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Final Report

ENGINEERING AND PHYSICO-CHEMICAL PROPERTIES OF INCINERATED SEWAGE SLUDGE

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SUMMARY

The ash produced by the incineration of sewage sludge from the Auburn treatment plant is predominantly silt size material with an average specific gravity of 2.93. The ash is composed mainly of calcium oxide (about 40% of its dry weight) with lesser amounts of iron oxide and a crystalline mixture of calcium pyrophosphate and calcium aluminum silicate.

Both the dry hearth ash and the ash from the disposal pond have a fairly high soluble salt content. The ash would tend to be quite aggressive towards metals both from an oxidation and bacterial corrosion point of view.

The hearth ash was compacted to maximum dry densities in the range 80 to 90 lb/cu ft at optimum water contents on the order of 30%. These compaction results were obtained using impact type compaction. Kneading compaction was not as effective; considerably lower dry densities were obtained, and the dry density was more or less independent of the moulding water content in the latter case.

The strength and penetration resistance of properly compacted hearth ash is remarkably high. Unconfined compressive strengths of both "as compacted" and "soaked after compaction" samples ranged as high as 10 TSF Compressive strength tests were run only on samples prepared by kneading compaction. Compacted hearth ash exhibited brittle behavior with failure occurring abruptly at strains between 1 and 2%. Compacted samples of hearth ash (by kneading method) tested in undrained, triaxial tests exhibited a failure envelope with a slope (or friction angle) of 35° and a cohesion intercept of 1.5 TSF. Proctor penetration resistances reached maximum values as high as 7000 to 13000 psi (depending upon the compactive effort used) for samples compacted to their maximum dry densities by impact compaction. Penetration resistance fell off sharply, however, for samples compacted wet of optimum. The penetration resistance of ash taken from the disposal pond and compacted was some 20 to 30% lower than that of the ash taken directly from the furnace and compacted under identical conditions.

The natural water content of the ash in the disposal pond is well over 100% (dry weight basis). It will be necessary, therefore, to dry this material out before it can be adequately compacted in order to meet strength and stability requirements. Drying may pose a practical difficulty in the field and force a different procedure for handling and disposal of the ash if it is to be subsequently used for fill or other purposes. Once compacted, however, an increase in moisture content appears to have no adverse effect on strength. Moisture retention tests indicate a drying rate in the laboratory of about 5% per day for material at a 6-in. depth.

Preliminary tests indicate the ash is not frost susceptible. Compressive strength and penetration resistance of samples subjected to as much as five cycles of freezing and thawing actually were higher than those of samples tested immediately after compaction without being soaked, frozen, and thawed. The high lime content of the ash probably accounts for this lack of frost susceptibility.

INTRODUCTION

This report describes the engineering and physico-chemical properties of ash produced by the incineration of sewage sludge. The particular ash described herein comes from the Auburn Sewage Treatment Plant, City of Pontiac, Michigan. The objective of the study was to characterize the ash and determine its suitability as a light weight backfill or structural fill material. Other potential uses of the ash, e.g., in building blocks, are also considered.

The properties of two types of ash from the plant are described in the report. The first is the ash taken directly from the incinerator—hereafter referred to as <u>hearth ash.</u> This material was obtained in a dry, powdery form. The second is ash taken from the disposal area—hereafter referred to as <u>lagoon ash</u>. The latter is simply hearth ash which has been mixed with treated effluent from the plant and them pumped as a slurry to a disposal pond where the solids settle out and the excess water drains off.

Fly ash produced from the burning of coal in thermal power stations has been used quite successfully in engineering practice. A compacted fly ash subgrade, for example, was used beneath the runway at Birmingham airport[1] in England. The use of stabilized fly ash as both an embankment and road subgrade material[2,3] has also been reported. Raymond[4] and his co-workers in England have described the physical and engineering properties of fly ash in some detail. With proper handling and precautions this material exhibits adequate strength and stability.

In contrast to ash produced from the burning of coal, virtually nothing is known about the engineering properties of ash produced by the incineration of sewage sludge. This preliminary report describes some essential features of the latter type of ash. Testing was conducted by staff of the Department of Civil Engineering in the Soil Mechanics Laboratory of The University of Michigan. Tests run included specific gravity and grain size determinations, analyses of ash solids and soluble salts, corrosion potential, and moisture retention characteristics of the ash.

The results of a series of strength tests on compacted samples of ash are reported herein. These included both unconfined and triaxial compression tests

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[1] Woolard, J. H.: Civil Engineering and Public Works Review, May 1967, p. 542.

[2] Raymond, S.: Proc. Inst. of Civil Engineers, Vol. 19, Aug. 1961.

[3] Raymond, S. and Smith, P. H.: Proc. Inst. of Civil Engineers, Vol. 24, Feb. 1963.

[4] Raymond, S., <u>et</u> <u>al</u>: Civil Engineering and Public Works Review, Sept. 1966, p. 1107.

on samples prepared by kneading compaction. Penetration-resistance tests on samples prepared by standard impact compaction methods are also described. The age hardening or thixotropic strength properties of compacted ash were determined. Finally, a series of modified freeze-thaw tests were run on samples of compacted hearth ash in order to evaluate its frost susceptibility.

PHYSICO-CHEMICAL PROPERTIES

SPECIFIC GRAVITY AND GRAIN SIZE ANALYSIS

Specific gravity of the ash solids and grain size distribution were determined by standard[5] methods. The average specific gravity of the ash solids was found to be 2.93. This is slightly higher than the average specific gravity for most soils which lies close to 2.65 (that of quartz). The grain size distribution of the hearth ash material is shown in Figure 1. The ash is composed almost entirely of silt size material (about 85% by weight), with about 10% clay size material and 5% sand sizes.

Based solely on its grain size distribution, the ash would be classified as highly frost susceptible. In conventional soils it is the silts which are the most subject to adverse frost effects. On the other hand, evidence (see reference, footnote 4) from tests on compacted fly ash indicated that this criteria does not always apply to compacted ash. In fact, results of freeze-thaw tests described in a subsequent section strongly support this latter view.

ANALYSIS OF ASH SOLIDS

1. X-Ray Diffraction Tests

X-ray diffraction can be used to identify crystalline constituents of a mixture. The diffraction peaks with their characteristic spacing and relative intensities are tabulated in Table I. A portion of the X-ray diffractogram showing the two most intense peaks which occurred at spacings of 3.35 and 3.20 Ångstroms is shown in Figure 2.

Analysis of the X-ray diffraction pattern indicates the presence of calcium pyrophosphate and some type of calcium-aluminum-silicate as the principle crystalline constituents of the ash.

2. Chemical Composition and pH

The pH of the ash was measured on a paste (mixed at a 5:1 dilution by weight of distilled water to dry ash). The results of the pH tests are shown in the summary in Table II. Both the hearth ash and lagoon ash are quite basic with an average pH of about 11. The high pH can be attributed to the presence

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[5] Black, C. D. (editor): Methods of Soil Analysis, Vol. 2, American Soc. Agronomy (1965).

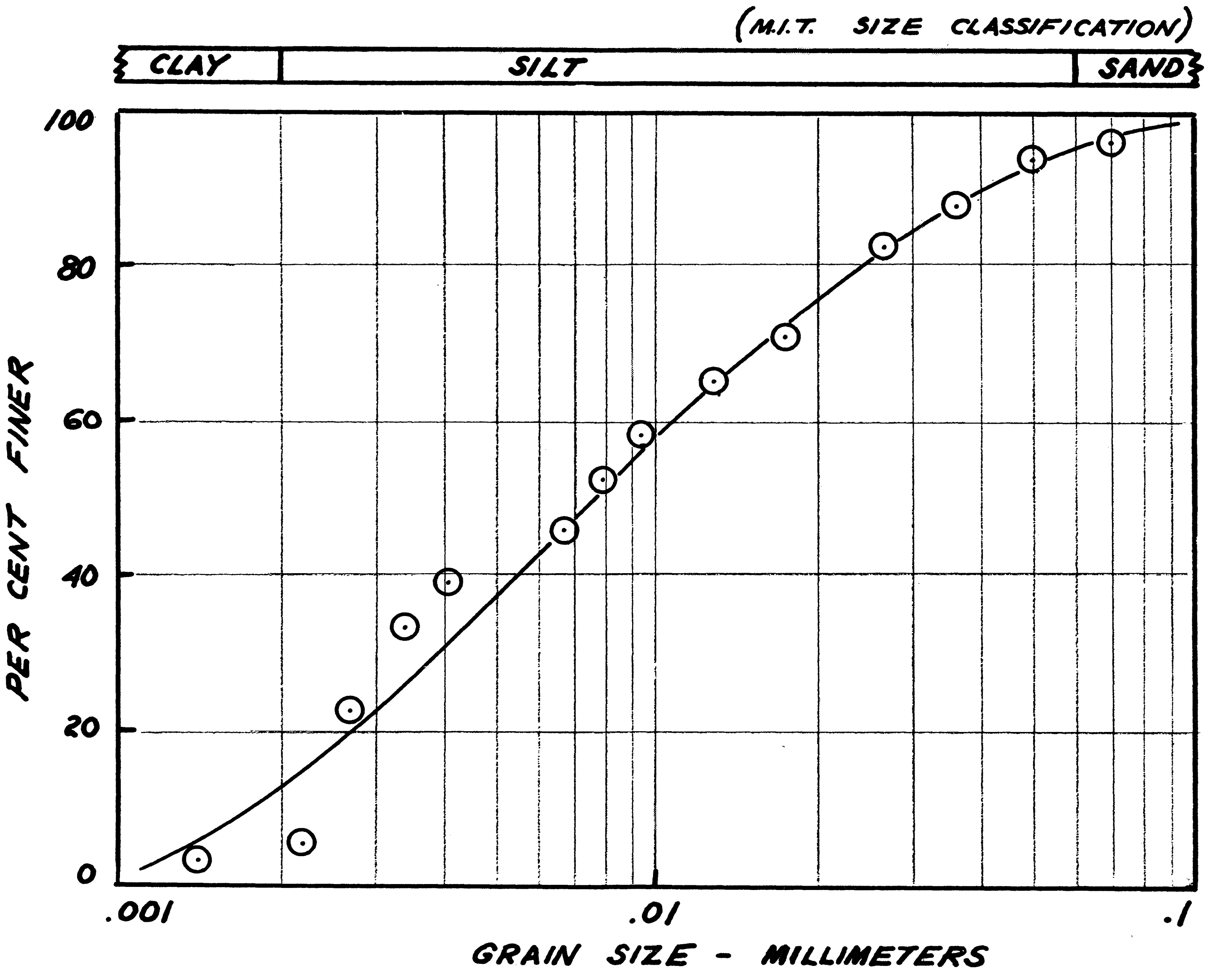

Figure 1. Grain size distribution of hearth ash from Auburn Sewage Treatment Plant.

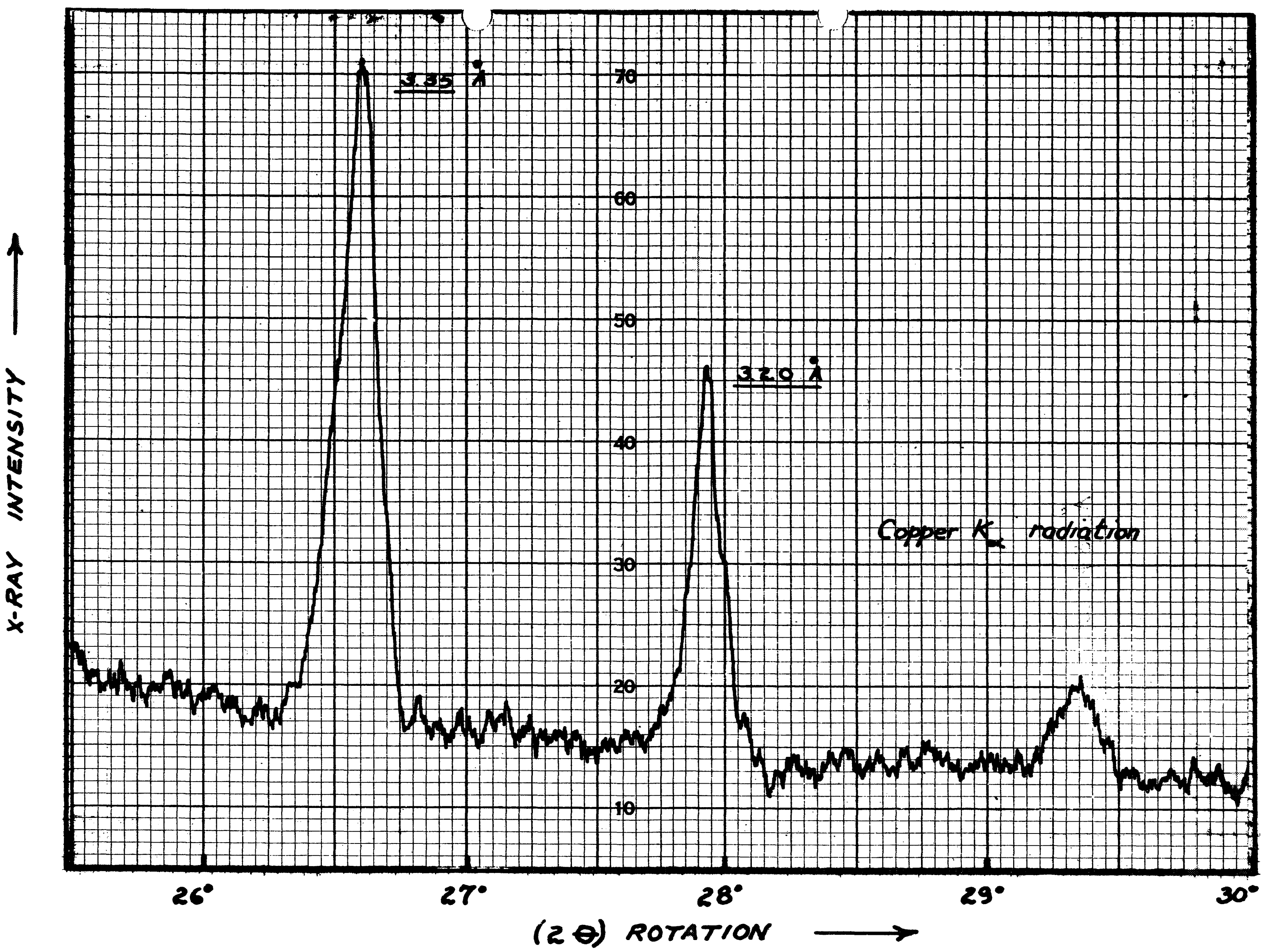

Figure 2. X-ray diffraction pattern of hearth ash showing major diffraction peaks.

TABLE I

X-RAY DIFFRACTION ANALYSIS OF HEARTH ASH
(Auburn Sewage Treatment Plant)

d-Spacing, Å	Relative Peak Intensity, %	Possible Mineral or Crystalline Compound
4.27	35	$AlPO_4$
3.35	100	$CaH_2P_2O_7$, Al_2SiO_5
3.02	61	$CaH_2P_2O_7$, Al_2SiO_5, $CaAl_2Si_2O_8$
2.86	21	?
2.68	18	$FeCl_3$
1.98	27	α-$CaSiO_3$
1.67	20	(2nd order for 3.35)

TABLE II

SUMMARY OF PHYSICO-CHEMICAL PROPERTIES OF ASH FROM THE AUBURN SEWAGE TREATMENT PLANT

Index Property	Hearth Ash	Lagoon Ash
Specific Gravity	2.93	-
Grain Size Distribution (M.I.T. Size Classification)	5% sand size 85% silt size 10% clay size	-
Average pH (5:1 dilution of solids)	10.9	11.3 top end 10.9 bottom end
Total Soluble, Salt Content, meq/100 gms dry ash	14.5	11.1 top end 7.8 bottom end
Soluble Calcium, meq/100 gms dry ash	11.5	6.1 top end
Bulk Resistivity of ash, ohm-cm	481 at $w/c = 58\%$ $\gamma_d = 49$ pcf	570 at $w/c = 112\%$ $\gamma_d = 43$ pcf
Average Water Content, % of dry wt.	.24	104 top end 121 bottom 1 foot depth
Redox Potential, volts at pH 7	-	+.38 top end +.45 bottom end

of lime which was added to the sludge during treatment.

The results of a chemical composition analysis are shown in Table III.

TABLE III

CHEMICAL COMPOSITION OF HEARTH ASH FROM THE AUBURN SEWAGE TREATMENT PLANT

Compound		Weight Percent
Aluminum Oxide		1.6
Iron Oxide		4.3
Calcium Oxide		40.0
Silicon Dioxide*		2.5
	Total Free Oxides	48.4
Moisture Content		0.3
Loss on Ignition		6.2
Acid Soluble Material**		45.0
Miscellaneous***		48.5
	Total Sample	100.0

*Total or elemental analysis for silicon.

**20 min digestion in 1N HCl.

***By difference... includes crystalline minerals identified in X-ray diffraction analysis.

The free metallic oxide content of the ash was determined in lieu of an elemental analysis. As can be seen from Table III, the free metallic oxides of aluminum, iron, and calcium account for almost half of the dry weight of the ash. Calcium oxide is the most abundant compound in the ash with a weight fraction of 40%.

Standard analytical methods were used for the determination of the various metal oxides (see reference, footnote 5). The exception to standard procedure occurred in the case of the calcium oxide determination. In this case, 1 g of dry ash was digested in 100 ml of 1N HCl for 20 min. The liquid supernatant was then filtered off and analyzed for its calcium ion content (after suitable dilution) using the standard EDTA method. The dry weight of solids remaining after acid digestion was also recorded in order to determine the total amount of acid soluble material in the ash. Calcium oxide constituted approximately 80% of the acid soluble material.

ANALYSIS OF ASH LEACHATE

Both the hearth ash and lagoon ash were leached with distilled water; the leachate was then analyzed for total soluble salt content and calcium ion in solution. Leaching was accomplished by placing 10 g of dry ash in 100 ml of distilled water, mixing vigorously for 10 min, and then filtering off the supernatant.

The leachate or supernatant was analyzed for total salt content by an electrical conductivity cell. A calcium ion electrode was used to determine the amount of calcium ion in solution. Results of the leachate analysis are tabulated in Table II.

Some loss of soluble salts has occurred in the disposal pond as evidenced by a progressive decrease in soluble salt content of the ash as it moves from the furnace to the disposal pond. In the disposal area itself, the soluble salt content of the ash is lowest at the bottom end where it has presumably been subject to a greater flushing or leaching action than at the top.

AGGRESSIVENESS OF ASH TOWARDS METALS

The physico-chemical properties used to determine probable aggressiveness of the ash towards metals were bulk resistivity, redox-potential, and pH. The bulk resistivity is a measure of the likelihood of oxidative corrosion, the other (redox-potential) being considered indicative of the risk of bacterial corrosion. These criteria were selected after extensive laboratory and field trial[6] on many different soils. A soil is considered agressive or nonaggressive according to the following scheme:

	Aggressive	Nonaggressive
Resistivity, ohm-cm	<2000	>2000
Redox-potential at pH - 7 (or <0.43 if clay)	<0.40	>0.40
Borderline cases to be resolved by: Water content, wt.%	>25	<25

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[6] Booth, G. H., et al.: Br. Corrosion Journal, Vol. 2, May 1967, p. 105.

Based on these criteria the ash from the Auburn plant would be considered definitely aggressive in so far as oxidative corrosion is concerned and a marginal risk as regards bacterial corrosion. Bulk resistivities and redox-potentials are tabulated in Table II.

MOISTURE RETENTION CHARACTERISTICS

The ash in the disposal pond has a deceptively high water content. A sampling of water contents at various locations revealed the following:

	Water Content, wt. %	
	At Surface	One Foot Deep
Top end of pond	92.5	116
Bottom end of pond	115	138

In order to properly compact the lagoon ash above, it will be necessary to dry it down to a water content in the vicinity of 30%. This requirement will be discussed in the section on engineering properties of compacted ash. In view of this requirement, it is important to obtain some idea of the drying or moisture retention characteristics of the ash from the disposal pond. Accordingly, a 6-in. lift of lagoon ash was deposited in an open container and allowed to dry in a room held at 23°C and 50% relative humidity. Periodic water contents were taken from the bottom of the 6-in. lift; the results of the drying are shown in Figure 3. A drying rate of approximately 5% change in water content per day was observed.

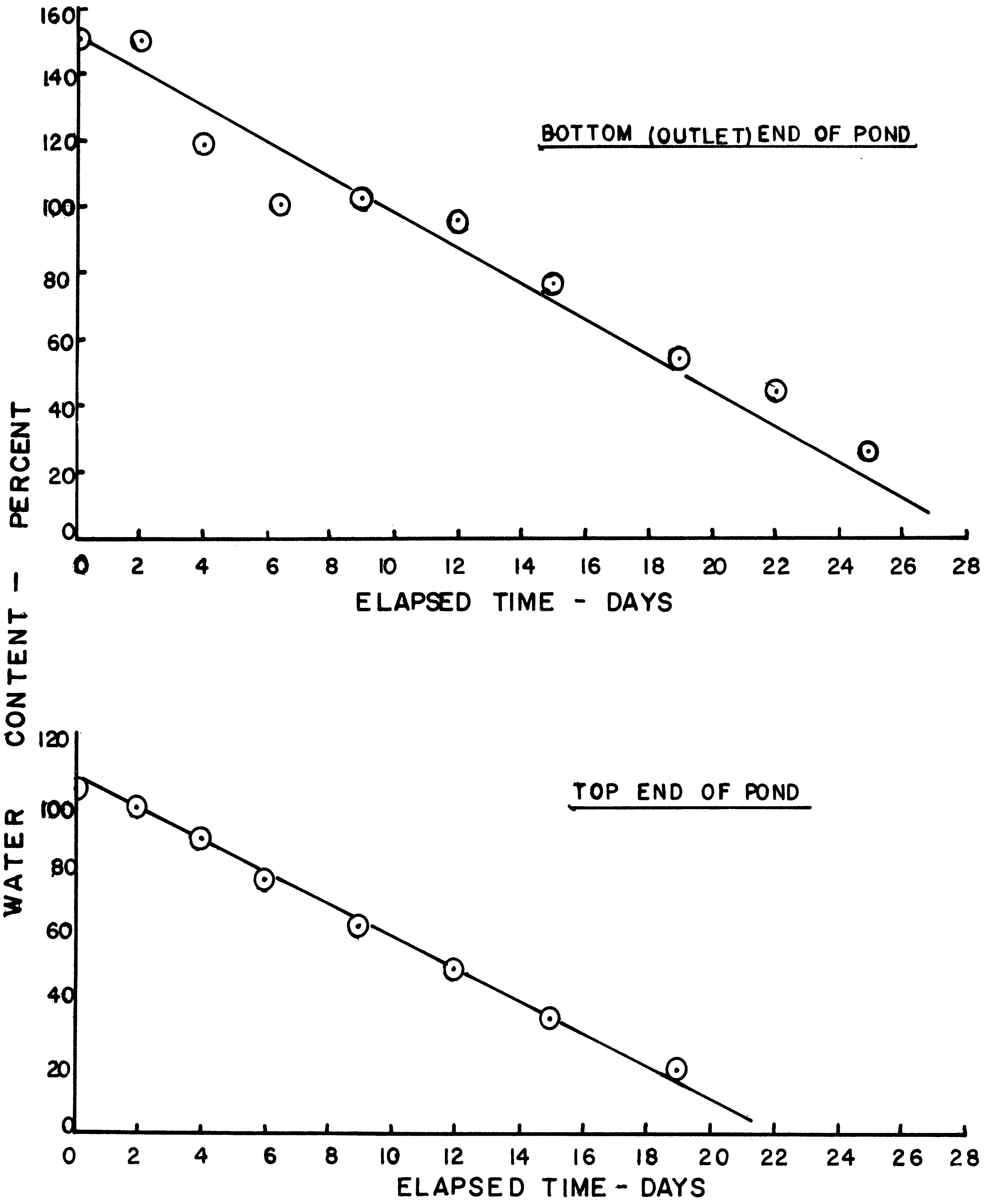


Figure 3. Drying characteristics of ash from the disposal pond. (Temp. = 23°C, R.H = 50%, 6 in. depth)

ENGINEERING PROPERTIES

COMPACTION CHARACTERISTICS

The ash was compacted by both impact and kneading compaction using the modified AASHO and Harvard miniature compaction methods, respectively. The compactive effort during impact compaction was varied by using either 10, 20, or 30 blows per layer from a 10-lb hammer falling a distance of 18 in. The compactive effort during kneading compaction was held constant at 20 tamps per layer using a tamper with a 40-lb spring.

The compaction curves obtained during both impact and kneading compaction on samples of hearth ash are shown in Figure 4. The hearth ash was compacted to maximum dry densities in the range 80 to 90 lb/cu ft at optimum water contents on the order of 30%. The ash taken from the disposal pond exhibited lower dry densities at the same moulding water contents and compactive efforts used for the hearth ash. The compaction characteristics of ash produced by incineration of sewage sludge are similiar to those of a conventional silty soil except for magnitude. Compacted dry densities are considerably less and moisture requirements about twice those of a conventional soil.

The preceding results were for impact compaction. Kneading compaction was not as effective; considerably lower dry densities were obtained and the dry density was more or less independent of the moulding water content. Kneading compaction probably introduces excessive remoulding and shear strain into the ash making it more difficult to obtain high dry densities. Inspite of lower dry densities (about 60 pcf) samples of hearth ash compacted by kneading compaction exhibited relatively high strength as discussed in the next section.

STRENGTH OF COMPACTED ASH

Both unconfined and triaxial compression tests were run on samples of hearth ash prepared by kneading compaction. Unconfined compression tests were run on samples compacted at different moulding water contents both in the "as compacted" condition and on samples compacted and then allowed to soak in water overnight. A summary of results of the unconfined compression tests is shown in Table IV. For samples prepared by kneading compaction, the moulding water content had no effect on strength (for water contents in the range 30 to 60%). Soaking had no adverse effects—in fact, strengths increased considerably after soaking, however, this may have been caused by thixotropic action. Compacted samples of hearth ash behaved in fairly brittle fashion during compression. Failure normally occurred abruptly at a strain of 1 or 2%. Typical stress-strain curves for compacted hearth ash in uniaxial compression are shown in Figure 5.

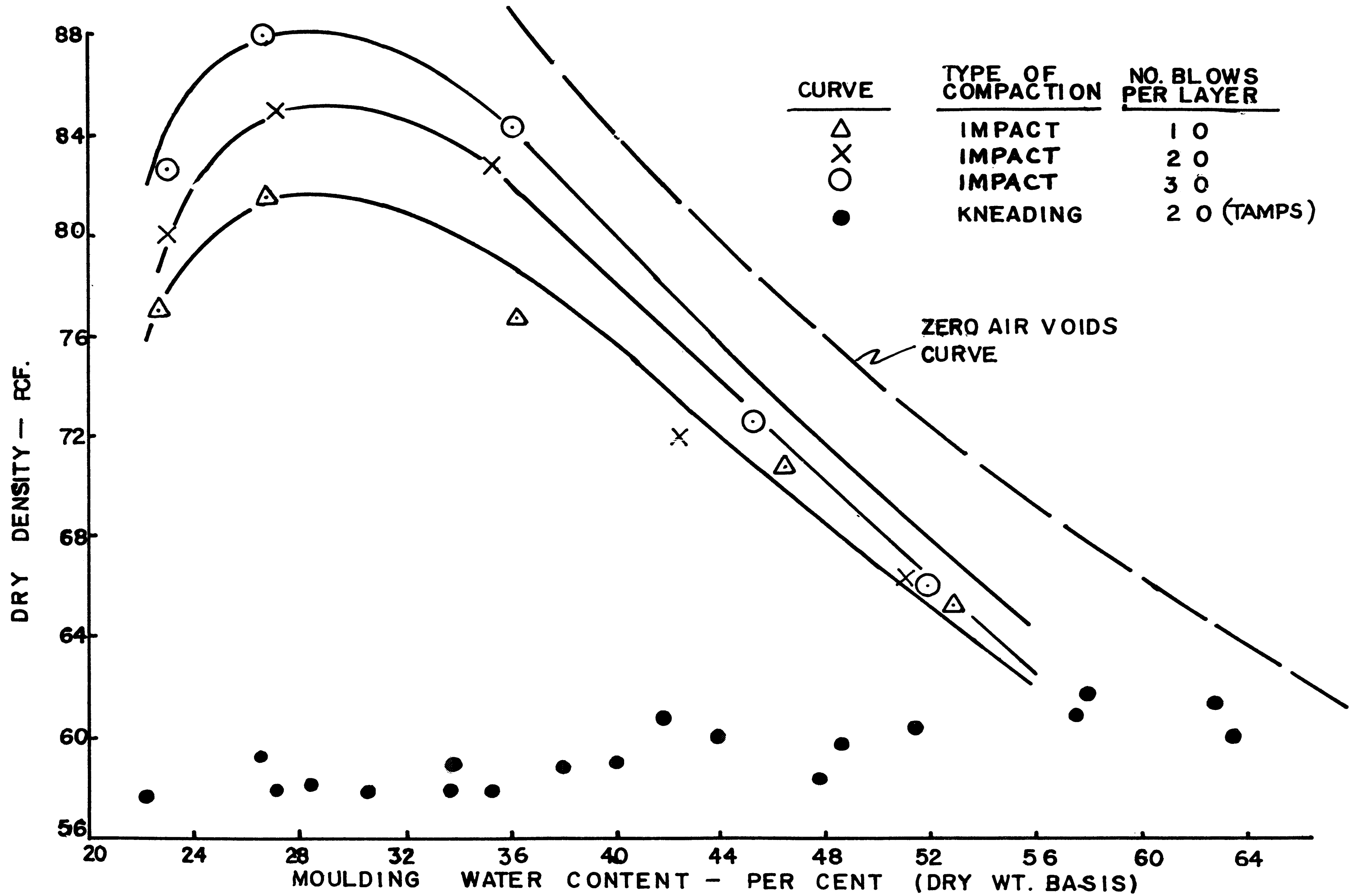


Figure 4. Compaction characteristics of hearth ash.

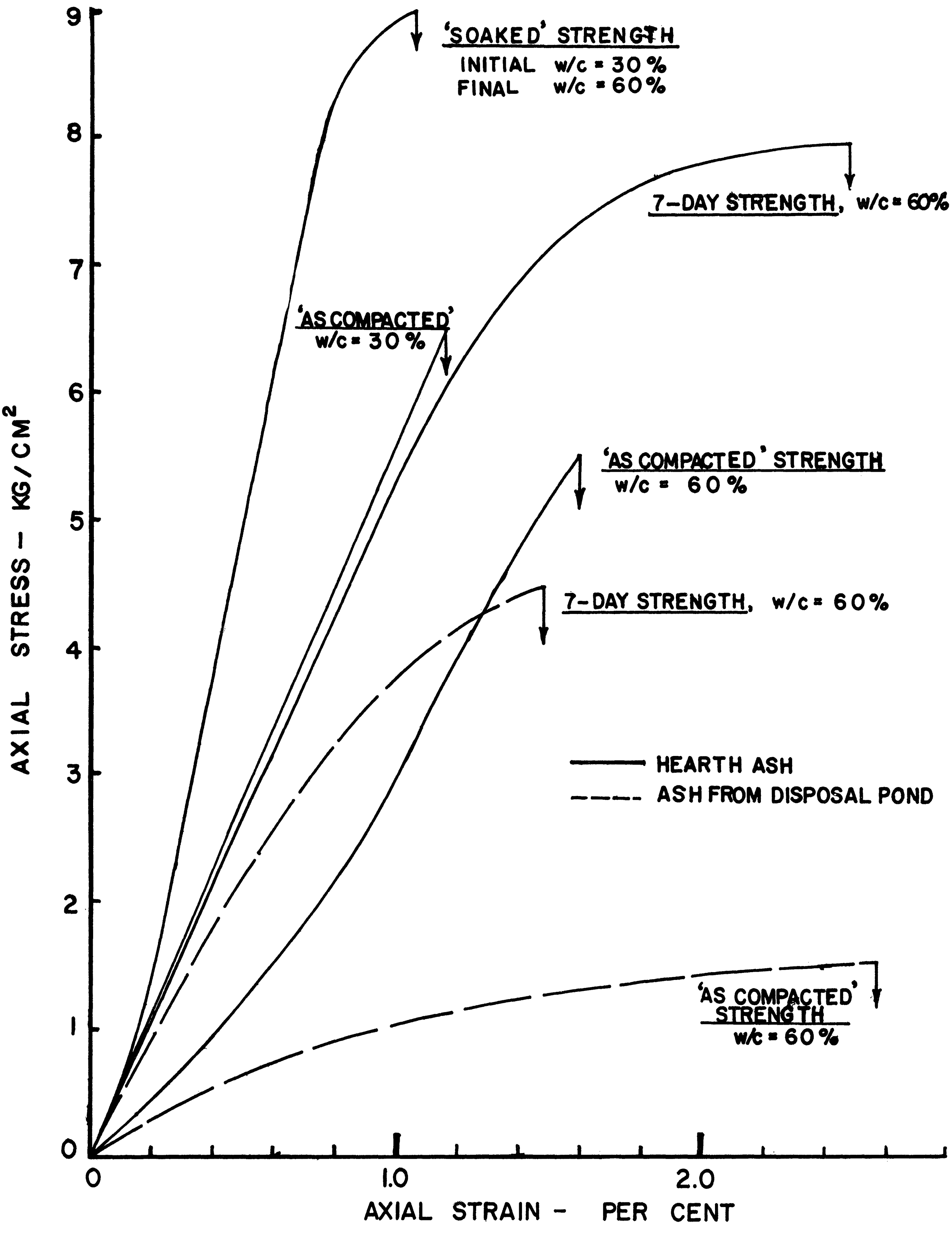


Figure 5. Typical stress-strain curves for compacted ash.

TABLE IV

SUMMARY OF UNCONFINED COMPRESSION TESTS ON COMPACTED SAMPLES OF HEARTH ASH-KNEADING COMPACTION

		"As Compacted" Results		"Soaked" Results			
Nominal Moulding Water Content, %	Water Content, %	Dry Density, pcf	Compressive Strength, Tsf	Initial Water Content, %	Soaked Water Content, %	Dry Density, pcf	Compressive Strength, Tsf
30	29.7	59.5	6.3	26.9	64.0	60.1	9.6
	28.4	58.1	5.2	26.5	65.6	59.2	9.4
40	38.9	59.8	6.9				
	38.0	59.4	5.3				
50	47.3	59.8	6.6				
	46.9	58.9	5.7				
60	63.9	59.8	5.5	62.7	64.8	61.4	10.6
	68.9	59.5	6.2	57.9	61.8	61.8	9.3

The results of triaxial compression tests to determine the shear envelope of compacted ash are shown in Figure 6. The triaxial compression tests were run on samples compacted by kneading compaction at 60% water content to dry densities of about 58±1 pcf. Inspite of this high moulding water content and low dry density, relatively high strength in triaxial compression was observed. A friction angle of 35° and a cohesion intercept of 1.5 TSF were recorded for the triaxial test.

PENETRATION RESISTANCE OF COMPACTED ASH

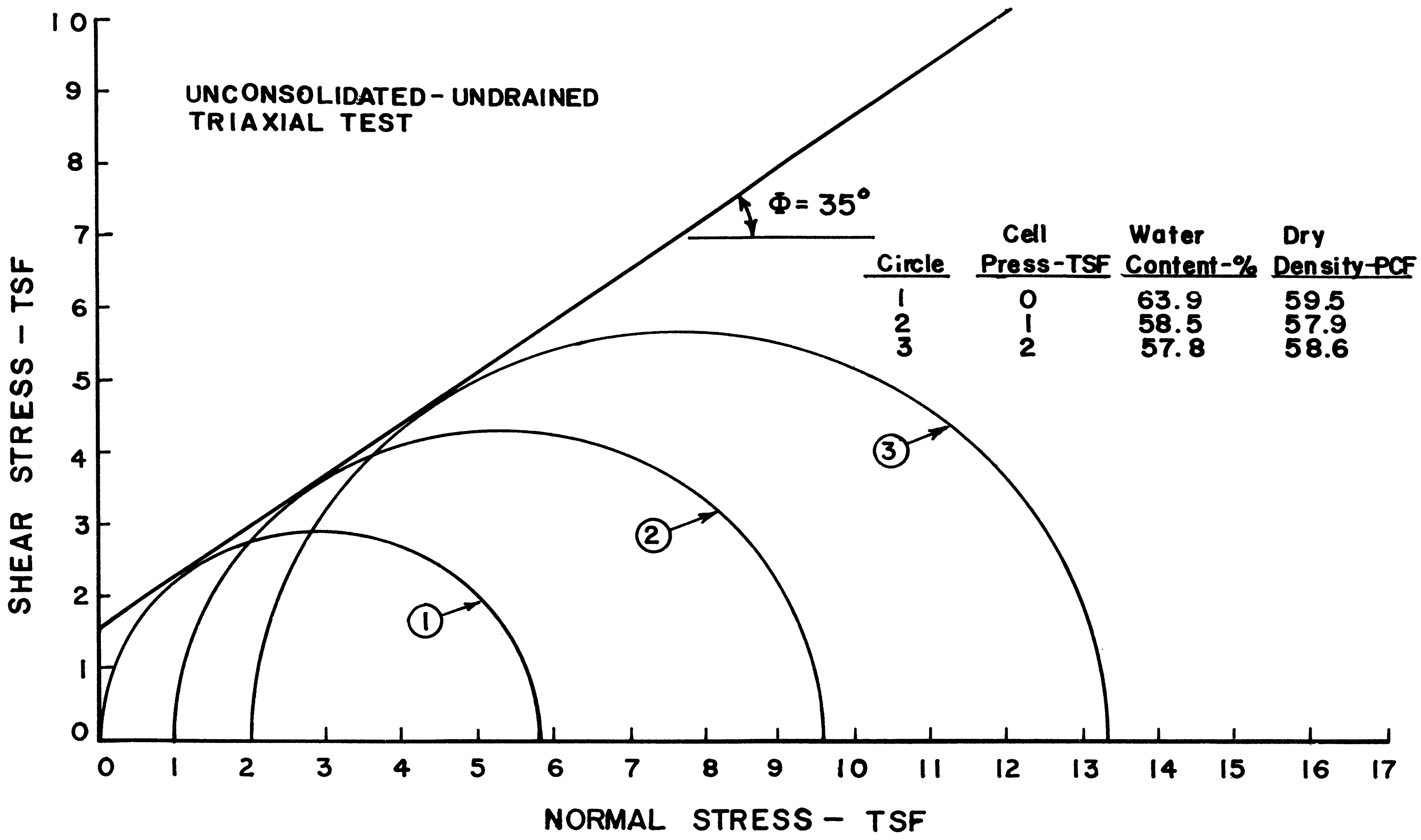
A modified, Proctor penetration resistance test was used to obtain an estimate of the strength and stability of ash compacted by impact compaction at various moulding water contents and compactive efforts. A penetration piston with a cross sectional area of 0.1 in.^2 was mounted in a Universal testing machine and forced into the compacted samples (while still in their compaction molds) for a distance of 3 in. at a penetration rate of 2 in./min. A penetration-resistance curve was automatically plotted for each test from which the maximum resistance could be obtained. The maximum usually occurred after a penetration of 2 in.

The penetration-resistances of compacted samples of hearth ash are shown in Figure 7. Penetration resistances as high as 13,000 psi were recorded for samples compacted to maximum dry density. Penetration resistances of compacted samples of lagoon ash were generally lower as shown in Figure 8. It is important to note that the penetration resistance, and hence the stability, falls off sharply for samples compacted wet of optimum.

AGE HARDENING (THIXOTROPIC) PROPERTIES

The age hardening characteristics of compacted samples of ash were studied by compacting a batch of samples under identical conditions and then testing duplicate samples from the batch at various elapsed time intervals. After compaction, each sample was sealed in a plastic bag and stored in an airtight container for a specified period of time. After the specified time interval the samples were tested in unconfined compression.

The results of the age hardening tests are shown in Figure 9 for both the hearth ash and the lagoon ash. Thixotropic strength increase occurs rapidly in the hearth ash and levels off after a few days. Initial strengths of the lagoon ash were considerably lower, but thixotropic strength gain continued throughout the entire time period and eventually appears to approach the terminal strength of the hearth ash.



Circle	Cell Press-TSF	Water Content-%	Dry Density-PCF
1	0	63.9	59.5
2	1	58.5	57.9
3	2	57.8	58.6

Figure 6. Total stress failure envelope for compacted hearth ash.

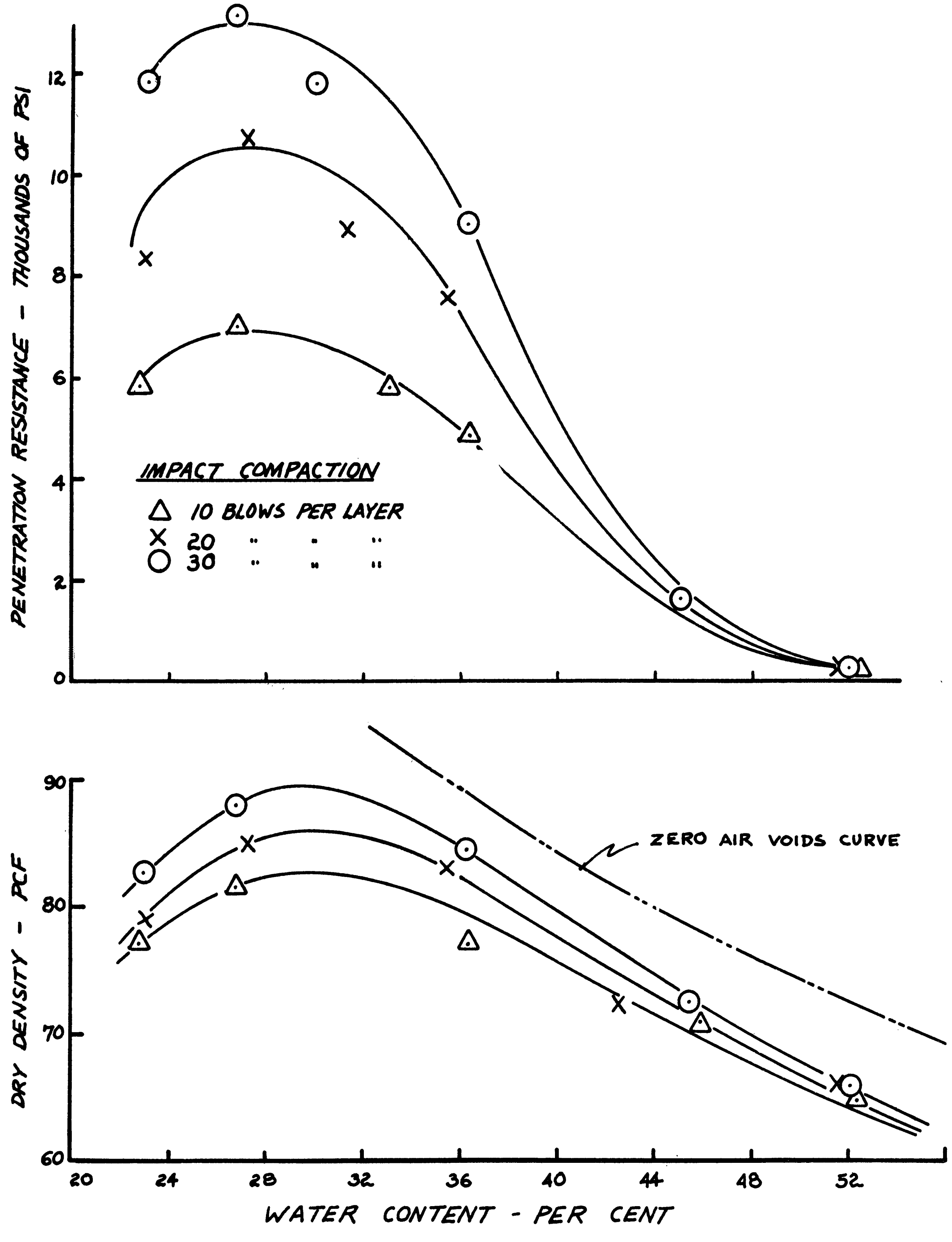


Figure 7. Penetration resistance of compacted hearth ash.

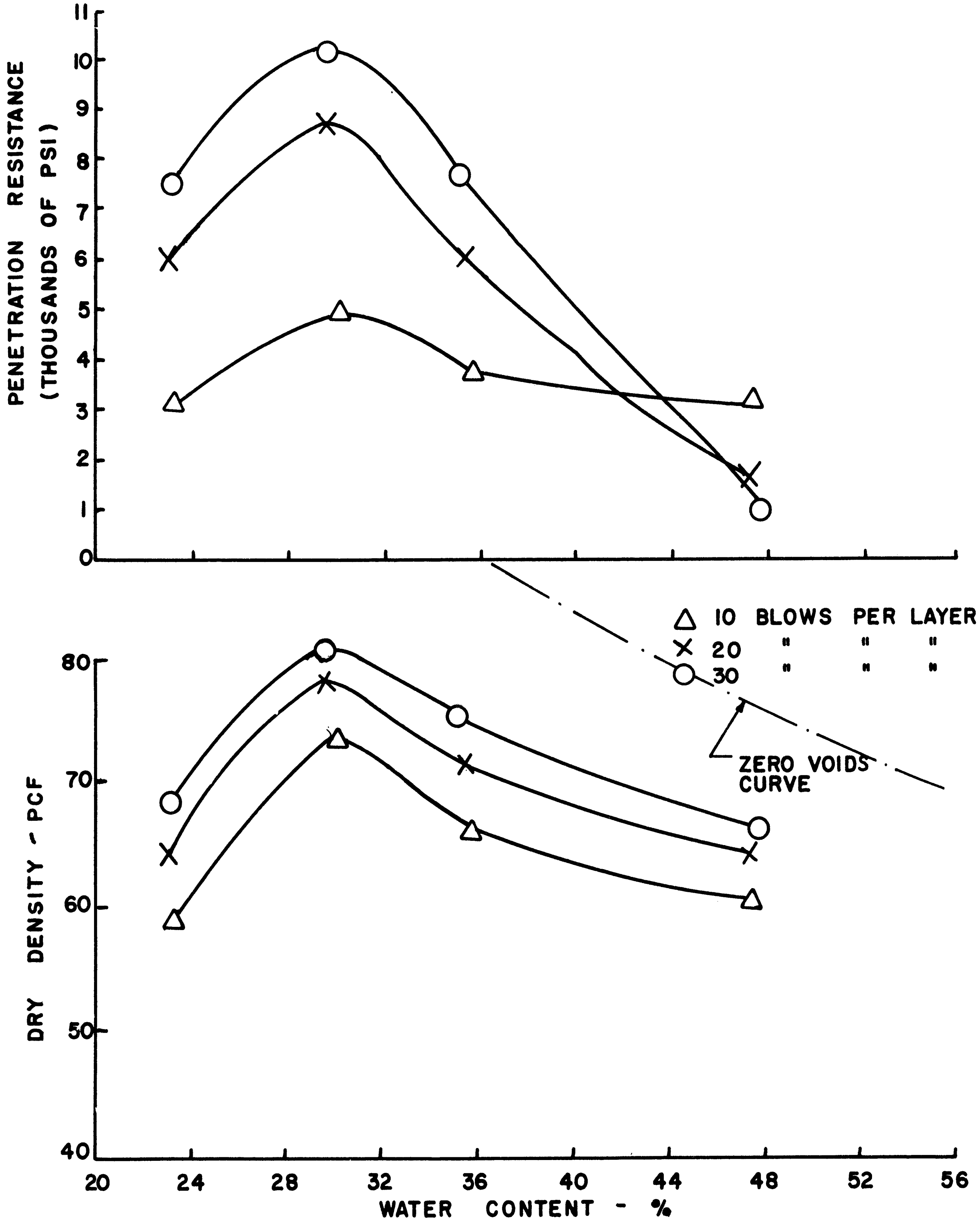


Figure 8. Penetration resistance of ash from top end of disposal pond.

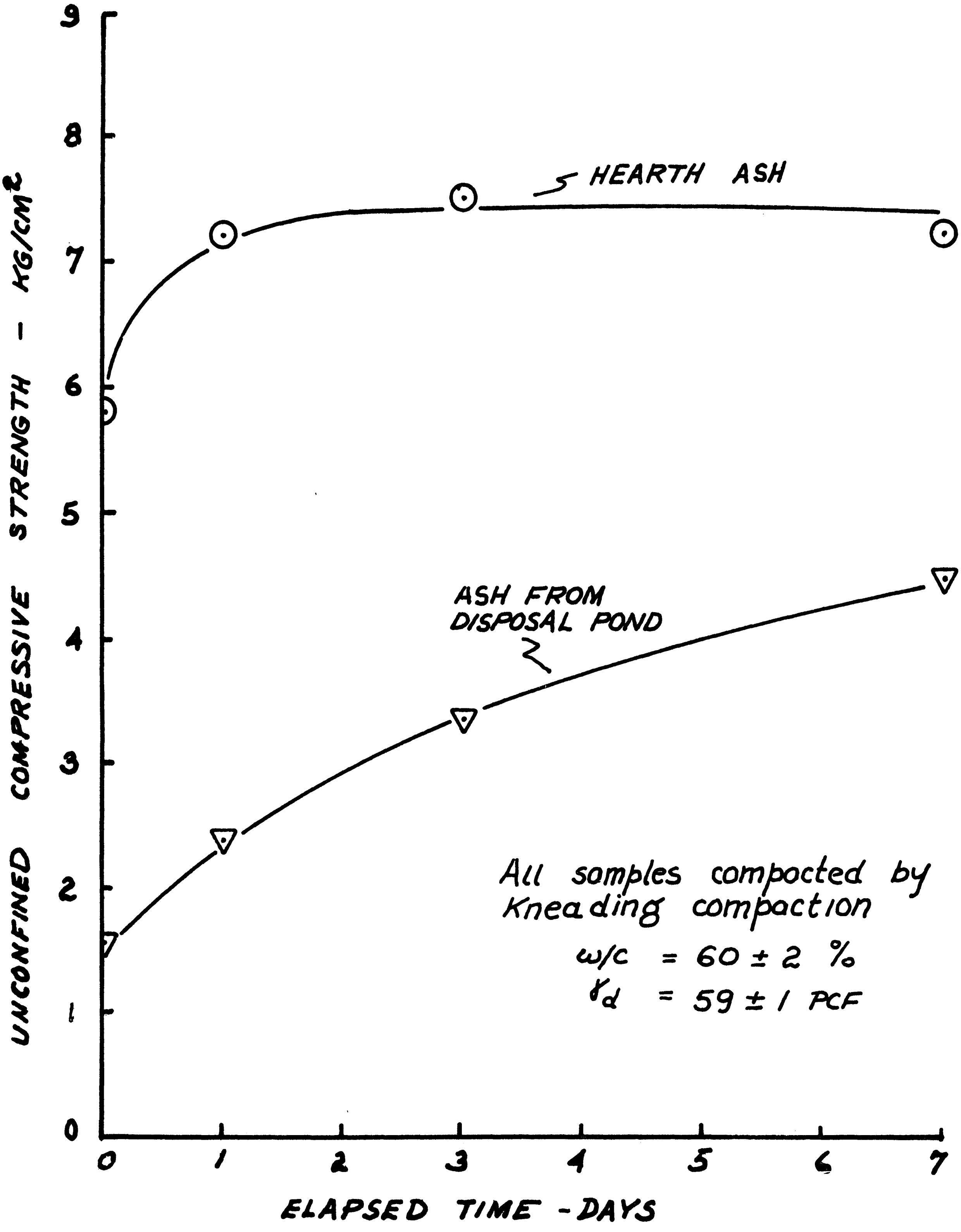


Figure 9. Age hardening characteristics of compacted ash from incinerator (hearth ash) and from disposal pond.

FREEZE-THAW TESTS

A series of modified freeze-thaw tests were devised in order to evaluate the durability of compacted ash against extremes of temperature. Frost heave tests were omitted because equipment was not available for this type of test. The latter requires a special freezing cabinet in which unfrozen water is supplied to the base of the samples during the freezing process. The freeze-thaw test by itself, however, is a severe measure of the frost resistance of a material.

The modified freeze-thaw test consisted of compacting the samples at various water contents, allowing them to soak in water overnight, subjecting them to a number of cycles of alternate freezing and thawing, and then determining their compressive strength or penetration resistance. A freezing temperature of -5°F was used. Compacted samples which were tested for penetration resistance were left in their compaction molds; samples tested for compressive strength were extruded from the mold before being subjected to freezing and thawing. A freeze or thaw cycle each lasted 24 hr.

The results of unconfined compression tests on samples of compacted hearth ash after 0, 1, and 5 freeze-thaw cycles are shown in Table V. Clearly, the cyclic freezing and thawing did not decrease strength. The increase is probably caused by thixotropic or age hardening effects discussed previously. The same trend was observed in the penetration resistance tests. Penetration resistances of samples compacted at optimum water content were some 20% higher after 5 freeze-thaw cycles than samples not subjected to this treatment.

TABLE V

RESULTS OF FREEZE-THAW TESTS ON COMPACTED SAMPLES OF HEARTH ASH

Nominal Moulding Water Content, %	Water Content, %	Dry Density, pcf	Number of Freeze-Thaw, Cycles	Strain at Failure, %	Unconfined Comp. Strength, TSF
30	32.2	62	0	1.8	7.7
30	29.6	65	1	1.2	20.7
40	39.6	67	1	1.9	11.8
30	30.2	66	5	1.1	13.5
40	42.3	63	5	1.8	10.9

The high lime content of the ash is undoubtedly the reason for its marked resistance to adverse frost effects. The soaking-freezing-thawing cycle in effect provided a crude "curing" treatment which tended to promote strength increase in the compacted ash.

CONCLUSIONS AND RECOMMENDATIONS

The ash produced by incineration of sewage sludge at the Auburn Sewage Treatment Plant has many of the requisite properties for a suitable foundation or subgrade material. When properly compacted the hearth ash has strengths higher than, or at least comparable to, conventional soils. The compacted ash does not swell, slake, or loose its strength upon soaking. The ash also exhibits considerable thixotropic strength gain with time after compaction.

Laboratory tests indicate that the ash from the disposal pond is generally weaker than the hearth ash when both are compacted under identical conditions.

An undesirable property of the ash is the strong likelihood it will be quite aggressive towards metals. If used as a fill material this fact will have to be borne in mind. Its aggressiveness towards cement or concrete was not evaluated; however, trouble in this direction is not anticipated.

The ash does not appear to be frost susceptible in spite of the fact that it is predominantly silt size material. Compressive strength and penetration resistances were not decreased by repeated freezing and thawing. Frost heave tests were not run on this material, but laboratory tests and field experience with fly ash reported in the literature show that with sufficient additions of lime or cement ash is rendered nonfrost susceptible. The high lime content of the incinerated sewage sludge from the Auburn plant appears to meet this requirement.

The ash probably will require some special handling or placement techniques if used as a structural or backfill material. To start with the lagoon ash (if it is to be used) must be dried to a water content of 30 to 40% before it can be compacted to give adequate strength and stability. This may pose a practical difficulty in the field in view of the slow drying rate of wet ash coupled with the need to keep rain off while it is drying. Placement of the ash will require spreading with a blade and tractor. This operation must give the ash sufficient bearing capacity upon which the compaction plant can operate. Kneading type compaction (e.g., sheeps-foot-rollers) should be avoided. Field experience reported in the literature on compacted fly ash and our own laboratory tests indicate that kneading type compaction introduces excessive shear strain into the ash and fails to compact it properly. A field test presently in progress at the Auburn Sewage Treatment plant, Pontiac, Michigan should reveal the feasibility of actually handling, placing, and compacting the ash in the field for fill or embankment purposes.

An alternative use of ash produced by incineration of sewage sludge is as a raw material for building blocks. The ash would probably make a suitable aggregate or mix for lightweight cement blocks. Another possibility would be its use in "rammed earth" construction or in compressed machine blocks which incorporate low level additions of cement (3-4% by weight) or asphalt emulsion to improve durability. The latter can be cheaply manufactured and in the case of conventional soils have been shown to have remarkably good structural qualities. The high lime content of ash from the Auburn plant makes its use in compressed blocks even more attractive. This possibility is presently being investigated by the Department of Civil Engineering at The University of Michigan.