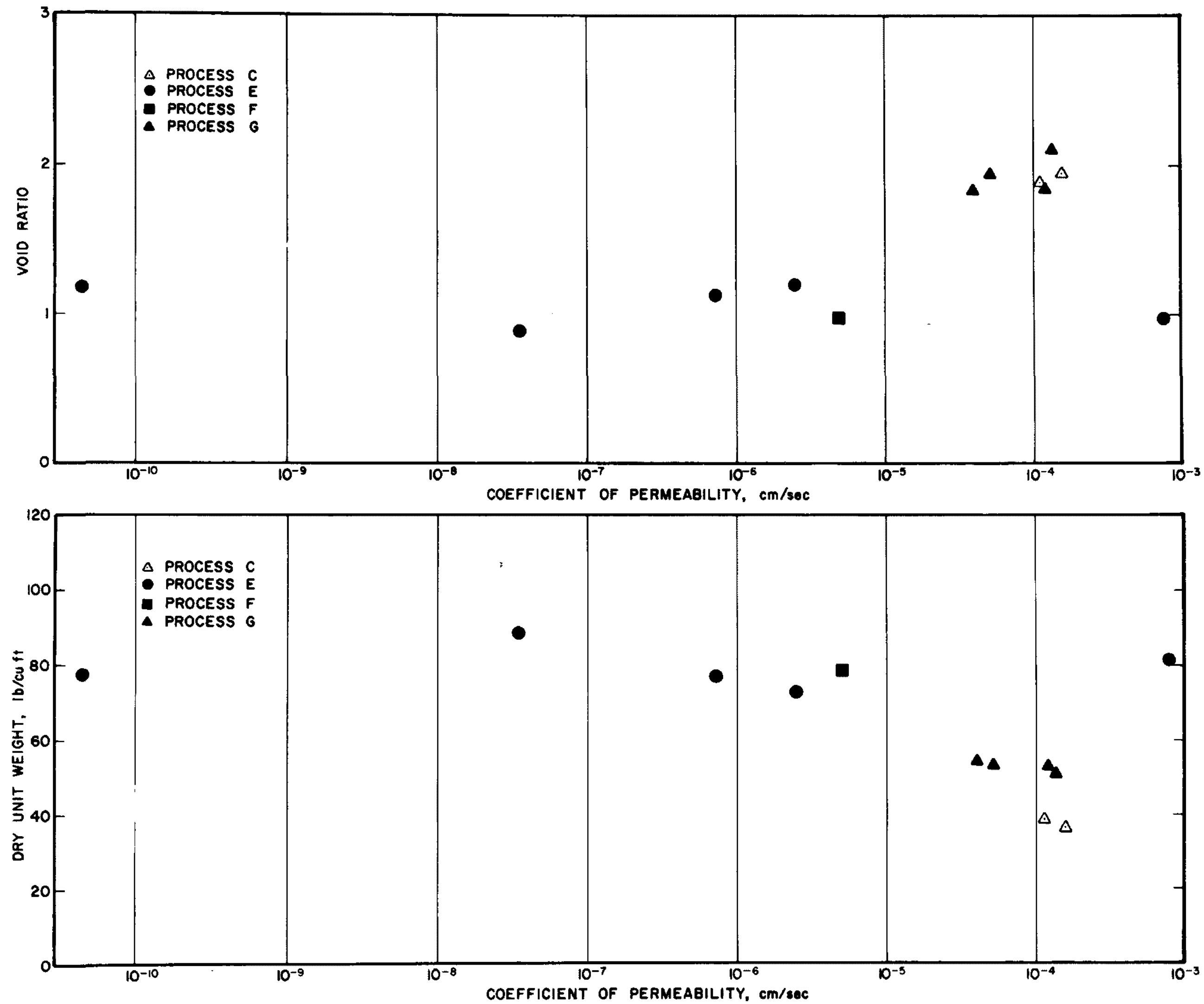


Figure 31. Influence of pore size on the permeability of sludges fixed by process C, E, F, or G.

To determine the relative durability of the fixed sludges, samples were subjected to the wet-dry tests and freeze-thaw tests described in Section 4. In the following paragraphs, the test results and the influence of k and strength on durability are discussed. The term durability refers to the ability of a material to resist natural weathering stresses simulated by repeated cycles of either wetting and drying or freezing and thawing.

The time span simulated by the test procedures is not well defined. The 12 test cycles of freeze-thaw could simulate 12 years' exposure to the elements, but the freezing and thawing of a thin lift of sludge could conceivably occur on each of 12 consecutive days. The same sort of argument could be made regarding the wet-dry test. Both tests are useful for determining the effect of different fixation processes on the durability of sludges, but neither test is suitable for estimating the performance of a fixed sludge mass in the field.

Prediction of the long-term stability of fixed sludge subjected to the environment is also hampered by the lack of field experience. Correlations between durability test data and field performance for stabilized soils are scarce, and such correlations for fixed sludge are non-existent. Careful monitoring of fixed sludge landfills is required to develop relations between laboratory testing and field performance. Due to these limitations the durability of fixed sludge is discussed only in terms of factors affecting test response and in comparing fixation processes. The fixed sludges that withstand the effects of durability testing with the least amount of ill effect are expected to be the most durable in the field, but no estimate of actual performance on the basis of laboratory testing is appropriate without field verification.

Wet-Dry Test Results

The results of the wet-dry tests are presented in Table 15 and Figure 32a as either percent of specimen weight lost after 12 test cycles or as the number of cycles required to disintegrate the specimen. Photographs of some of the test specimens after 4 and 12 test cycles are shown in Figures 33 and 34, respectively. Most specimens disintegrated after fewer than 12 cycles, with 9 specimens failing during the first cycle. Seven of the 30 specimens tested remained intact after 12 cycles and the percent of specimen weight loss ranged from 0.00% to 41.70%. The 4 specimens of sludges fixed by process E all survived the test, as did the only specimen of sludge fixed by process D. The 12 test cycles did not result in the removal of a measurable amount of material from the specimen of sludge fixed by process D, which indicates only that the plastic coating was not damaged during the test. One sludge fixed by process A survived, but that specimen experienced the loss of 41.70% of its original weight.

Freeze-Thaw Test Results

Table 15 and Figure 32b present the results of the freeze-thaw tests. Nineteen of the 22 specimens failed during the test, 14 of these within the first 2 cycles. The percent weight loss of the 3 specimens remaining intact ranged from 0.00% to 28.65%. As with the wet-dry test, sludge 200 fixed by

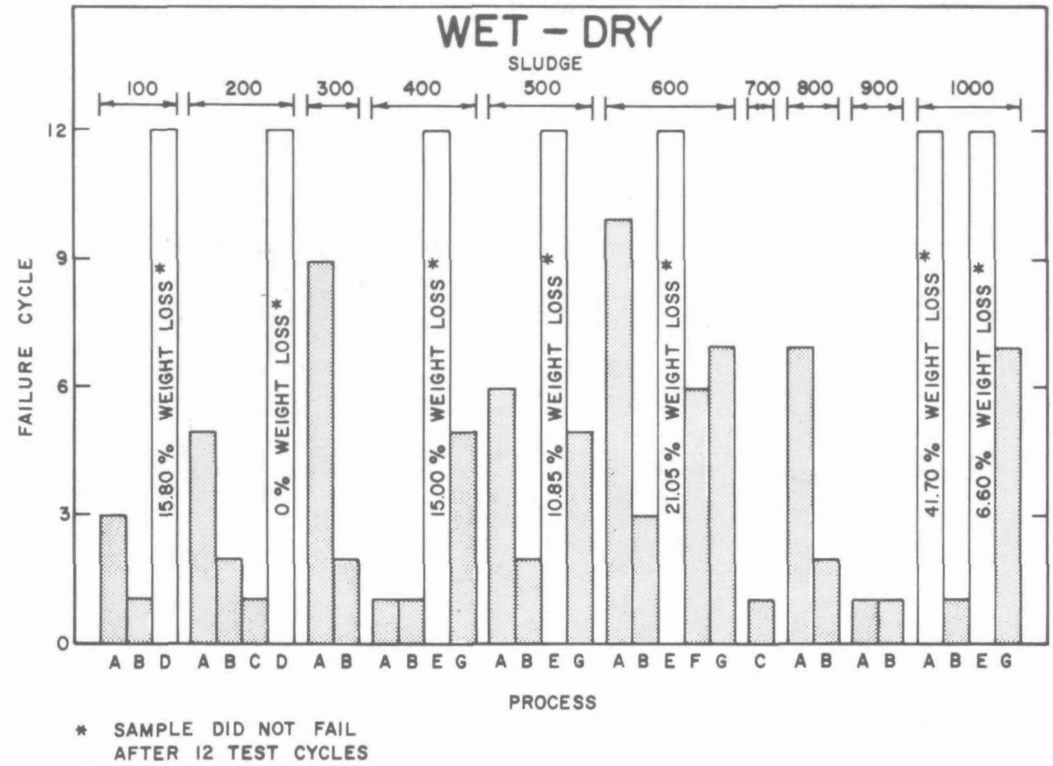
TABLE 15. SUMMARY OF DURABILITY TESTING OF FIXED SLUDGES

Sludge	Percent wt. loss after 12 test cycles* Wet-dry	Freeze thaw	Number of wet-dry test cycles to fail*	Number of freeze-thaw test cycles to fail*
A-100			3	2
A-200			5	
A-300			9	
A-400			1	
A-500			6	6
A-600			10	
A-800			7	
A-900			1	1
A-1000	41.70†			
B-100			1	1
B-200			2	1
B-300			1	1
B-400			1	1
B-500			2	1
B-600			3	2
B-800			2	1
B-900			1	2
B-1000			1	1
C-200			1	12
C-700			1	12
D-200	0.00	0.00		
E-100	15.80†			10
E-400	15.00†			7
E-500	10.85†	26.65†		
E-600	21.05†			
E-1000	6.60†	18.30†		
F-600			6	4
G-400			5	2
G-500			5	
G-600			7	
G-1000			7	2

* One test specimen unless otherwise noted.

† Average value for two specimens.

Note: Data reported as number of test cycles to fail or weight loss after 12 test cycles (e.g. E-100, 15.80% weight loss after 12 wet-dry cycles and disintegration after 10 freeze-dry cycles).



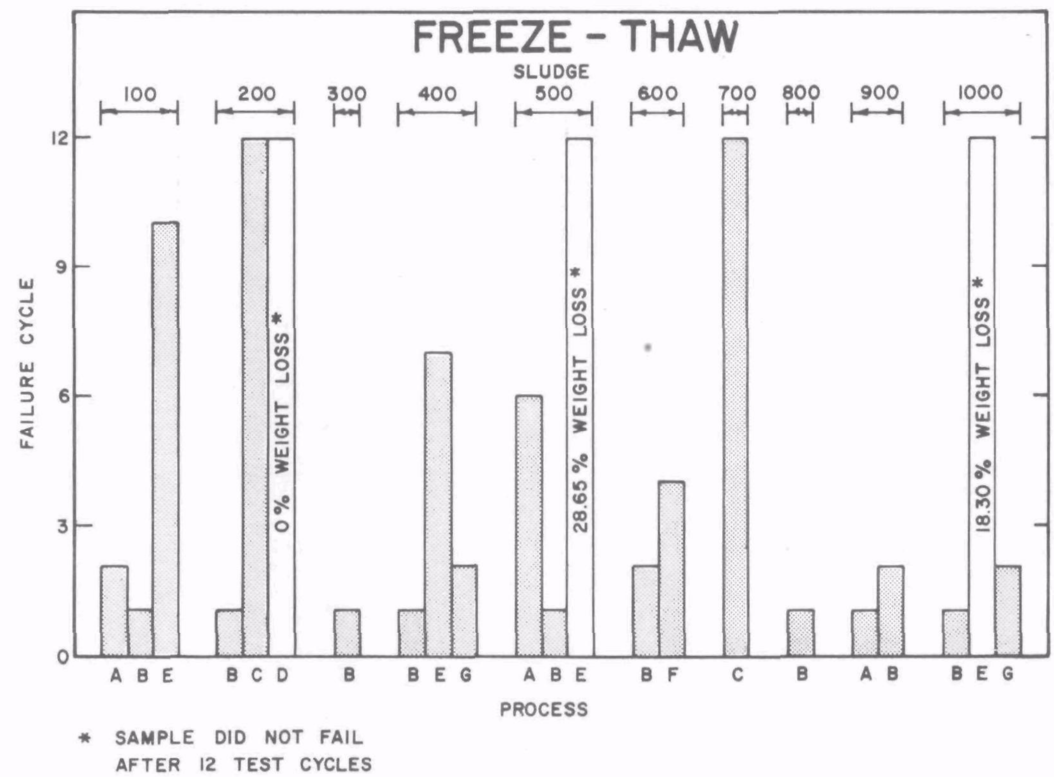


Figure 32. Summary of durability testing of fixed sludges.

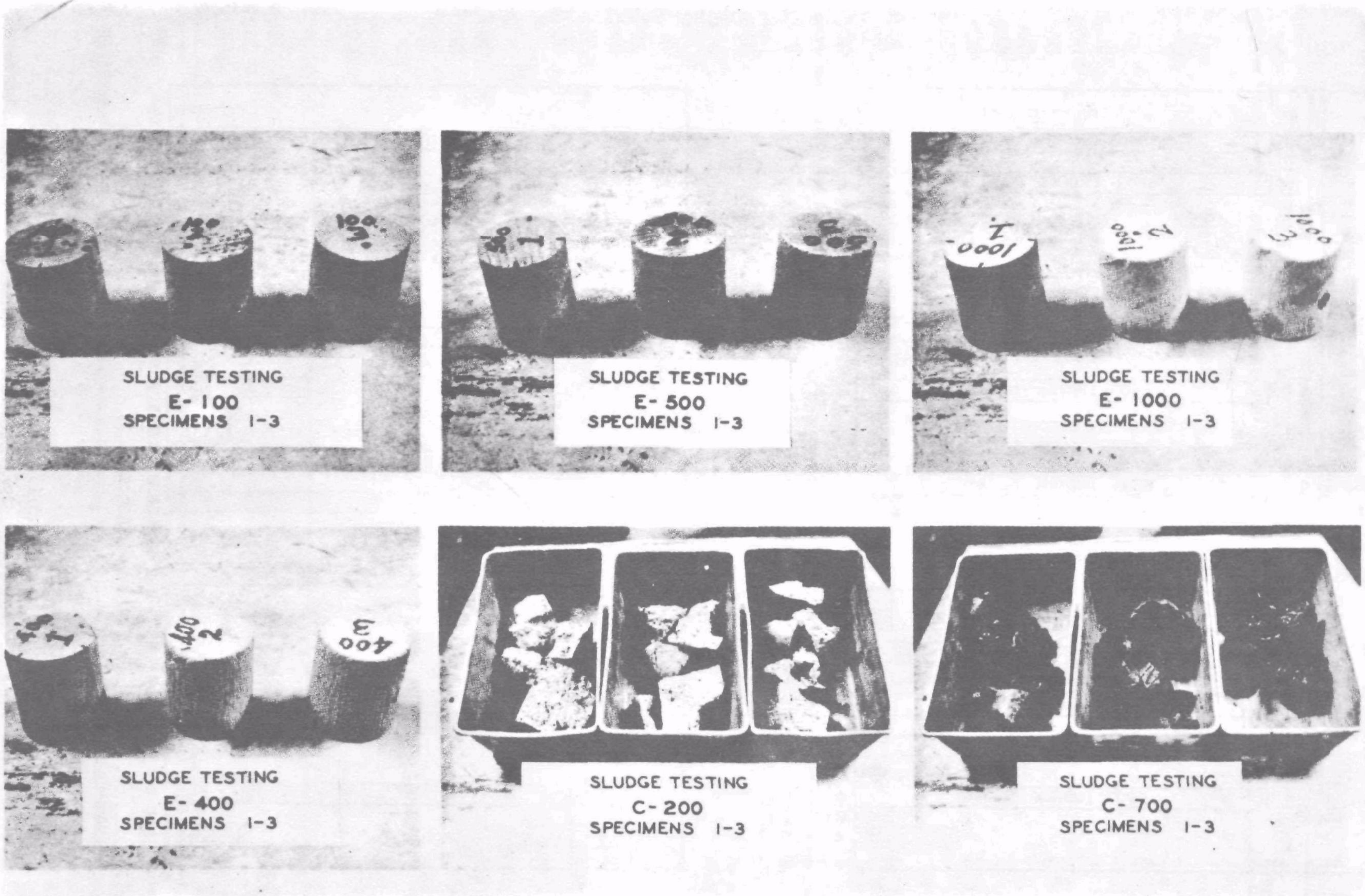


Figure 33. Photographs of test specimens after 4 wet-dry test cycles, sludges fixed by process C or E (from Reference 1).

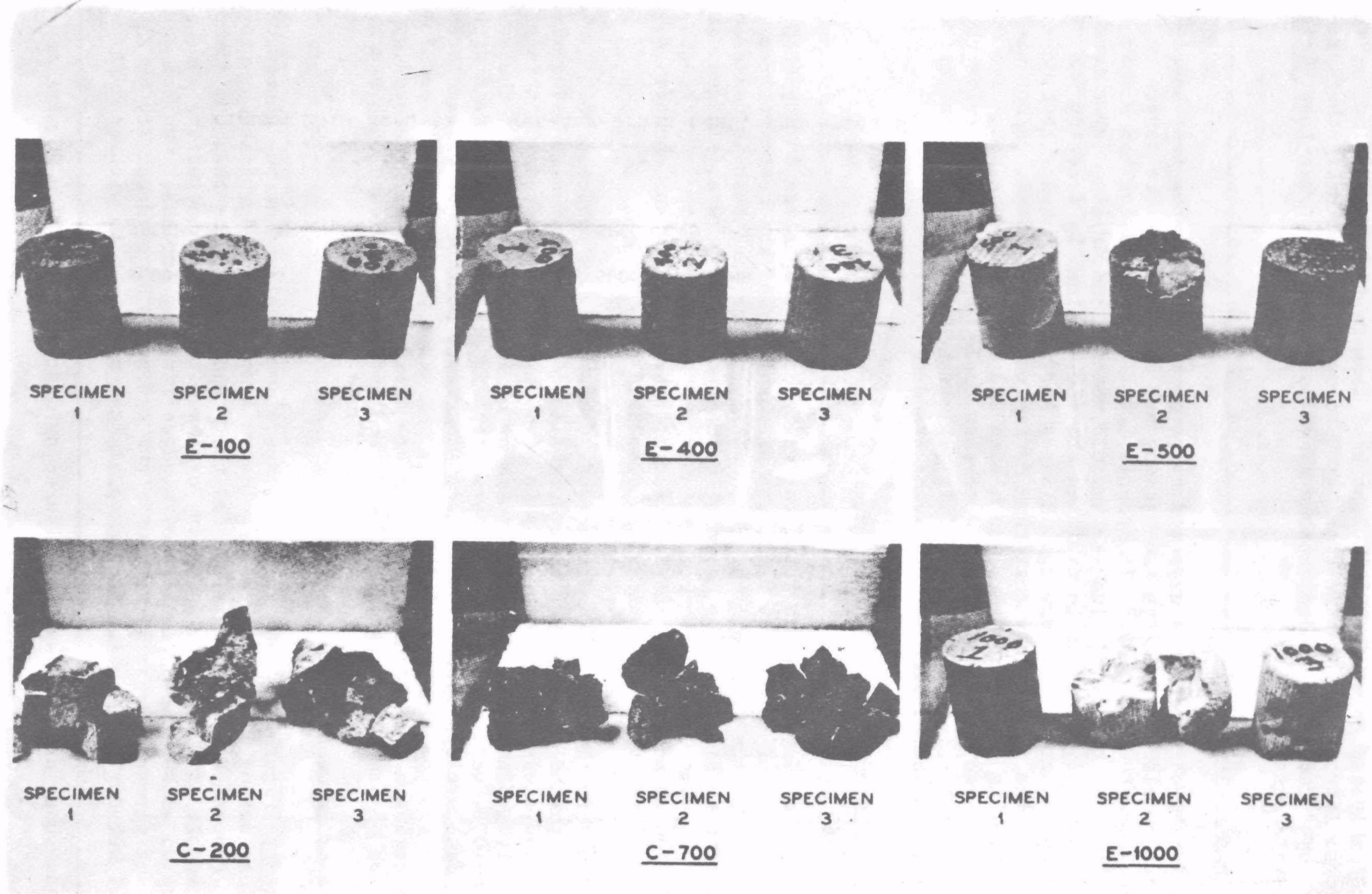


Figure 34. Photographs of test specimens after 12 wet-dry test cycles, sludges fixed by process C or E (from Reference 1).

process D exhibited no measurable weight loss from testing, again indicative of the durability of the plastic coating. Process E was the only other process that produced fixed sludge capable of withstanding 12 freeze-thaw cycles without disintegration.

Comparison of Test Severity

The freeze-thaw test was expected to be more severe on the test specimens because cycles of freezing and thawing are known to be more severe on soil than are wet-dry cycles.[9] In general freezing and thawing had a more harmful effect on the fixed sludges than did wetting and drying; fewer test cycles were usually required to disintegrate the specimen by freezing and thawing than by wetting and drying. Sludges surviving both tests lost more weight during the freeze-thaw test than during the wet-dry test. A notable exception to this trend, however, was sludge 200 fixed by process C. Two specimens survived until the 12th freeze-thaw cycle, but did not survive the first cycle of wetting and drying. This performance is process-dependent; no other sample exhibited such a significant trend reversal.

Influence of Permeability and Compressive Strength on Durability

Since water is allowed to enter and exit the test specimen during each of the two types of durability test, the permeability of the test specimen should influence the test results. In addition, since each test is designed to evaluate the ability of the material tested to resist stress, sludges with high strength were expected to be more durable than those with low strength. In the following paragraphs, the influences of permeability and unconfined compressive strength on durability are discussed.

An investigation of the influence of permeability or compressive strength on durability requires that durability tests be conducted using samples of fixed sludge that differ only in permeability or compressive strength, respectively. Since multiple test specimens of fixed sludges (e.g., the samples of A-100), were not identical, only specific statements consistent with the test data are appropriate; and these statements must not be extrapolated for application to all fixed sludges. The influence of permeability and compressive strength are discussed below on the basis of the data generated by the testing of samples not grossly different* and must be viewed with caution.

Influence of Permeability--

Wet-dry--Figure 35 shows the influence of permeability on the percent weight loss during 12 wet-dry test cycles on samples of sludge fixed by process E. Process E was the only process that resulted in more than one fixed sludge capable of surviving 12 wet-dry cycles without disintegration; and, as Figure 35 shows, the durability of sludges fixed by process E was not a function of permeability. In Figure 36 the influence of permeability on the number of wet-dry test cycles the fixed sludges were able to withstand is

*Specimens whose dry unit weight differed by more than 10 lb/cu ft were considered grossly different.

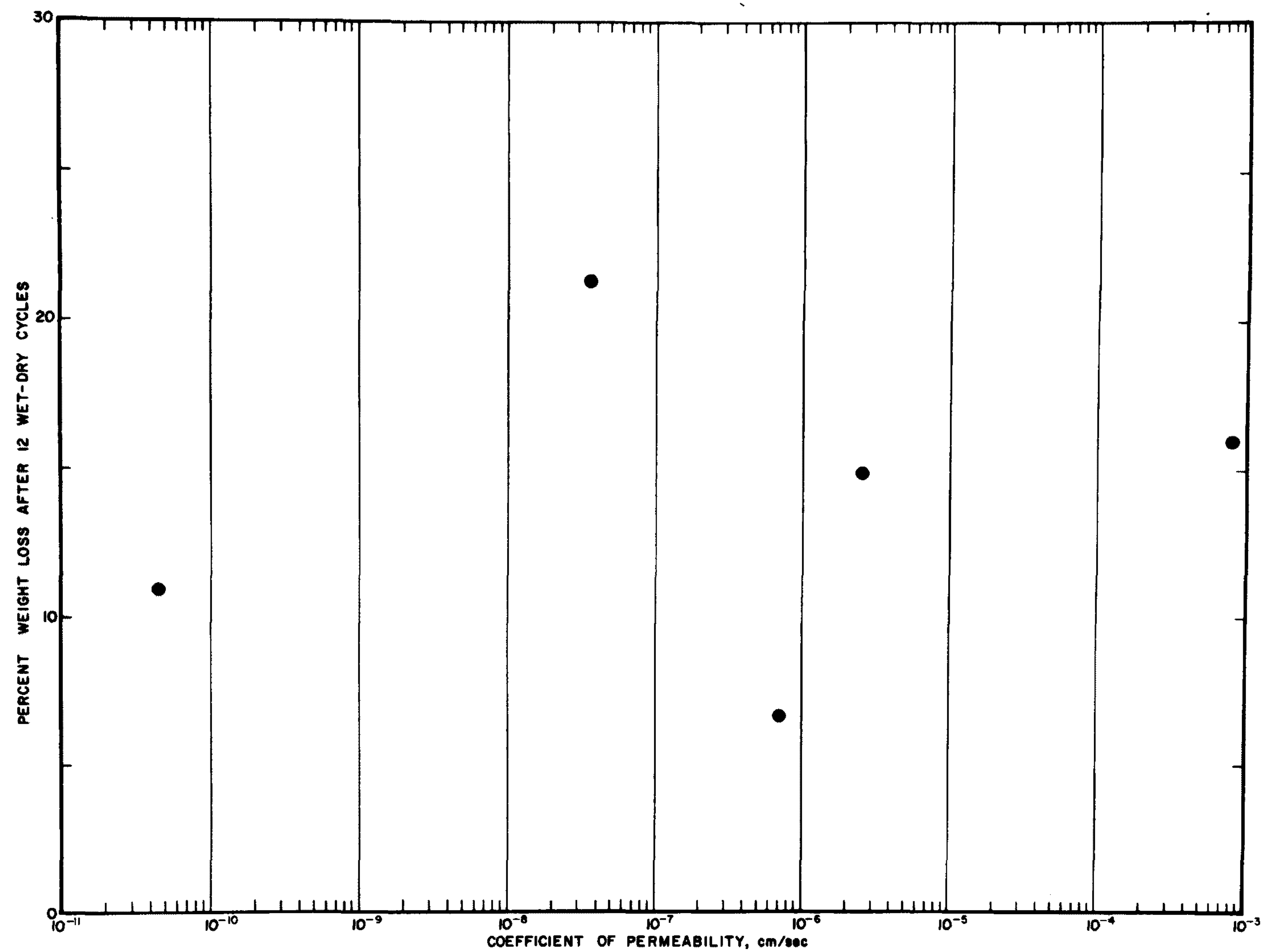


Figure 35. Influence of permeability on the durability of sludges fixed by process E.

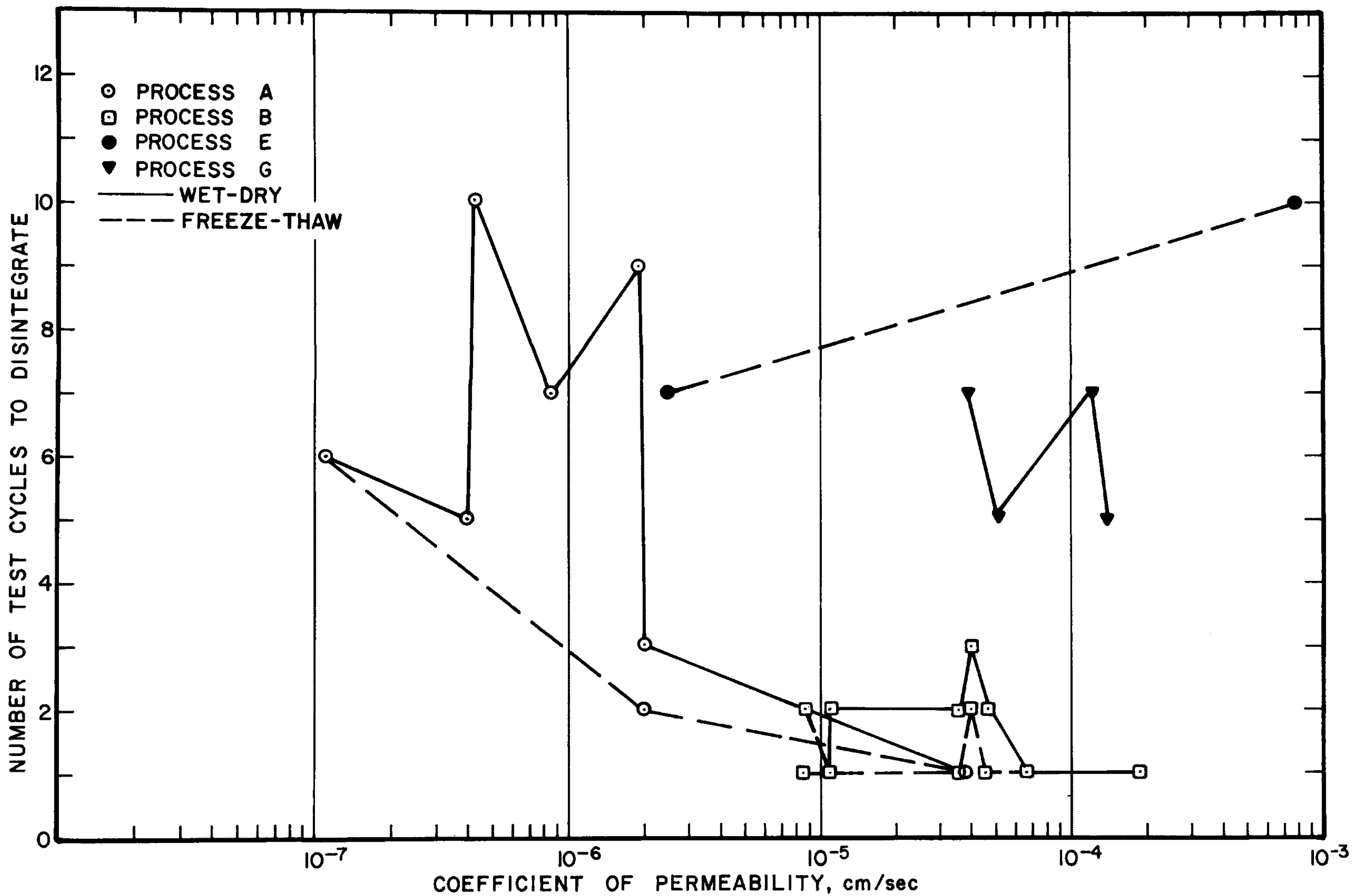


Figure 36. Influence of permeability on the durability of fixed sludges.

shown. Although there is considerable scatter in the data, the durability of sludges fixed by process A generally increased with decreasing permeability. Permeability apparently did not influence the durability of sludges fixed by process B or G.

One sample of sludge fixed by process D was subjected to the wet-dry test, and this sample experienced no weight loss during the test. This exceptional durability is attributed to the nature of the fixed sludge, which was coated with plastic. Since the fixed sludge is absolutely impermeable, or waterproof, wetting and drying have no effect on sample integrity.

Freeze-thaw--Figure 36 shows the influence of permeability on the durability of sludges fixed by processes A, B, and E. Decreasing permeability generally indicated increasing durability for sludges fixed by process A, showed decreasing durability for sludges fixed by process E, and had no influence on sludges fixed by process B. The influence of permeability on the resistance of fixed sludges to freeze-thaw cycles seems to be process-dependent, but more data are required to substantiate this.

As in the case of the wet-dry test, fixed sludge D-200 showed no measurable loss in weight during the freeze-thaw test. The resistance of this sludge to freeze-thaw cycles is attributed to the durability of the plastic coating. In addition, since the process includes drying the sludge prior to encapsulation, little water exists within the sludge mass to expand and break the plastic coating.

Influence of Compressive Strength--

Wet-dry--The influence of compressive strength on the resistance to wet-dry cycles is shown in Figure 37a for sludges fixed by Process E. Process E was the only process resulting in more than one fixed sludge capable of surviving the wet-dry test without disintegration, and the effect of compressive strength on percent weight loss is not well-defined, although a trend toward decreasing durability with increasing compressive strength is suggested.

For the samples that did not survive the wet-dry test, those sludges fixed by processes A, B, or G (Figure 37b), the erratic data suggest that durability increased with compressive strength, opposite of the trend of sludges fixed by process E.

Freeze-thaw--Two samples of sludge fixed by process E survived the freeze-thaw test without disintegration, and the effect of compressive strength on their durability is shown in Figure 37a. As with the wet-dry test, stronger (higher compressive strength) sludges fixed by process E were less durable than weaker sludges fixed by this process.

For the fixed sludges that disintegrated during the freeze-thaw test, the effect of compressive strength on durability is shown in Figure 37c. Sludges fixed by processes A or E were generally more durable with increasing compressive strength, while the durability of sludges fixed by process B or G was not influenced by compressive strength.

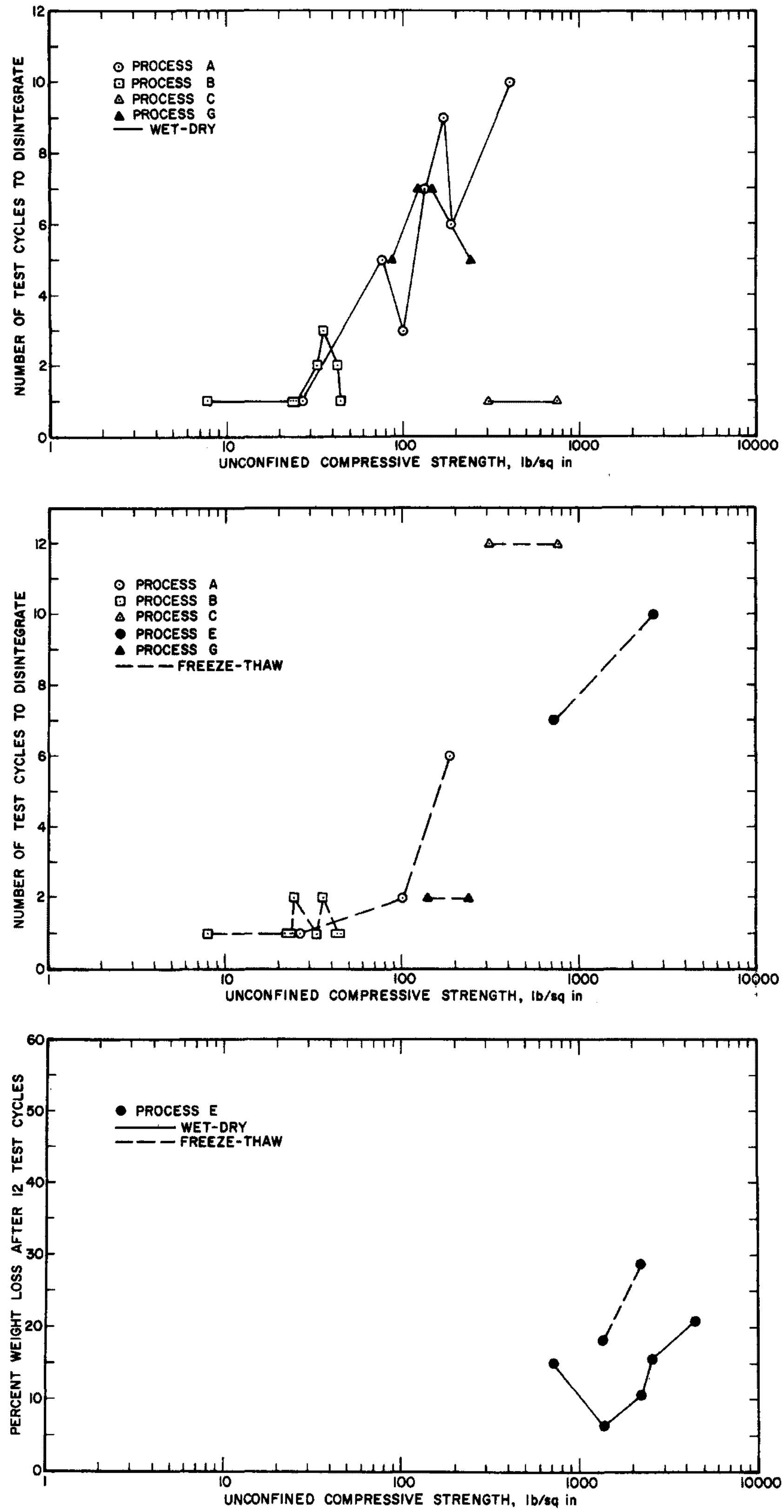


Figure 37. Influence of compressive strength on the durability of fixed sludges.

SECTION 6

DISPOSAL OF FIXED SLUDGE

In this section experience with the behavior of soil and other materials with laboratory properties similar to those of fixed sludge is used as the basis for a discussion of the disposal of fixed sludge. The discussion in this section is concerned with the disposal of fixed sludge only. The discussion is brief and somewhat speculative because of the lack of information on the performance of fixed sludge in the field.

The discussion is limited to the use of fixed sludge for landfilling and embankment construction. Using fixed sludge for land reclamation (landfill) could increase the economic value of marginal land by increasing its suitability for productive use, and the substitution of fixed sludge for soil in embankment construction would reduce the requirements for soil with which the embankment would otherwise have been constructed. The use of fixed sludge for landfilling and embankment construction requires that factors including compaction, bearing capacity, consolidation, and slope stability be considered; and these factors are discussed below.

COMPACTION

Fixed sludge will generally not require compaction, and all but sludges fixed by process B or F are too hard to be compacted by conventional methods. Compaction may be required, however, to reduce the void spaces. Fixed sludges often have cracked (process B) or honeycombed structures (processes A, C, E, F, and G), and compaction may be an effective method for making a sludge mass more continuous.

Compaction of Soil-Like Fixed Sludge

Sludges fixed by process B or F are similar in consistency to very stiff or cemented soils, and can be broken into small particles with moderate effort. The compaction of these materials can be evaluated by comparing their compaction characteristics with those of similar soils.

The compaction tests performed on samples of sludge fixed by process B showed that the compactive effort of the 15-blow test (7400 ft-lb/cf) did not substantially increase the unit weight of the material over that resulting from the fixation process (Table 10). This suggests that moderate compaction, by use of available equipment, will be useful only for producing a more homogeneous mass of sludge and that increased density will result only from the application of a much larger compactive effort, requiring several passes of heavy compaction equipment.

Should a high degree of compaction be required, the sludge should be spread in thin (12-18 in) lifts, cured, and pulverized by passes with a steel-wheel or sheepsfoot roller. Table 6 shows that steel-wheel and rubber-tire rollers are effective for compacting gravelly soil and that sheepsfoot and rubber-tire rollers are suitable for fine-grain soils. Preliminary selection of compaction equipment can be made from this table based on the effectiveness of pulverization (i.e., the degree to which the sludge chunks were ground-up); but, if compaction is critical to the performance of the landfill, test sections should be prepared to evaluate different combinations of equipment and determine the most economical procedure that will accomplish the required compaction.

Compaction of Non-Soil-Like Fixed Sludges

Sludges fixed by process A, C, E, or G are hard after curing and therefore not suitable for compaction by rolling; but the use of vibrators of the type used during concrete construction will probably increase the density and integrity of lifts of fixed sludge. As the sludge is placed for curing, the vibrator could be used to consolidate the mass and could be especially effective for preventing honeycombing, characteristic of many fixed sludge samples (see Figures 1-10).

BEARING CAPACITY

Insufficient information is available to discuss bearing capacity in detail, but the wide range of measured unconfined compressive strength indicates that fixed sludges should exhibit a wide range of bearing capacity; samples with high unconfined compressive strength are expected to have larger bearing capacities than those of materials with lower values. Sludges fixed by processes that result in concrete-like materials would probably have such a high bearing capacity that performance would be limited by the strength of the foundation soil. Thus, these fixed materials should not be restricted in use to any great degree by their bearing capacity and should be suitable for on-site uses such as the construction of service roads to and around the disposal area and off-site uses such as landfill and roadway subgrade construction.

CONSOLIDATION

The rate and amount of consolidation of a deposit of soil under load are estimated from the results of consolidation tests, but no sludge consolidation tests were conducted during this study. Some general indications of fixed sludge consolidation characteristics are suggested by the results of the unconfined compression test; but these are useful only for a qualitative comparison between sludges, because the lack of lateral sample restraint affects the deformation of the sample under load.

The consolidation of fixed sludge will probably be inversely proportional to the compressive strength; strong fixed materials are expected to be deformed less than are weaker materials under the same loading conditions. Among the sludges with comparable strength, those with high moduli of elasticity will undergo smaller deformation than will those with low moduli of elasticity under the same load.

Regardless of the type of sludge or of the fixing process, any analysis of settlement of a sludge landfill or embankment must include an analysis of the soils underlying the deposit. Sludges fixed by all processes except process B are considerably stronger than most soils, and the settlement of structures constructed on such deposits will be due to the consolidation of layers of compressible foundation soils. Settlement due to deformation of the sludge layer will be very minor in comparison to that of the foundation soils as long as the integrity of the sludge is maintained.

EMBANKMENTS OF SOIL-LIKE FIXED SLUDGE

Embankments of soil-like fixed sludges are expected to perform well if designed conservatively and constructed carefully. Since the fixed sludges exhibit considerable strength, slopes can be expected to be stable, provided that the embankment is compacted to a continuous mass, similar to the test specimens. Weathering may be of considerable concern to slope stability, however, because wet-dry cycles and freeze-thaw cycles were shown to be capable of disintegrating sludges fixed by process B or F (Section 5). Proper drainage to reduce or prohibit the exposure of the embankment to freezing and thawing and to wetting and drying may be useful to protect the integrity of the embankment, but may be prohibitively expensive. The use of a soil cover will protect the sludge from erosion, can provide insulation against weathering, and improves aesthetics by supporting vegetation.

Slopes may also be subject to failure due to liquefaction or thixotrophy. The compaction of the fixed materials includes pulverization of chunks of fixed sludge into smaller particles. Careful control of pulverization to result in gravel-size particles and careful compaction will reduce the susceptibility of the sludge to liquefaction and thixotrophy, unless water in the deposit can cause the agglomerated sludge particles to "melt" into silt and fine-sand size particles in which case considerable settlement can be expected. Careful control of moisture during and after construction will also reduce the risk of failure by liquefaction or thixotrophy.

EMBANKMENTS OF NON-SOIL-LIKE FIXED SLUDGE

The construction of embankments of sludges fixed by process A, C, E, or G is expected to be similar to the construction of rock fills, because excavation of fixed material, by using rippers or blasting to loosen the material and a power shovel to excavate and load it, will result in large chunks of material that will not be easily crushed for compaction. Embankments of large chunks of fixed sludge will be free-draining and not susceptible to frost, and for these reasons they are expected to be very stable.

REFERENCES

1. Mahloch, J. L., et al, Pollutant Potential of Raw and Chemically Fixed Hazardous Industrial Wastes and Flue Gas Desulfurization Sludges, Interim Report. U. S. Environmental Protection Agency, Cincinnati, OH, July 1976.

2. U. S. Army, Office, Chief of Engineers, Laboratory Soils Testing, Engineer Manual 1110-2-1906, 30 November 1972.

3. American Society for Testing and Materials (ASTM), Annual Book of ASTM Standards, Part 11, Philadelphia, PA, 1973.

4. The Unified Soil Classification System, Technical Memorandum No. 3-357, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, April 1960.

5. Means, R. E. and J. V. Parcher, Physical Properties of Soils, Charles E. Merrill Books, Inc., Columbus, OH, 1963.

6. Terzaghi, K, and Ralph B. Peck, Soil Mechanics in Engineering Practice, John Wiley and Sons, Inc., New York, NY, January 1967.

7. Hough, B. K., Basic Soils Engineering, The Ronald Press Company, New York, NY, 1957.

8. Cedergren, H. R., Seepage, Drainage, and Flow Nets, John Wiley and Sons, Inc., New York, NY.

9. Wang, S. Y., A Laboratory Study of the Durability Characteristics of Lime-Soil Mixtures, MS Thesis, Purdue University, West Lafayette, IN, 1950.

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/2-77-139	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE PHYSICAL AND ENGINEERING PROPERTIES OF HAZARDOUS INDUSTRIAL WASTES AND SLUDGES		5. REPORT DATE August 1977 (Issuing Date)
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. J. Bartos, Jr. and M. R. Palermo		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Effects Laboratory U. S. Army Engineer Waterways Experiment Station P. O. Box 631 Vicksburg, Mississippi 39180		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. IAG-D4-0569
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Jan. 1975-Aug. 1976
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

This report presents the results of a laboratory testing program to investigate the properties of raw and chemically fixed hazardous industrial wastes and flue gas desulfurization (FGD) sludges.

Specimens of raw and fixed sludges were subjected to a variety of tests commonly used in soils engineering. The grain-size distributions, Atterberg limits, specific gravities, volume-weight-moisture relationships and permeabilities of raw and fixed sludges were determined. Selected fixed sludges were subjected to appropriate engineering properties (compaction and unconfined compression) tests and durability (wet-dry and freeze-thaw) tests.

Test results show that fixing can cause significant changes in the properties of sludge, that fixed sludges are similar to soil, soil-cement, or low-strength concrete, and that properties are process-dependent. On the basis of test specimen behavior, fixed sludges can be expected to exhibit substantial engineering strength and suitability for landfill and embankment construction, although the durability tests show that weathering can be a problem unless the fixed sludges are protected by an earth cover.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wastes Stabilization Sulfates Sludge Soils Management	Flue Gas Cleaning Chemical Fixation Waste	13B
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 89
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

☆U.S. GOVERNMENT PRINTING OFFICE: 1977— 757-056/6497