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Radon Diffusion in Candidate Soils for Covering Uranium Mill Tailings

Prepared by W. B. Silker, D. R. Kalkwarf

Pacific Northwest Laboratory
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Diffusion coefficients were measured for radon in 34 soils that had been identified by mill personnel as candidate covers for their tailings piles in order to reduce radon emission. These coefficients referred to diffusion in the total pore space of the soils. They were measured in the laboratory by a steady-state method using soil columns compacted to greater than 80% of their Proctor maximum packing densities but with moisture contents generally less than would be expected at a tailings site. An empirical equation was used to extrapolate measured coefficients to values expected at soil-moisture contents representative of tailings sites in the western United States. Extrapolated values for silty sands and clayey sands ranged from 0.004 to 0.06 cm^2/s. Values for inorganic silts and clays ranged from 0.001 to 0.02 cm^2/s.

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EXECUTIVE SUMMARY

The purpose of this study was to measure the diffusion coefficients of radon in candidate soils for covering uranium mill tailings and to estimate the range of values that can be expected at the tailings sites. Such information is needed in order to calculate the depth of cover soil required to reduce the emitted radon flux from mill tailings to prescribed levels. Samples of 34 soils were obtained from almost all mill sites in the western United States and used to prepare 10-cm high soil columns in the laboratory. Each soil was compacted to a density greater than 80% of its Proctor maximum in order to simulate values expected for an applied earthen cover, but the moisture content was generally less than would be expected at a tailings site. Diffusion coefficients for radon in the total pore space of these columns were measured by a steady-state method, and the values were found to range from 0.005 to 0.06 cm^2/s for soils with porosities between 0.3 and 0.4 and containing 0.01 to 0.2 water by volume. The relative standard deviation of values obtained by this method for a dry sand was ±5%. The diffusion coefficient used here is equivalent to the quantity, D/P, in the diffusion equations presented in the Generic Environmental Impact Statement prepared by the U. S. Nuclear Regulatory Commission.(1)

In order to estimate the range of radon diffusion coefficients that can be expected for each of these soils at tailings sites, the following equation was utilized to extrapolate measured values to those applicable at different soil-moisture contents:

$$D' = D \exp \left\{-4 \left[(m' - m) - (m' - m)P^2 + (m')^5 - m^5\right]\right\}$$

In this equation, D is the diffusion coefficient, P is the soil porosity, m is the moisture saturation (fraction of pore space filled with water) and the primes distinguish extrapolated values from measured values. This equation is based on an empirical relationship between D, P and m, formulated by Rogers et al.(2) which predicts the D values measured in this study to within a factor of three. The long-term moisture contents of the soils at the individual tailings sites were estimated to be in the ranges: 4 to 9% of dry weight for sands and 10 to 13% of dry weight for clays, based on data reported for similar soils at tailings sites.(2) Extrapolating the measured diffusion coefficients to these moisture contents with the above equation gave values in the range 0.004 to 0.06 cm^2/s for both silty sands and clayey sands and values in the range 0.001 to 0.02 cm^2/s for inorganic silts and clays.

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INTRODUCTION

Over the years, operating uranium mills have generated large quantities of tailings material, which contain essentially all of the ^{230}Th and its daughter ^{226}Ra present in the original ore. Radon-222, a radioactive decay product of ^{226}Ra, is generated continuously in the tailings and, being a noble gas, is transported by diffusion through the tailings and escapes to the atmosphere. The radon flux can be reduced by covering the tailings with soil. The soil increases the diffusion path of radon to the atmosphere and provides time for radioactive decay of ^{222}Rn ($T_{½}$ = 3.82d) within the cover. The depth of soil required to keep the flux or atmospheric concentration of radon below prescribed limits will be determined by calculation, and this requires knowledge of the diffusion coefficient for radon in that soil.

The purpose of this study was to measure the diffusion coefficients of radon in candidate soils for covering uranium mill tailings and to estimate the range of values that can be expected for these materials. Uranium mill operators have identified local deposits of soils that are candidate materials for covering their tailings piles, and 34 samples from these deposits were collected from 15 of the active mill sites in the western United States. Diffusion coefficients for radon in these cover materials were determined with the Radon Attenuation Test Facility, which is described in detail elsewhere.(3)

MATERIALS AND METHODS

Sample Acquisition and Characterization

In 1980, 19 uranium mills were operating in the states of Colorado, New Mexico, Utah, Washington and Wyoming. The managers were contacted and most agreed to assist in identifying and sampling soil deposits that were candidate covers for their particular tailings piles. The samples were selected from 15 mills by personnel from this laboratory during site visits and conferences with mill geologists or other individuals familiar with the options available for cover materials. The nature of the material in each deposit varied greatly, and included local outcroppings, exposed strata, general top soil or overburden and stockpiles of material that had been reserved in anticipation of use as a tailings cover. Grab samples containing 100 to 200 kg of soil were taken at a single location within each deposit and should be considered typical rather than completely representative of that deposit.

Subsamples of the soils were prepared for measurement of their radon diffusion coefficients by tumbling them individually in a small cement mixer to break up larger aggregates and to homogenize the material. The subsamples were then air-dried and their moisture contents were measured gravimetrically. Other soil properties were measured by standard ASTM methods.(4) The specific gravities of the soil particles were measured in this laboratory by ASTM method D-854-58. Other physical properties of the soil samples were measured at the Pacific Testing Laboratories, Richland, Washington. The soils were prepared according to ASTM method D421, and the particle-size distributions were evaluated by ASTM methods

D422 and D1140. The maximum packing densities optimum moisture contents were evaluated by the five-point Proctor method, ASTM method D1557. The plastic limits and indices were measured by ASTM methods D423 and D424, and each soil was given an engineering classification according to ASTM method D2487.

Measurement of Radon Diffusion Coefficients

All measurements of radon diffusion coefficients were made at 21 ± 1°C with the Radon Attenuation Test Facility (RATF),[3] which is based on a method described by Cohen.[5] This is a steady-state diffusion method in which a packed column of test soil of known depth is sealed to an air chamber containing a radon source of known and constant strength. The radon concentration, $(C_b)o$, in the soil at the bottom of the column was evaluated by measuring the radon concentration in the air below the soil column and multiplying this value by $P-0.74\theta$, where P is the porosity of dry soil and θ, is the volumetric fraction of water in the soil. This factor can be derived as follows:

$$\begin{aligned}(C_b)_o &= C_g(V_g/V_b + C_w(V_w/V_b) \\ &= C_g(P-\theta) - C_w\theta = C_g(P-\theta) + fC_g\theta \qquad \text{(Equation 1)}\end{aligned}$$

where:

$(C_b)_o$ = steady-state concentration of radon per unit volume of soil at the bottom of the soil column (pCi/cm^3)

C_g = steady-state concentration of radon per unit volume of soil gas (pCi/cm^3)

C_w = steady-state concentration of radon per unit volume of soil water (pCi/cm^3)

V_b volume of bulk soil (cm^3)

V_g = volume of gas in V_b (cm^3)

V_w = volume of water in V_b (cm^3)

f = distribution coefficient of radon between water and gas.

The value of f is 0.26[6] at 21°C and 1 atmosphere total pressure, and substituting this value into Equation 1 gives:

$$(C_b)_o = (P-0.74\theta)C_g \qquad \text{(Equation 2)}$$

The radon diffusion coefficient can then be evaluated by the equation:

$$\frac{(C_b)}{J_o} = \frac{k(1-e^{-2kx})}{\lambda(1+e^{-2kx})} = \frac{k}{\lambda}\tanh(kx) \qquad \text{(Equation 3)}$$

where J_o = radon flux measured with no soil in place (pCi/cm^{2}s)

λ = radon decay constant (s^{-1})

x = depth of soil (cm)

k = $(\lambda/D)^{1/2}$

D = diffusion coefficient for radon in the total pore space of bulk soil (cm^2/s)

The prepared soils were compacted to a depth of 10 cm in a hollow Lucite cylinder with an inner diameter of 14.0 cm, weighed to determine the packing density, and sealed to the radon source of the RATF. After equilibration, the steady-state radon concentration in the bottom chamber was determined by several measurements taken over a 7 to 14 day period. Each measurement consisted of withdrawing 5 cm^3 of gas from the 800-cm^3 bottom chamber, absorbing the radon on charcoal and counting its daughter ^{214}Bi by gamma-ray spectrometry. The diffusion coefficient for radon in the pores of the column of soil was then evaluated from these data and the characteristic J_o flux for the radon source employed according to Equation 3.

The diffusion coefficient used in this study is equivalent to the quantity, D/P, in the diffusion equations presented in the GEIS.(1) The quantity D in the GEIS is the effective diffusion coefficient for radon in bulk soil and will be designated D_e in the remainder of this document. It is defined by the equation:

$$J = -D_e \frac{\partial C_p}{\partial x} \qquad \text{(Equation 4)}$$

where: J = radon flux from a soil column (pCi/cm^2s)

C_p = concentration of radon in the pore space of the soil (pCi/cm^3)

x = height above the bottom of the soil column (cm)

The quantity D used in this report is defined by the equation:

$$J = -D \frac{\partial C_b}{\partial x} \qquad \text{(Equation 5)}$$

where: C_b = concentration of radon in the bulk soil (pCi/cm^3)

The quantities, C_p and C_b, are related by the equation:

$$C_b = PC_p \qquad \text{(Equation 6)}$$

Substituting this expression into Equation 5 shows that:

$$J = -D \frac{\partial (PC_p)}{\partial x} = -DP \frac{\partial C_p}{\partial x} = -D_e \frac{\partial C_p}{\partial x} \qquad \text{(Equation 7)}$$

or

$$D = D_e/P \qquad \text{(Equation 8)}$$

RESULTS

Physical Properties of Candidate Cover Soils

A variety of soil types were included among the 34 candidate cover soils. The types and physical parameters of the soils are listed in the Appendix. The parameters include values for the Proctor maximum packing density and optimum moisture content, liquid limit, plastic limit, plasticity index, specific gravity and particle-size analysis.

Radon Diffusion Coefficients in Candidate Cover Soils

Diffusion coefficients for radon in the various candidate cover soils are listed in Table 1 together with other relevant parameters for the subsamples tested. These subsamples are listed by number only since consent was not given by all of the mill operators for public identification of the specific mill site from which a sample was obtained. Values for the diffusion coefficients ranged from 0.005 to 0.06 cm^2/s at porosities between 0.3 and 0.4. Since radon diffusion coefficients are functions of both soil moisture and compaction, the values listed in Table 1 apply only for the particular experimental conditions shown.

Precision and Accuracy of the Diffusion-Coefficient Measurements

Columns of dry Dunite, an olivine sand, were prepared and used to determine the precision and accuracy of diffusion coefficients measured in the RATF. Only particles which passed through a 125-mesh screen were used, and each column was compacted to a porosity of 0.44. The same column was tested on the five different radon sources used in this study, and different columns were tested on the same source. The results are shown in Table 2. The average value of the diffusion coefficient was found to be 0.062 cm/s with a relative standard deviation of ±5%.

The accuracy of the method was judged by comparing the average diffusion coefficient shown above with that obtained by a completely independent method. The diffusion coefficient for radon in columns of Dunite, compacted to a porosity of 0.45, and measured by a transient-diffusion method[9], averaged 0.061 cm^2/s with a relative standard deviation of ±12%.

Extrapolation of Measured Diffusion Coefficients to Field Conditions

In order to estimate the diffusion coefficient of radon through soil covering a tailings pile from the coefficient measured under laboratory conditions, consideration must be given to any differences in the porosity and moisture content of the soil at the two locations. It was assumed that the diffusion coefficients listed in Table 1 were measured at compactions that

TABLE 1

RADON DIFFUSION COEFFICIENTS AND OTHER PARAMETERS OF SOIL COLUMNS

Soil No.	ASTM* Class	Dry Packing Density (g/cm^3)	% of Maximum Proctor Compaction	Dry Porosity P	Volumetric Fraction Moisture θ	Moisture Saturation $m = \theta/P$	Diffusion Coefficient D (cm^2/s)
1-A	SC	1.65	83	0.389	0.059	0.15	0.034
1-B	SC	1.73	87	0.347	0.091	0.26	0.028
2-A	CL	1.55	82	0.430	0.057	0.13	0.038
2-B	SC	1.74	84	0.360	0.050	0.14	0.052
2-C	SM-SC	1.76	87	0.336	0.060	0.18	0.030
3-A	SM-SC	1.68	91	0.387	0.055	0.14	0.016
3-B	SM	1.81	90	0.363	0.018	0.05	0.030
3-C	CL	1.61	85	0.392	0.025	0.06	0.028
4-A	SM	1.83	89	0.307	0.043	0.14	0.028
4-B	SM	1.86	93	0.311	0.014	0.05	0.020
5-A	SM	1.62	92	0.406	0.123	0.30	0.016
6-A	SM	1.79	87	0.298	0.060	0.20	0.024
6-B	CL	1.84	97	0.319	0.110	0.34	0.010
7-A	SC	1.78	90	0.343	0.096	0.28	0.033
7-B	SM	1.72	86	0.349	0.052	0.15	0.026
7-C	SC	1.68	89	0.375	0.086	0.23	0.027
8-A	ML-CL	1.53	81	0.425	0.029	0.07	0.033
8-B	SM	1.93	90	0.293	0.047	0.16	0.038
9-A	SC	1.71	85	0.389	0.063	0.16	0.023
9-B	SC	1.72	83	0.360	0.033	0.09	0.038
9-C	ML	1.55	108	0.335	0.082	0.24	0.013
10-A	SM	1.83	99	0.304	0.081	0.27	0.050
10-B	CL	1.68	89	0.391	0.085	0.22	0.024
10-C	SM	1.83	90	0.327	0.027	0.08	0.022
11-A	SC	1.82	92	0.323	0.179	0.55	0.005
11-B	SC	1.69	93	0.372	0.157	0.42	0.012
12-A	SC	1.62	82	0.384	0.066	0.17	0.036
12-B	SM-SC	1.70	86	0.368	0.060	0.16	0.037
13-A	CL	1.76	97	0.343	0.054	0.16	0.025
14-A	SM	1.87	92	0.297	0.023	0.08	0.062
14-B	SM	1.82	105	0.336	0.114	0.34	0.027
14-C	SC	1.82	92	0.325	0.044	0.14	0.034
15-A	SM	1.64	98	0.357	0.112	0.31	0.022
15-B	SC	1.63	91	0.358	0.068	0.19	0.060

* SM = silty sand; SC = clayey sand; SM-SC = borderline classification; CL = inorganic clay, low plasticity;
M = inorganic silt, low plasticity.

TABLE 2

RADON DIFFUSION COEFFICIENTS OF DUNITE SAND

Soil Column Designation	Column Length (cm)	Radon Source Number	Diffusion Coefficient (cm^2/s)
A	10	1	0.065
A	10	2	0.067
A	10	3	0.062
A	10	4	0.062
A	10	5	0.060
B	10	5	0.058
C	30	5	0.058
D	75	5	0.060

would normally be attained in the field. All soils were at 80 to 110% of their Proctor maximum densities, and compactions in this range were achieved in large-scale soil covers at the Grand Junction uranium mill tailings site[7]. However, the moisture contents of the soils shown in Table 1 are generally lower than those anticipated at tailings sites. Fortunately, several empirical relationships have been devised to relate the diffusion coefficient of radon in a soil to the soil's moisture content. Three of these relationships were investigated for their abilities to predict the values measured in this investigation. The relationship which provided the best fit was then selected as the basis for extrapolating measured values of the diffusion coefficient to those anticipated at tailings sites.

The following equation was devised by Nelson et al.[8]:

$$D_e^* = 0.74\, D_a^o (P-\Theta)^{2.16} + \alpha\Theta D_w^o \qquad \text{(Equation 9)}$$

where: D_e^* = an effective diffusion coefficient for radon in the soil

D_a^o = the diffusion coefficient for radon in air = 0.11 cm^2/s at 20°C, 1 atm[9]

$P-\Theta$ = the air-filled porosity of the soil

α = the tortuosity of the soil pores and assumed to equal 0.66

D_w^o = the diffusion coefficient for radon in water = 1.1×10^{-5} cm^2/s at 18°C[10]C.

The effective diffusion coefficient, D_e^* is not the same effective diffusion coefficient used in the GEIS[1] but can be related to it and to the diffusion coefficient, D, measured in this study, as follows:

$$J = -D_e \frac{\partial C_{ap}}{\partial x} \qquad \text{(Equation 10)}$$

where: C_{ap} = concentration of radon in the air-filled pore space of the soil (pCi/cm^3).

The quantities, C_{ap} and C_b, are related by the equation:

$$C_b = (P-\Theta) C_{ap} \qquad \text{(Equation 11)}$$

Substituting this expression into Equation 5 shows that:

$$J = -D \frac{\partial[(P-\Theta)C_{ap}]}{\partial x} = -D(P-\Theta)\frac{\partial C_{ap}}{\partial x} = -D_e^* \frac{\partial C_{ap}}{\partial x} \qquad \text{(Equation 12)}$$

or

$$D_e^* = (P-\Theta) D \qquad \text{(Equation 13)}$$

and

$$D_e^* = \frac{(P-\Theta) D_e}{P} \qquad \text{(Equation 14)}$$

Substituting Equation 13 into Equation 9 gives:

$$D = 0.74D_a^0(P-\theta)^{1.16} + \alpha\Theta D_w^0/(P-\Theta) \qquad \text{(Equation 15)}$$

As shown in Figure 1, Equation 15 predicted the measured diffusion-coefficient values to within a fact of four; but the predicted values were generally too low.

Another empirical equation for predicting radon diffusion coefficients in a soil column as a function of moisture content is that of Rogers, et al[11]. This equation is:

$$D_e/P = D = 0.106 \exp(-0.261M) \qquad \text{(Equation 16)}$$

where M is the percentage moisture in the soil, calculated on a "wet-weight basis, i.e.:

$$M = 100\left(\frac{\text{weight of soil water}}{\text{weight of wet soil}}\right) \qquad \text{(Equation 17)}$$

Values for M can be computed from the volumetric fraction of water, Θ, and the dry packing density, ρ, by means of the equation:

$$M = \frac{100\Theta\sigma}{\rho+\Theta\sigma} \qquad \text{(Equation 18)}$$

where σ = density of water = 1.00 g/cm^3 from 0 to 30°C.

Equation 18 can be verified by substituting the definitions of

Θ, σ and ρ into it, i.e.:

$$M = \frac{100\left(\frac{\text{vol. water}}{\text{vol. soil}}\right)\left(\frac{\text{wt. water}}{\text{vol. water}}\right)}{\left(\frac{\text{wt. dry soil}}{\text{vol. soil}}\right) + \left(\frac{\text{vol. water}}{\text{vol. soil}}\right)\left(\frac{\text{wt. water}}{\text{vol. water}}\right)} = \frac{100(\text{wt. water})}{(\text{wt. wet soil})} \qquad \text{(Equation 19)}$$

A comparison of measured radon diffusion coefficients and values predicted by Equation 16 are shown in Figure 2. This equation also predicted the measured values to within a factor of four, but the predicted values were generally too high.

A third empirical equation for predicting radon diffusion coefficients in soils was developed by Rogers et al.[2] in order to improve upon Equation 16. This equation is:

$$D - D_a^0 T \exp[-4(m - mP^2 + m^5)] \qquad \text{(Equation 20)}$$

where: m = the moisture saturation of the soil = Θ/P

and the other symbols have the same definitions as used previously. A

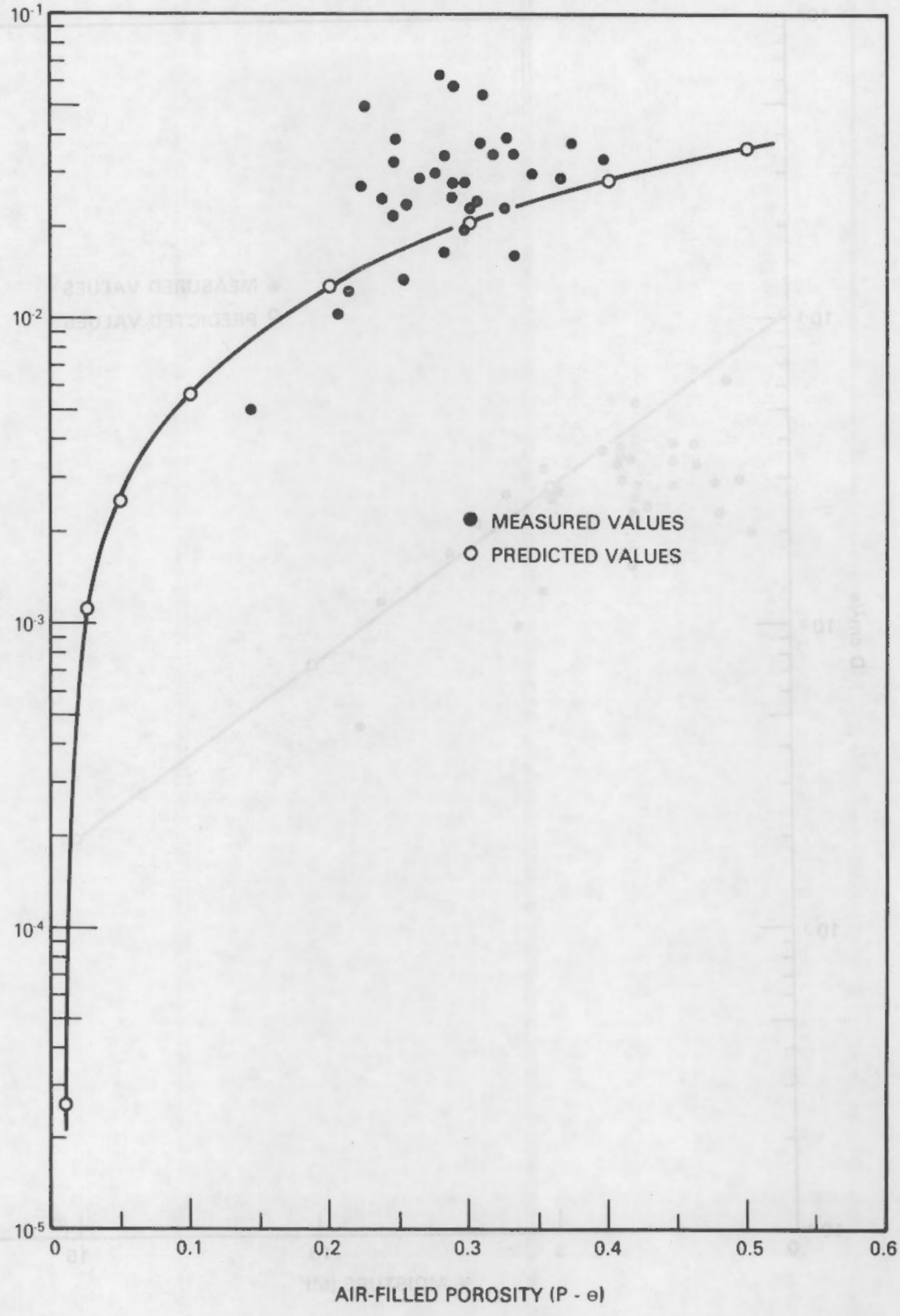

Figure 1. Comparison of Measured Diffusion Coefficients for Radon in Candidate Cover Soils with Those Predicted by the Equation: $D_e^* = (P-\Theta)D = 0.74\ D_a^o\ (P-\Theta)^{2.16} + \alpha\Theta D_w^o$ (8)

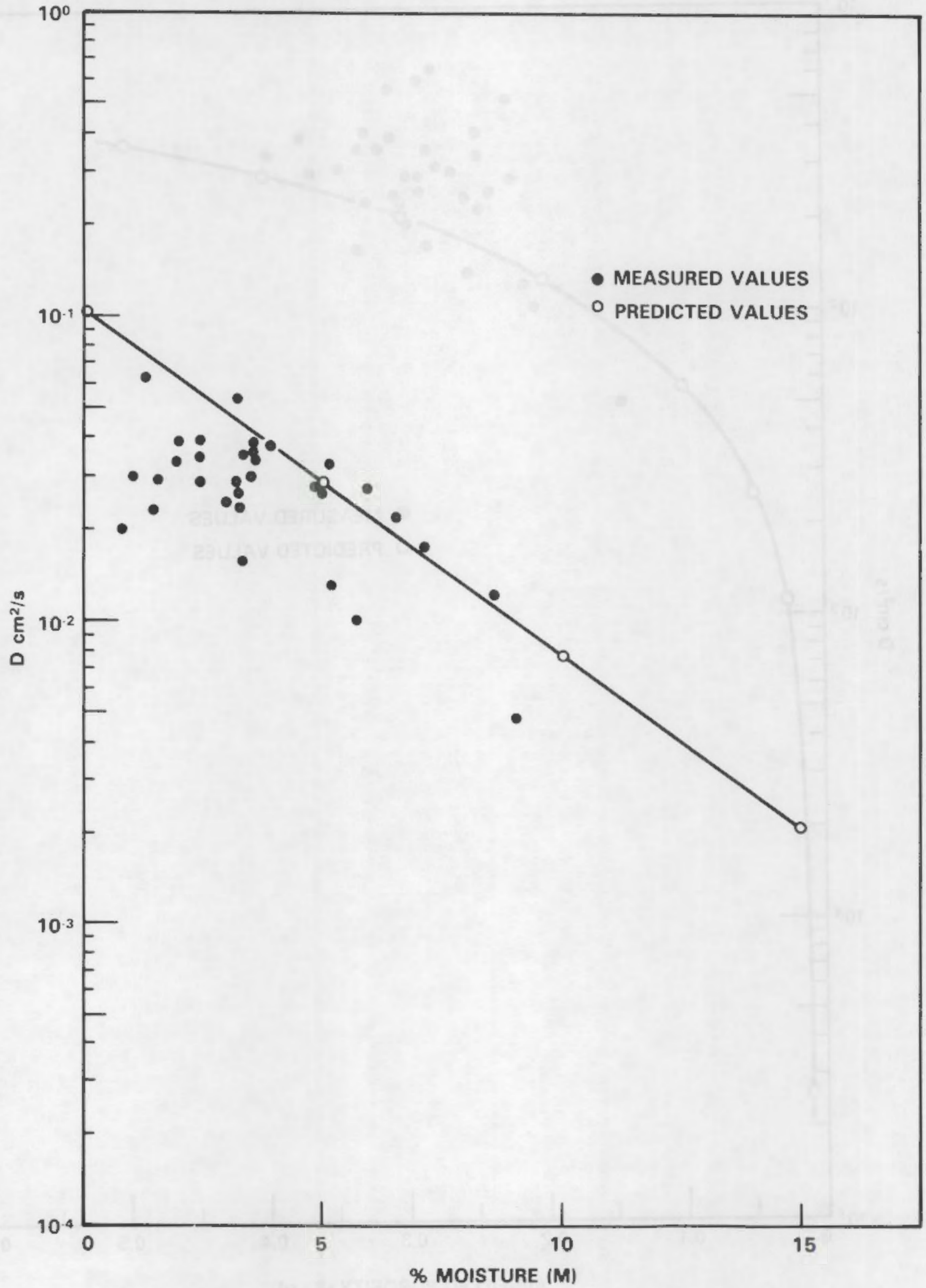

Figure 2. Comparison of Measured Diffusion Coefficients for Radon in Candidate Cover Soils with Those Predicted by the Equation: $\frac{De}{P} = D = 0.106 \exp(-0.261M)$ [11].

comparison of the measured radon diffusion coefficients and values predicted from this equation, with $D_a^o = 0.11\ cm^2/s$ and $T = 0.66$, are shown in Figure 3. The predicted values were within a factor of three from the measured values and were generally higher than these values.

Since Equation 20 provided the best fit to the diffusion coefficients measured in this study, it was selected as the basis for extrapolating these values to those expected at different soil moistures. Letting primes distinguish extrapolated values from measured values, the extrapolated value for the diffusion coefficient is given by:

$$D' = D \exp \left\{ -4 \left[(m'-m) - (m'-m)P^2 + (m')^5 - m^5 \right] \right\} \quad \text{(Equation 21)}$$

In this equation, the value for the porosity, P, is held constant since the compaction used in the laboratory was considered representative of field conditions.

Published measurements of moisture content in soils near uranium tailings sites in the western United States indicate that the quantity, w = weight of soil water/weight of dry soil, varies from 0.04 to 0.09 for sands and from 0.10 to 0.13 for clays[2]. These limits for w were converted to limits for m by means of the equation:

$$m = \frac{w\rho}{P\sigma} \quad \text{(Equation 22)}$$

where all the symbols have the same meaning as used previously in this document; and values for D' were calculated at these limits using Equation 21. The results are shown in Table 3. D' values in the range 0.004 to 0.06 cm^2/s were obtained for both silty sands and clayey sands and values in the range 0.001 to 0.02 cm^2/s were obtained for inorganic silts and clays.

DISCUSSION

The diffusion coefficients measured for radon in the columns of candidate cover soils were in reasonable agreement with values published for other soils. This is indicated by the ability of Equation 15, 16 and 20, derived from an independent data base, to predict the diffusion coefficients measured in this study to within a factor of three or four. It seems significant, however, that these coefficients can differ by factors of up to four even in nominally similar types of soils compacted to the same air-filled porosity. Although this variation may reflect difficulties in preparing reproducible soil columns, the data on Dunite do not support such an explanation. It seems more probable that unidentified soil properties affect this variation. Most of the tested soil samples were classified as silty or clayey sands, but these general engineering classifications probably include soils of significantly different chemical properties which could affect the shape and adhesiveness of the soil particles and hence their abilities to attenuate gas diffusion.

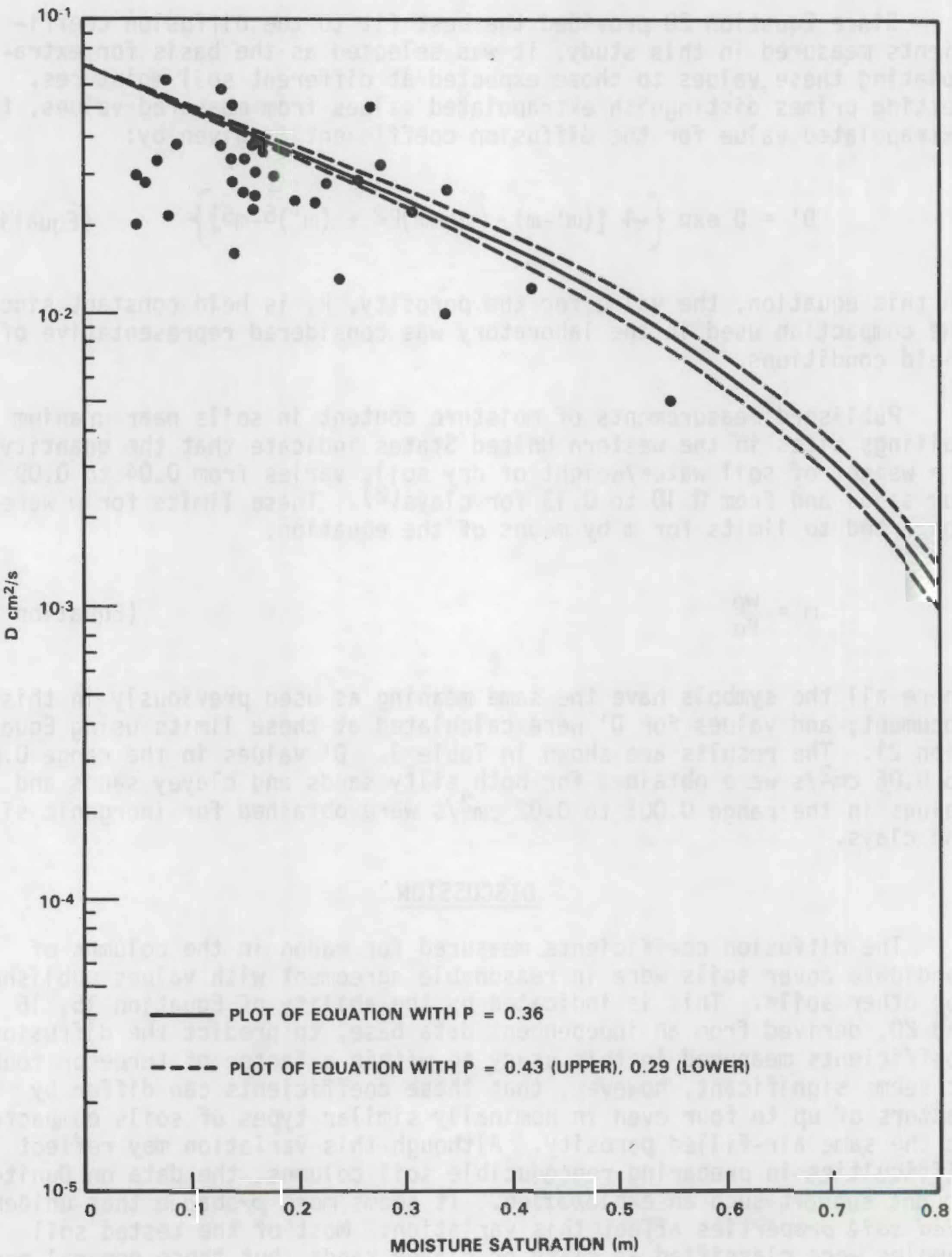

Figure 3. Comparison of Measured Diffusion Coefficients for Radon in Candidate Cover Soils with Those Predicted by the Equation: $D = 0.070 \exp[-4(m - mP^2 + m^5)]$ [2]

TABLE 3

EXTRAPOLATED VALUES FOR RADON DIFFUSION COEFFICIENTS IN CANDIDATE COVER SOILS

Soil No.	ASTM* Class	Dry Porosity P	Extrapolated Diffusion Coefficient D' (cm^2/s) (w=0.04)	(w=0.09)	w=0.10)	(w=0.13)
1-A	SC	0.389	0.032	0.015		
1-B	SC	0.347	0.035	0.014		
2-A	CL	0.430			0.018	0.012
2-B	SC	0.360	0.043	0.018		
2-C	SM-SC	0.336	0.027	0.010		
3-A	SM-SC	0.387	0.014	0.007		
3-B	SM	0.363	0.018	0.007		
3-C	CL	0.392			0.008	0.005
4-A	SM	0.307	0.020	0.006		
4-B	SM	0.311	0.014	0.004		
5-A	SM	0.406	0.026	0.013		
6-A	SM	0.298	0.021	0.006		
6-B	CL	0.319			0.003	0.001
7-A	SC	0.343	0.043	0.016		
7-B	SM	0.349	0.022	0.009		
7-C	SC	0.375	0.032	0.014		
8-A	ML-CL	0.425			0.013	0.008
8-B	SM	0.293	0.026	0.006		
9-A	SC	0.389	0.022	0.010		
9-B	SC	0.360	0.027	0.011		
9-C	ML	0.335			0.005	0.003
10-A	SM	0.304	0.056	0.016		
10-B	CL	0.391			0.011	0.006
10-C	SM	0.327	0.013	0.004		
11-A	SC	0.323	0.020	0.006		
11-B	SC	0.372	0.029	0.013		
12-A	SC	0.384	0.036	0.017		
12-B	SM-SC	0.368	0.034	0.014		
13-A	CL	0.343			0.006	0.002
14-A	SM	0.297	0.033	0.008		
14-B	SM	0.336	0.042	0.015		
14-C	SC	0.325	0.025	0.008		
15-A	SM	0.357	0.034	0.015		
15-B	SC	0.358	0.060	0.026		

* SM = silty sand; SC = clayey sand, SM-SC = borderline classification;
CL = inorganic clay, low plasticity; M = inorganic silt, low plasticity.

These results also suggest that diffusion coefficients extrapolated from measured values will be more accurate than those calculated solely from empirical equations currently available relating soil properties. However, the functional relationships embodied in these equations seem adequate for the purpose of extrapolation since they need only provide a small correction to a measured diffusion coefficient.

CONCLUSIONS

An array of 34 candidate soils for covering uranium mill tailings in the western United States exhibited radon diffusion coefficients ranging from 0.005 to 0.06 cm^2/s when measured at packing densities corresponding to greater than 80% of their Proctor maximum densities. Since the diffusion coefficients were not measured at similar moisture contents, empirical equations relating these soil properties were tested with the experimental data in order to establish the best basis for extrapolating measured diffusion coefficients to those expected at other soil-moisture contents. The equation, $D = 0.070 \exp[-4(m - mP^2 + m^5)]$ provided the best fit and was used as the basis for the extrapolations. With soil-moisture contents at 4 to 9% of dry weight, values expected for sands near tailings piles, the extrapolated diffusion coefficients for silty sands and clayey sands ranged from 0.004 to 0.06 cm^2/s. With soil-moisture contents at 10 to 13% of dry weight, values expected for clays near tailings piles, the extrapolated diffusion coefficients for inorganic silts and clays ranged from 0.001 to 0.02 cm^2/s.

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REFERENCES

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2. Rogers, V. C., K. K. Nielson, D. C. Rich, G. M. Sandquist and M. L. Mauch, Radon Attenuation with Earthen Covers, 1982 Annual Report to the U. S. Department of Energy on UMTRAP Technology Development, RAE-33-14 (1982).

3. Silker, W. B., A Radon Attenuation Test Facility, U. S. Nuclear Regulatory Commission Report NUREG/CR-2243 (1981).

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9. Nielson, K. K., D. C. Rich and V. C. Rogers, Comparison of Radon Diffusion Coefficients Measured by Transient-Diffusion and Steady-State Laboratory Methods, U. S. Nuclear Regulatory Commission Report NUREG/CR-2875 (1982).

10. Rona, E., Diffusionsgrösse and Atomdurchmesser der Radium Emanation Zeit. physik Chem. 92: 213-218 (1917).

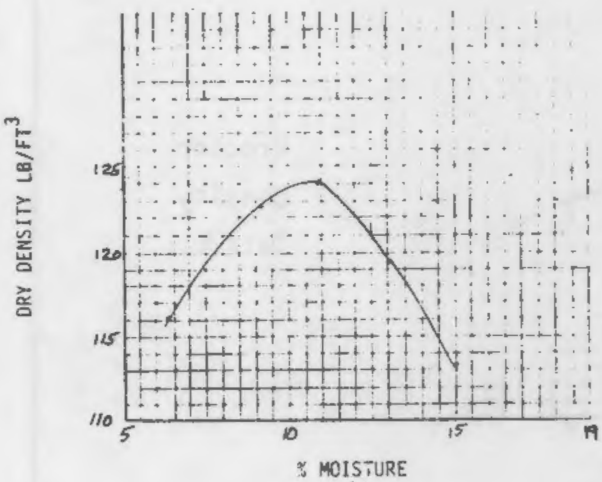
11. Rogers, V. C., R. F. Overmeyer, K. M. Putzig, C. M. Jensen, K. K. Nielson and B. W. Sermon, Characterization of Uranium Tailings Cover Materials for Radon Flux Reduction, U. S. Nuclear Regulatory Commission Report NUREG/CR-1081 (1980).

APPENDIX

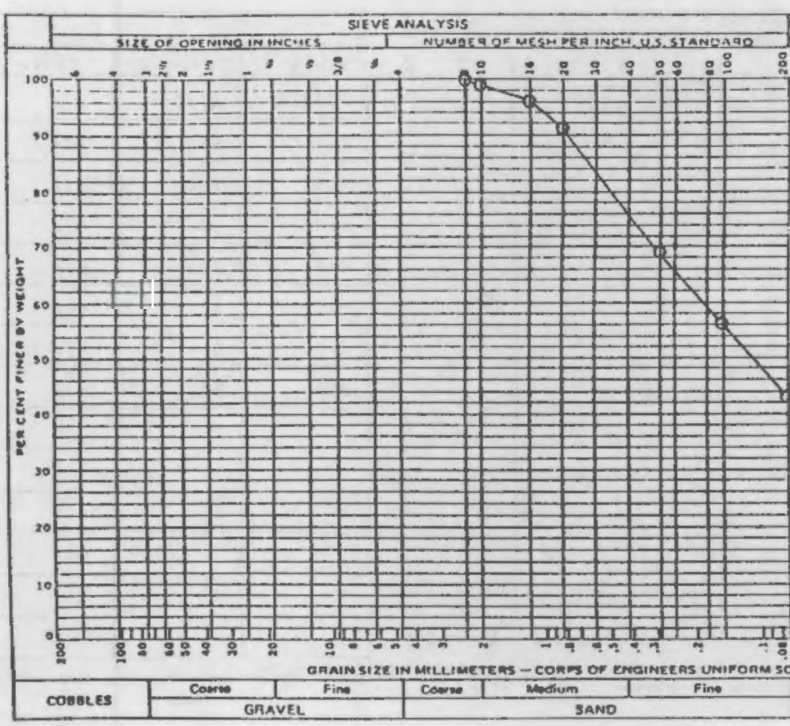
PHYSICAL PROPERTIES OF CANDIDATE COVER SOILS

Appendix

Sample Number: 1 - A
Contractor Soil Classification: Clay
Engineering Soil Classification: Clayey Sand
Proctor Maximum Density lb./ft^3: 124.6
Optimum Moisture %: 11.1
Liquid Limit: 36
Plastic Limit: 15
Plasticity Index: 21
Specific Gravity, g/cm^3 2.70



Proctor
Density
Data



Sieve	%passing	Spec.
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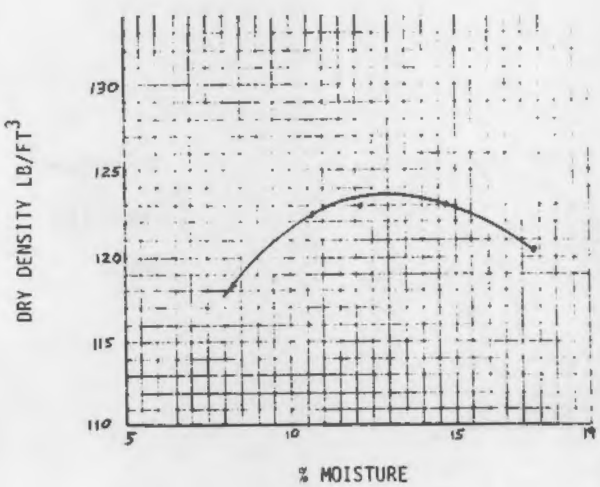
#4	N/A	N/A
#8	100	N/A
#10	99	N/A
#16	96	N/A
#20	91	N/A
#50	69	N/A
#100	56	N/A
#200	43.1	N/A

Appendix

Sample Number:	1 - B
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	123.5
Optimum Moisture %:	13.0
Liquid Limit:	33
Plastic Limit:	21
Plasticity Index:	12
Specific Gravity, g/cm^3	2.65



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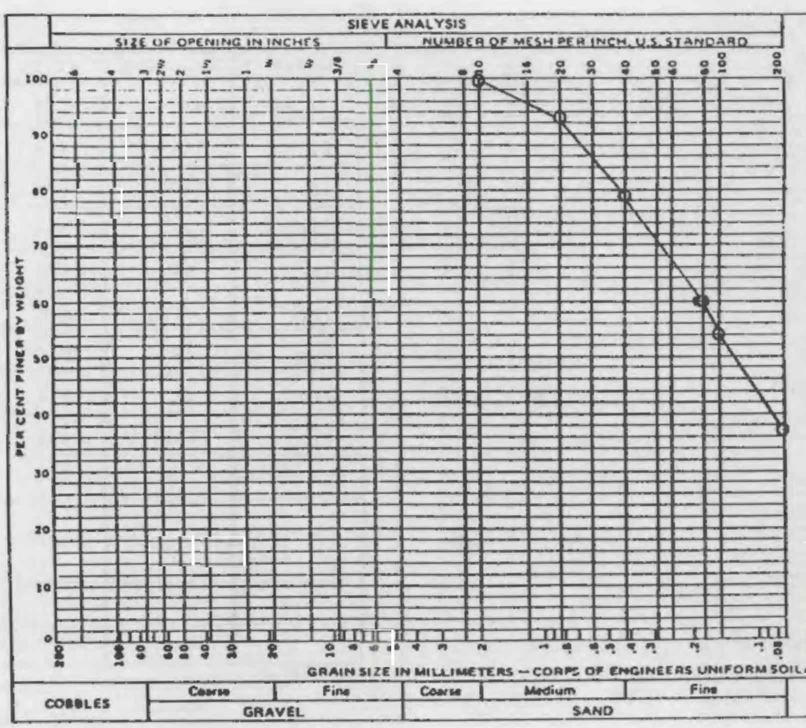

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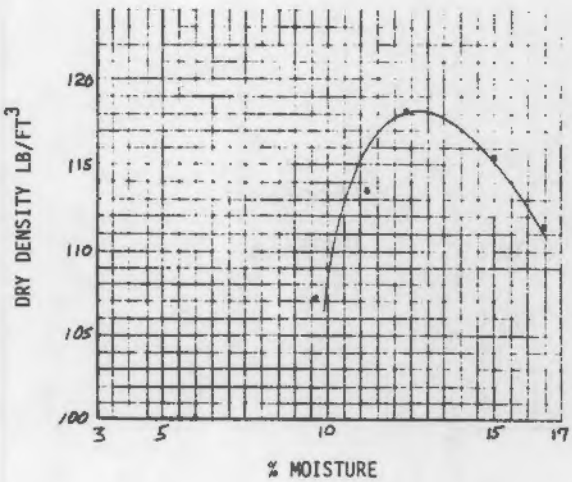
#10	100	N/A
#20	93	N/A
#40	79	N/A
#80	60	N/A
#100	54	N/A
#200	37.6	N/A

Appendix

Sample Number: 2 - A
Contractor Soil Classification: Clay
Engineering Soil Classification: Inorganic Clay
Proctor Maximum Density lb./ft^3: 118.5
Optimum Moisture %: 12.7
Liquid Limit: 33
Plastic Limit: 20
Plasticity Index: 13
Specific Gravity, g/cm^3 2.72



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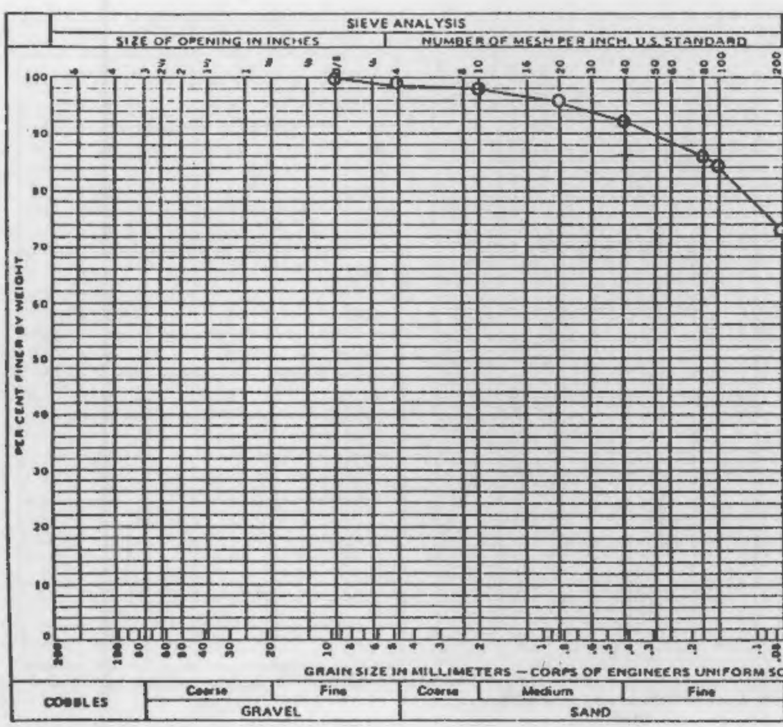

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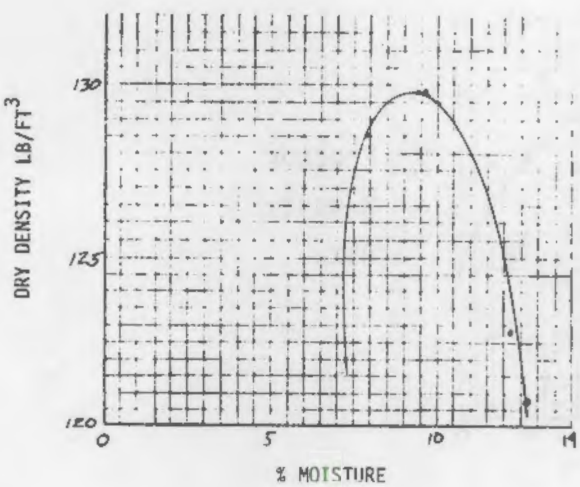
#10	98	N/A
#20	96	N/A
#40	92	N/A
#80	86	N/A
#100	84	N/A
#200	73.0	N/A

Appendix

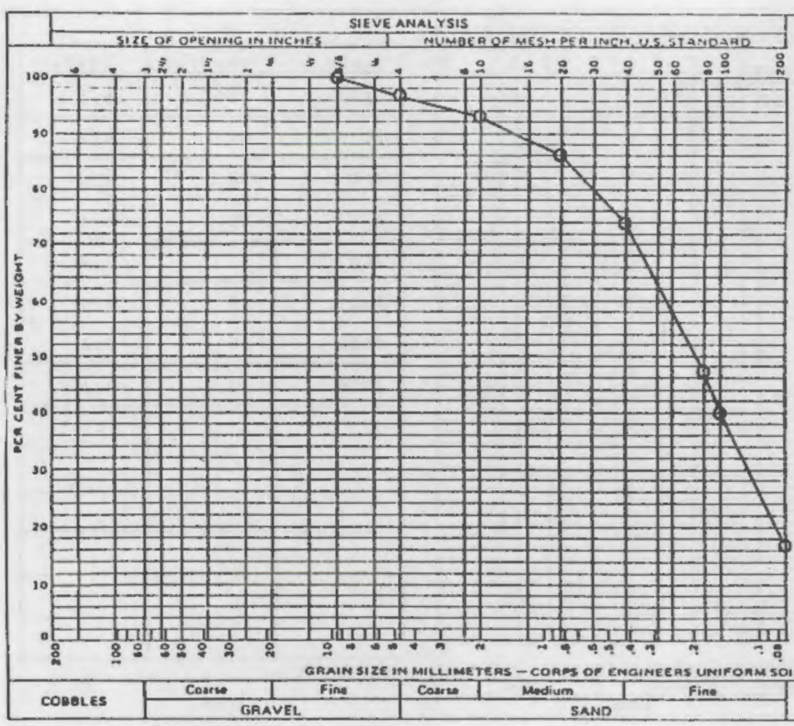
Sample Number:	2 - B
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	129.8
Optimum Moisture %:	9.6
Liquid Limit:	26
Plastic Limit:	16
Plasticity Index:	10
Specific Gravity, g/cm^3	2.72



Proctor

Density

Data



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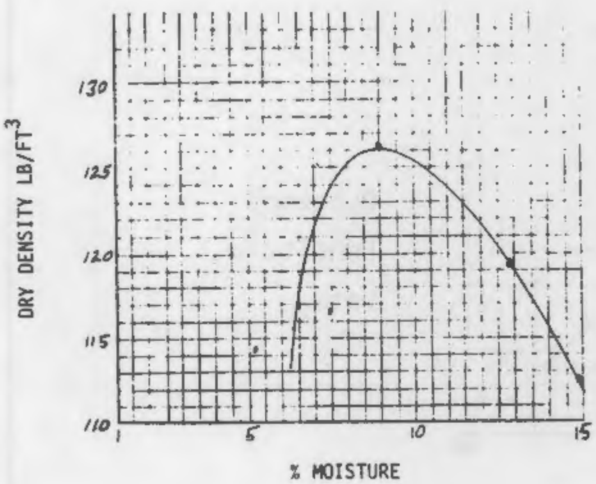
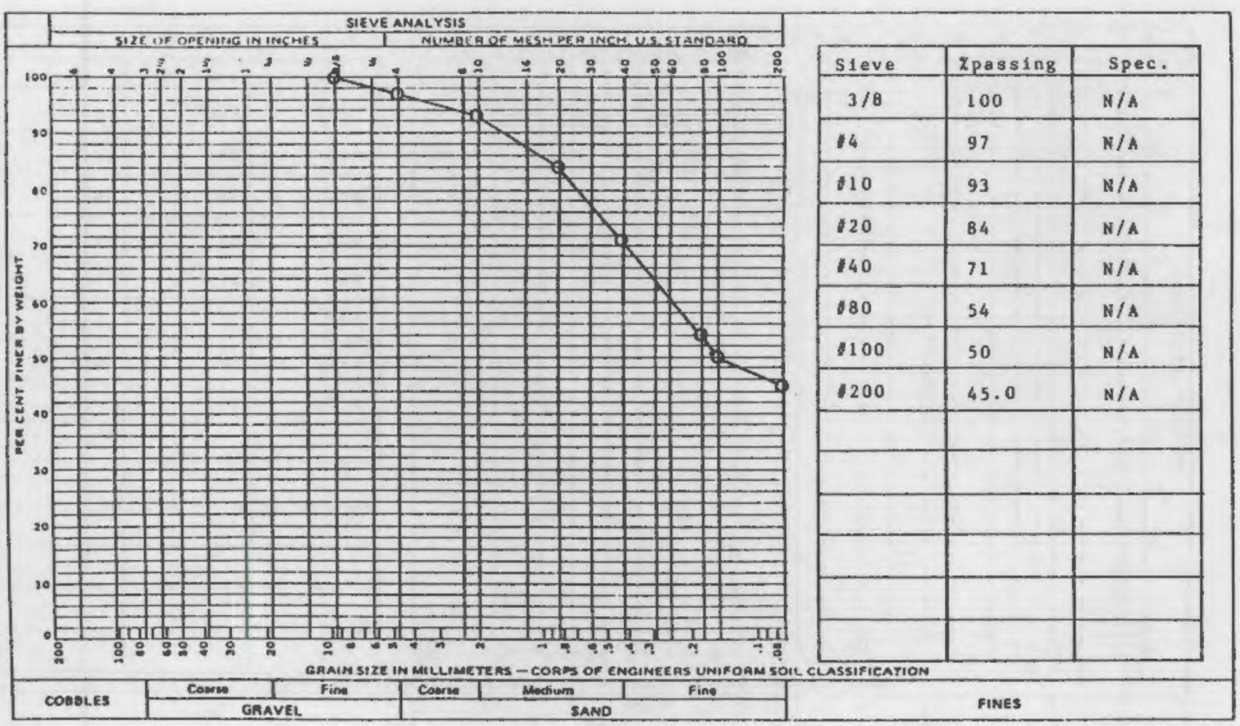
#20	86	N/A
#40	74	N/A
#80	47	N/A
#100	40	N/A
#200	16.7	N/A

Appendix

Sample Number:	2 - C
Contractor Soil Classification:	Clayey Sand - Silty Sand
Engineering Soil Classification:	
Proctor Maximum Density lb./ft^3:	126.2
Optimum Moisture %:	8.9
Liquid Limit:	23
Plastic Limit:	19
Plasticity Index:	4
Specific Gravity, g/cm^3	2.65



Proctor Density Data



Sieve	%passing	Spec.
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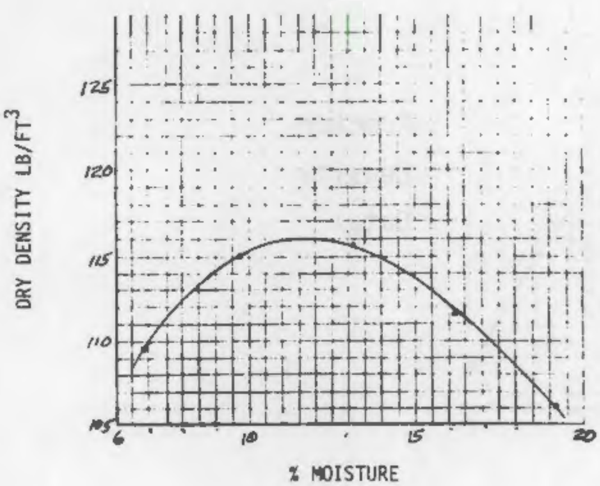
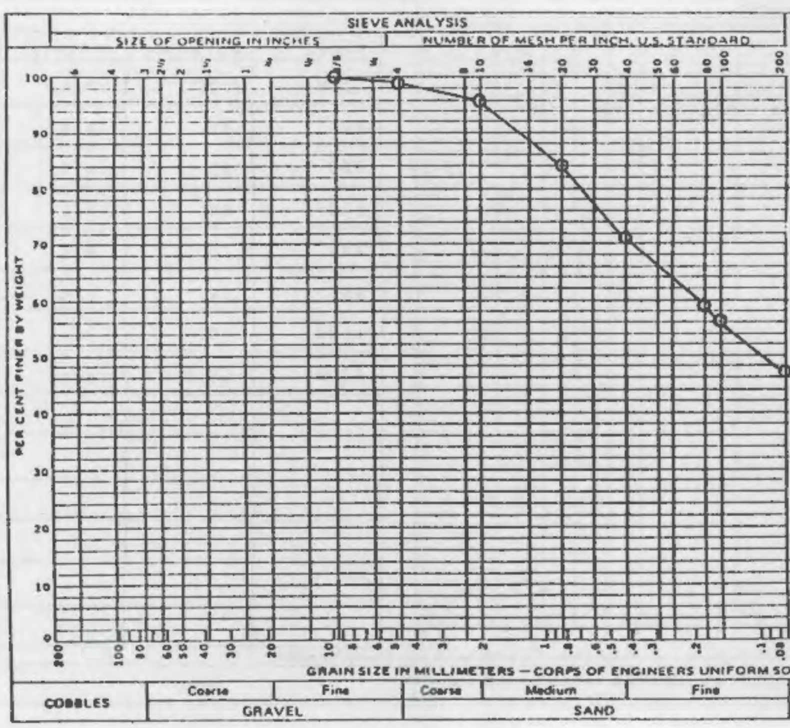
#4	97	N/A
#10	93	N/A
#20	84	N/A
#40	71	N/A
#80	54	N/A
#100	50	N/A
#200	45.0	N/A

Appendix

Sample Number: 3 - A
Contractor Soil Classification: Clay Sand
Engineering Soil Classification: Clayey Sand
Proctor Maximum Density lb./ft^3: 115.8
Optimum Moisture %: 11.5
Liquid Limit: 34
Plastic Limit: 47
Plasticity Index: NP
Specific Gravity, g/cm^3 2.74



Proctor Density Data



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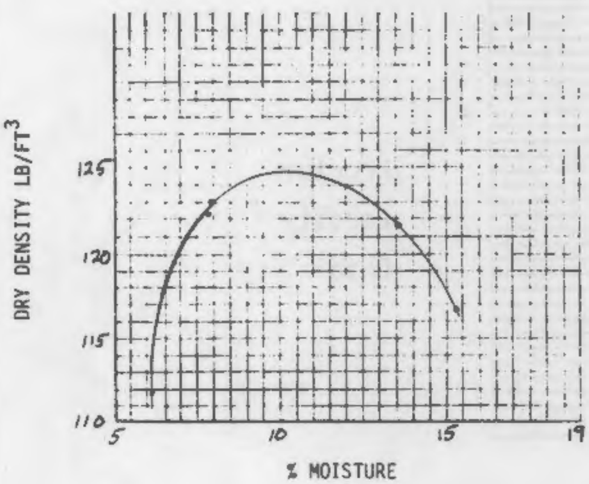
#10	96	N/A
#20	84	N/A
#40	71	N/A
#80	59	N/A
#100	56	N/A
#200	46.9	N/A

Appendix

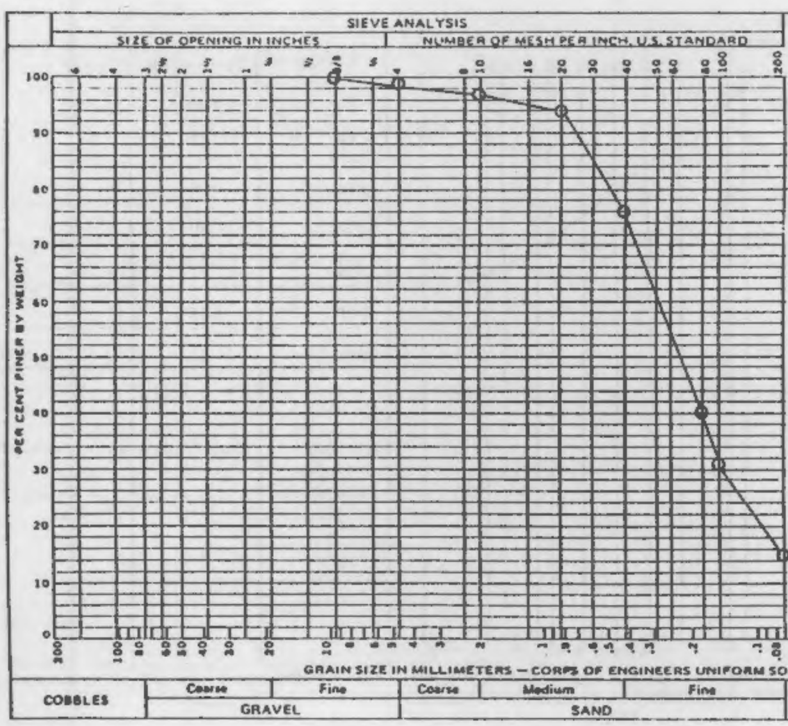
Sample Number:	3 - B
Contractor Soil Classification:	Fine Sand
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	124.9
Optimum Moisture %:	10.2
Liquid Limit:	NP
Plastic Limit:	NP
Plasticity Index:	NP
Specific Gravity, g/cm^3	2.84



Proctor

Density

Data



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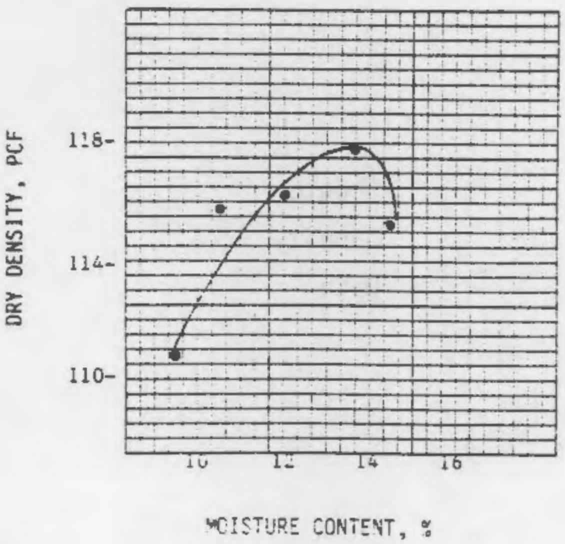
#4	99	N/A
#10	97	N/A
#20	94	N/A
#40	76	N/A
#80	40	N/A
#100	31	N/A
#200	15.7	N/A

Appendix

Sample Number: 3 - C
Contractor Soil Classification: Clay
Engineering Soil Classification: Inorganic Clay, low plasticity
Proctor Maximum Density lb./ft.^{3}: 117.9
Optimum Moisture %: 13.7
Liquid Limit: 34
Plastic Limit: 22
Plasticity Index: 14
Specific Gravity, g/cm^3 2.65



Proctor

Density

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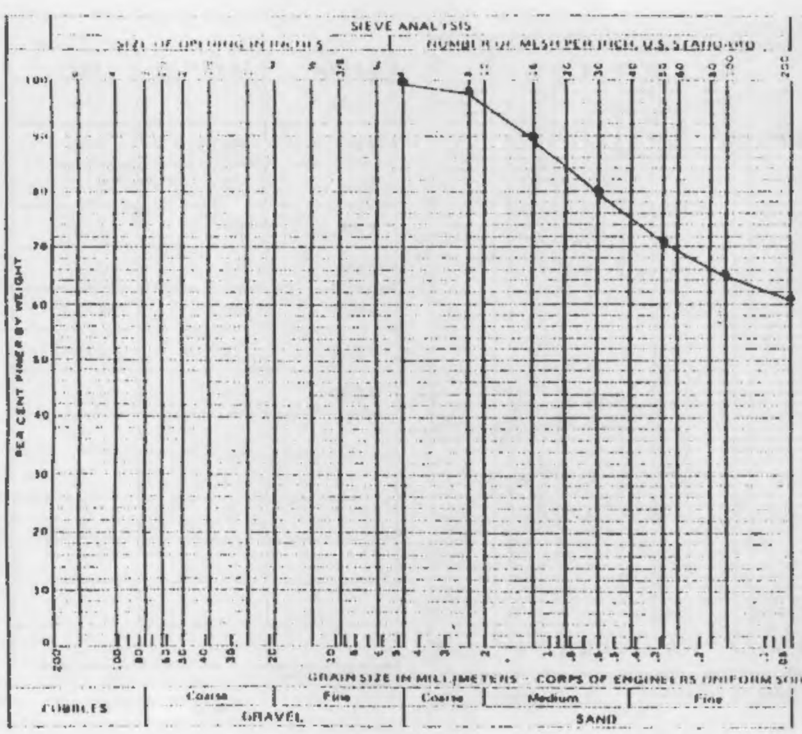
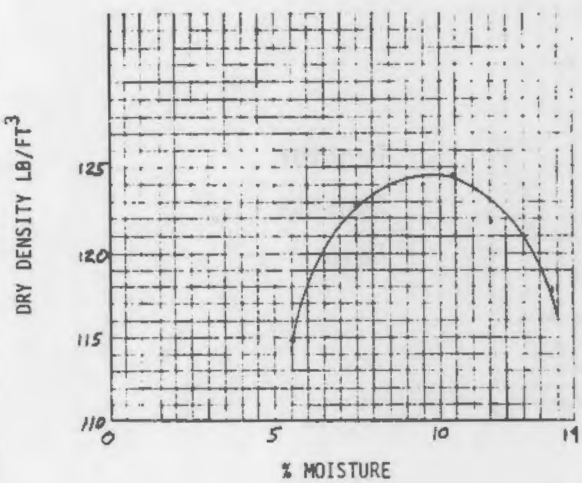


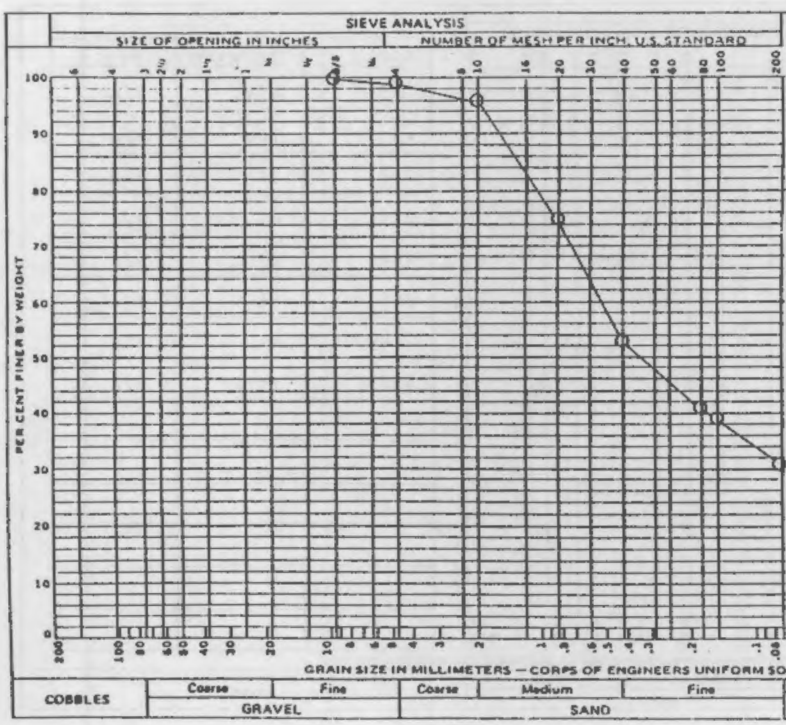
Sieve	%passing	Spec.
#4	100	
#8	98	
#16	90	
#30	80	
#50	71	
#100	65	
#200	61	

Appendix

Sample Number:	4 - B
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	124.5
Optimum Moisture %:	9.6
Liquid Limit:	NP
Plastic Limit:	NP
Plasticity Index:	NP
Specific Gravity, g/cm^3	2.70



Proctor Density Data



Sieve	%passing	Spec.
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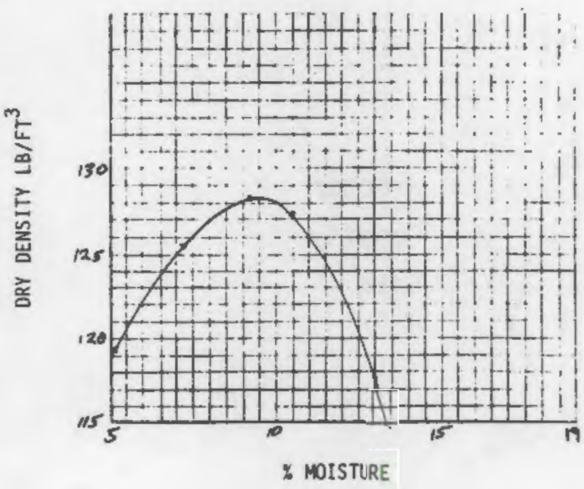
#4	99	N/A
#10	96	N/A
#20	75	N/A
#40	53	N/A
#80	41	N/A
#100	39	N/A
#200	30.7	N/A

Appendix

Sample Number:	4 - A
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	128.5
Optimum Moisture %:	9.5
Liquid Limit:	25
Plastic Limit:	25
Plasticity Index:	NP
Specific Gravity, g/cm^3	2.64



Proctor

Density

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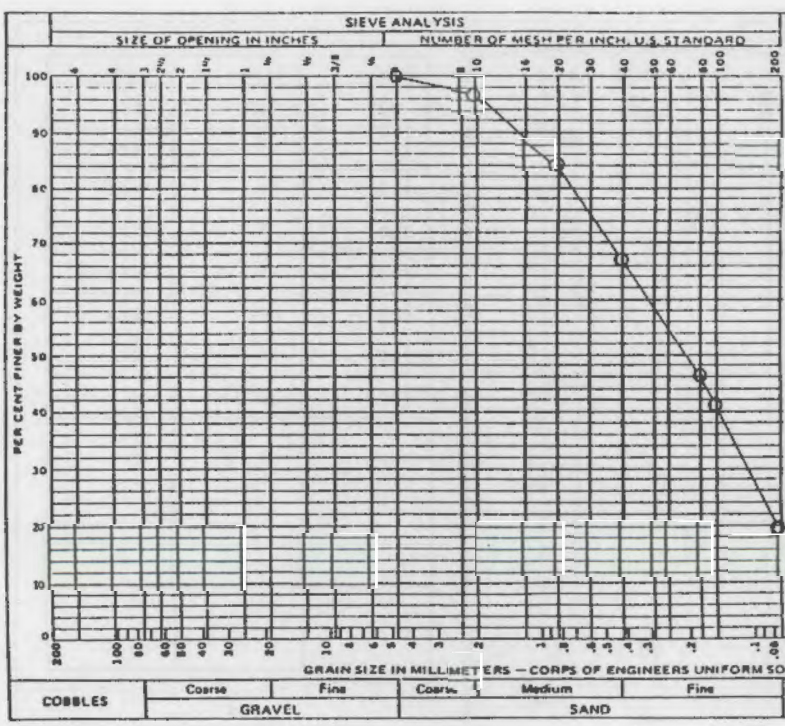

Sieve	%passing	Spec.
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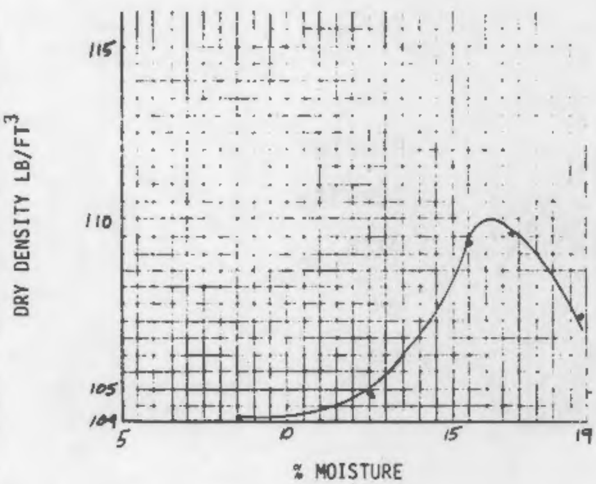
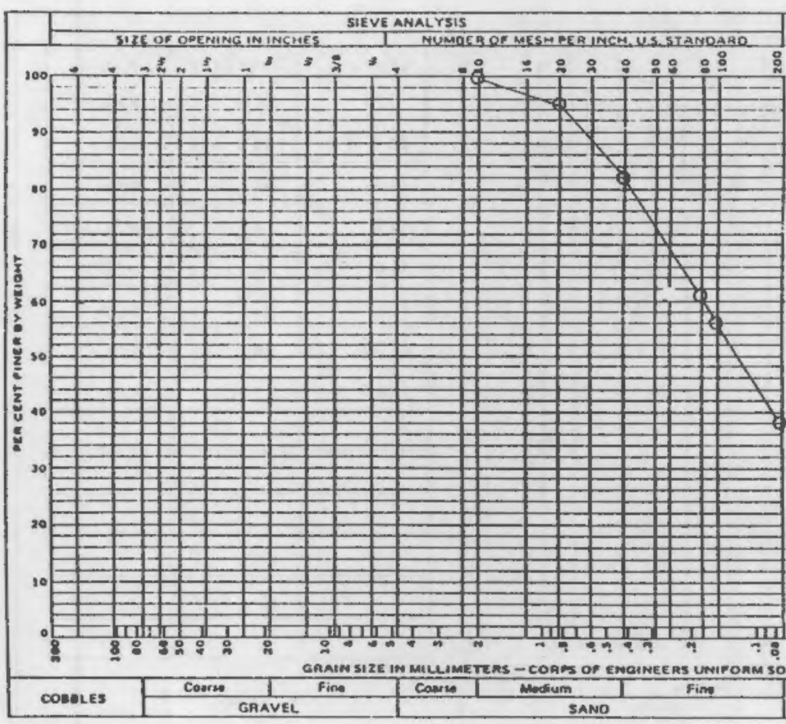
#4	100	N/A
#10	97	N/A
#20	84	N/A
#40	67	N/A
#80	46	N/A
#100	41	N/A
#200	19.9	N/A

Appendix

Sample Number:	5 - A
Contractor Soil Classification:	Clay Overburden
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	110.0
Optimum Moisture %:	16.3
Liquid Limit:	48
Plastic Limit:	28
Plasticity Index:	20
Specific Gravity, g/cm^3	2.73



Proctor Density Data



Sieve	%passing	Spec.
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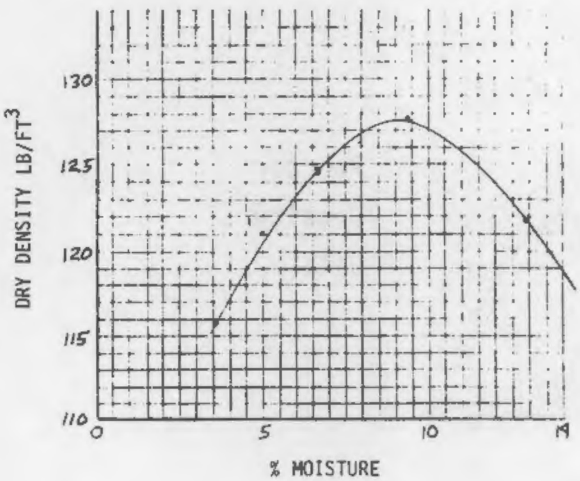
#4	N/A	N/A
#10	100	N/A
#20	95	N/A
#40	82	N/A
#80	61	N/A
#100	56	N/A
#200	38.1	N/A

Appendix

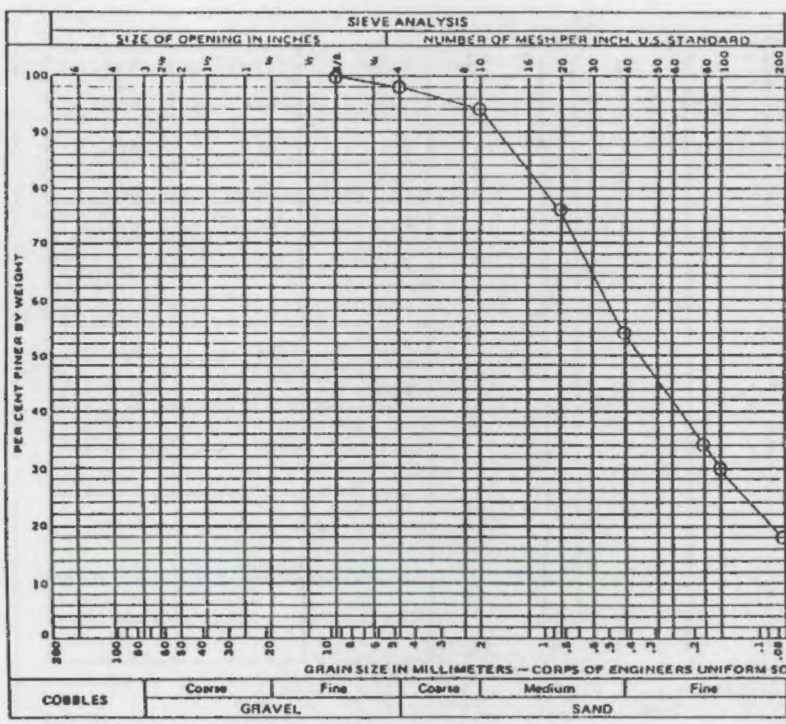
Sample Number: 6 - A
Contractor Soil Classification: Overburden
Engineering Soil Classification: Silty Sand
Proctor Maximum Density lb./ft^3: 127.8
Optimum Moisture %: 9.4
Liquid Limit: NP
Plastic Limit: NP
Plasticity Index: NP
Specific Gravity, g/cm^3 2.55



Proctor

Density

Data



Sieve	%passing	Spec.
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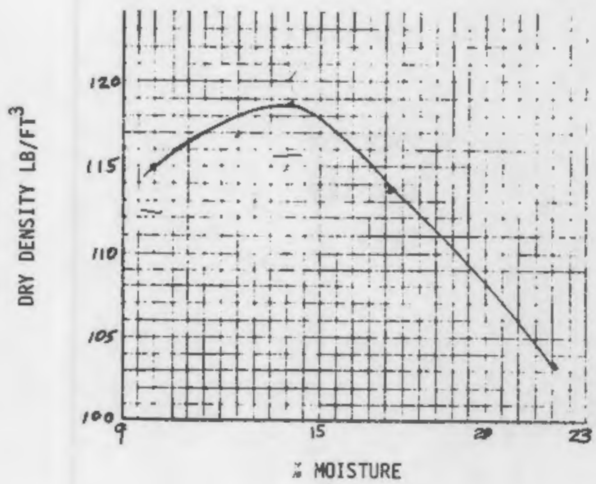
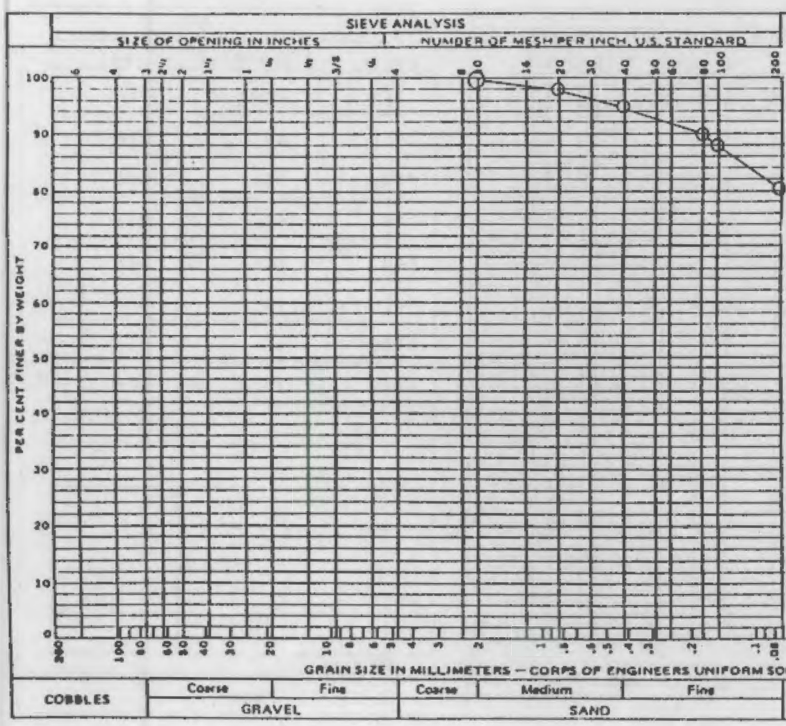
#4	98	N/A
#10	94	N/A
#20	76	N/A
#40	54	N/A
#80	34	N/A
#100	30	N/A
#200	19.1	N/A

Appendix

Sample Number:	6 - B
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Inorganic Clay, low plasticity
Proctor Maximum Density lb./ft^3:	118.8
Optimum Moisture %:	14.6
Liquid Limit:	43
Plastic Limit:	24
Plasticity Index:	19
Specific Gravity, g/cm^3	2.70



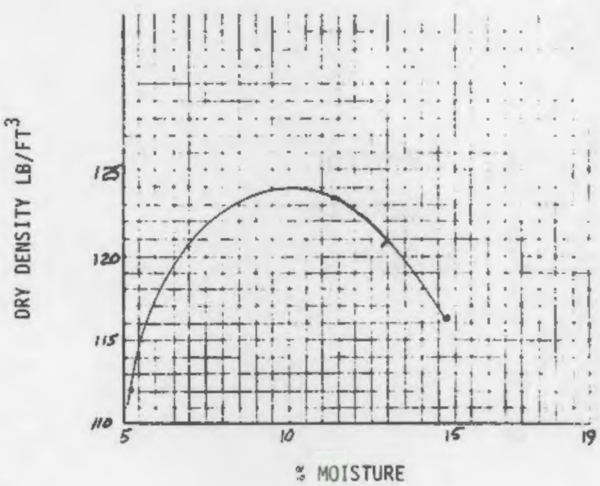
Proctor
Density
Data



Sieve	%passing	Spec.
3/8	N/A	N/A
#4	N/A	N/A
#10	100	N/A
#20	98	N/A
#40	95	N/A
#80	90	N/A
#100	88	N/A
#200	80.8	N/A

Appendix

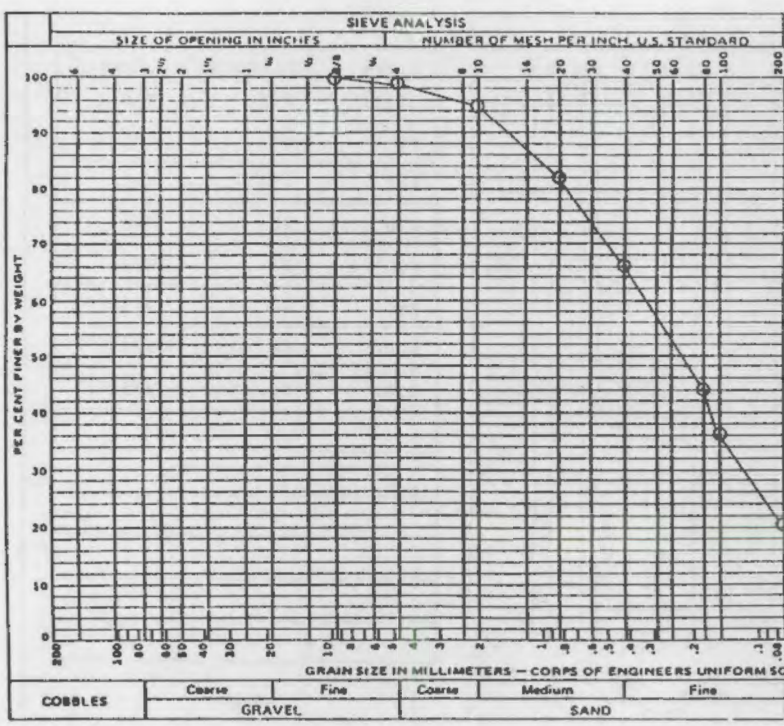
Sample Number:	7 - A
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	123.8
Optimum Moisture %:	10.0
Liquid Limit:	41
Plastic Limit:	24
Plasticity Index:	17
Specific Gravity, g/cm^3	2.71



Proctor

Density

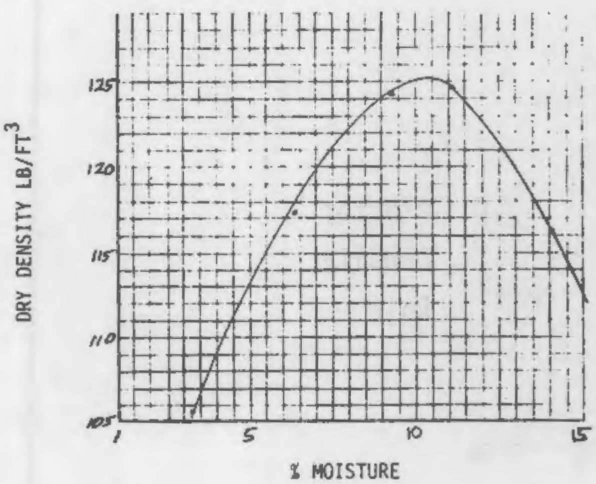
Data



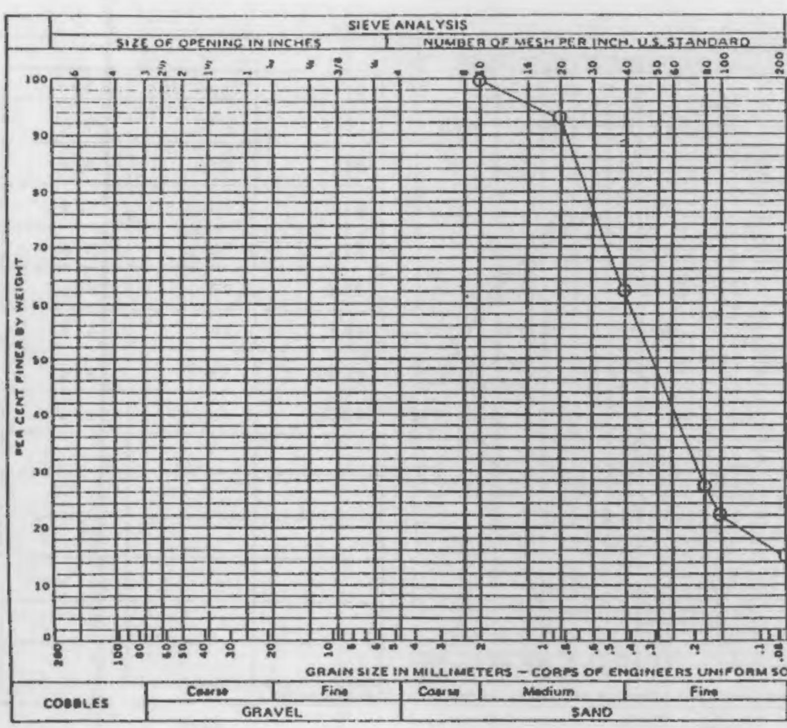
Sieve	%passing	Spec.
3/8	100	N/A
#4	99	N/A
#10	95	N/A
#20	82	N/A
#40	66	N/A
#80	44	N/A
#100	36	N/A
#200	20.8	N/A

Appendix

Sample Number: 7 - B
Contractor Soil Classification: Clay
Engineering Soil Classification: Silty Sand
Proctor Maximum Density lb./ft^3: 125.2
Optimum Moisture %: 10.2
Liquid Limit: NP
Plastic Limit: NP
Plasticity Index: NP
Specific Gravity, g/cm^3 2.64



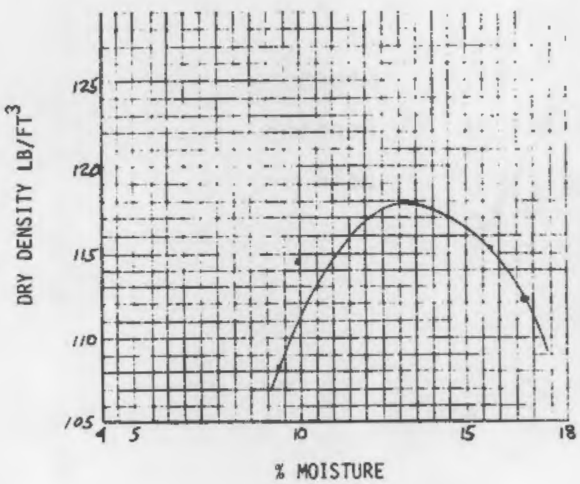
Proctor Density Data



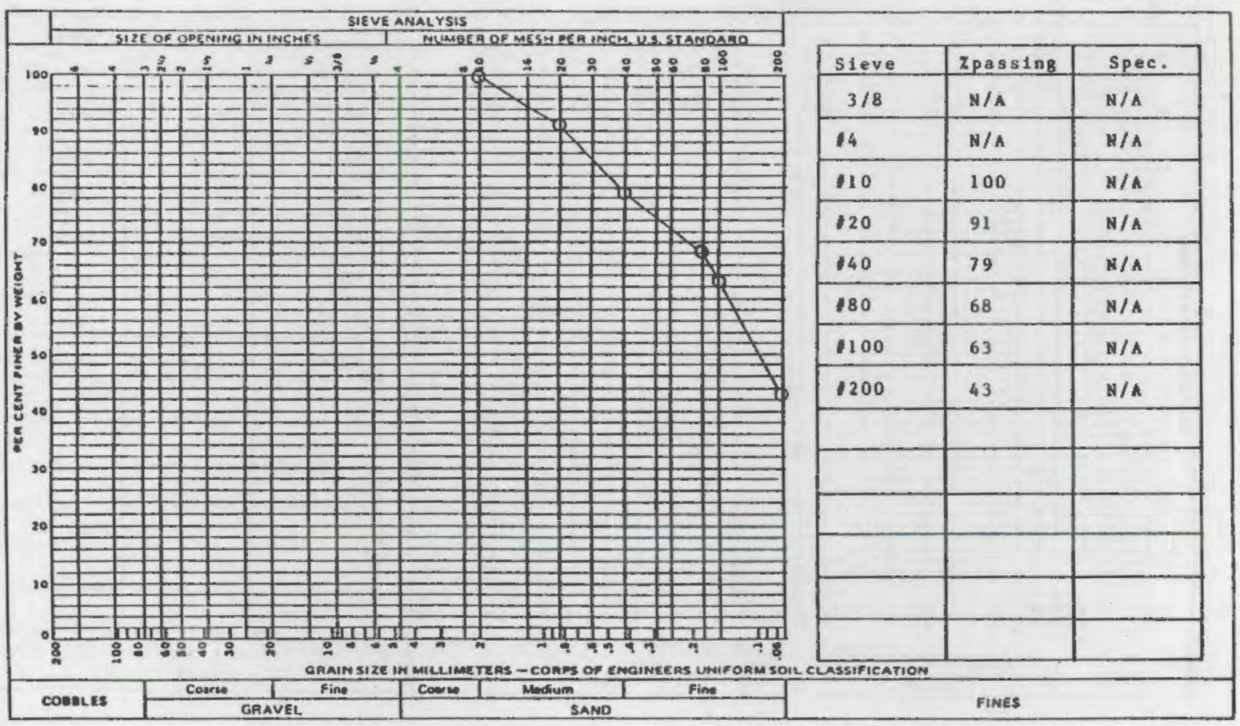
Sieve	%passing	Spec.
3/8	N/A	N/A
#4	N/A	N/A
#10	100	N/A
#20	93	N/A
#40	62	N/A
#80	27	N/A
#100	22	N/A
#200	14.8	N/A

Appendix

Sample Number: 7 - C
Contractor Soil Classification: Clay
Engineering Soil Classification: Clayey Sand
Proctor Maximum Density lb./ft^3: 118.0
Optimum Moisture %: 13.1
Liquid Limit: 34
Plastic Limit: 21
Plasticity Index: 13
Specific Gravity, g/cm^3 2.69



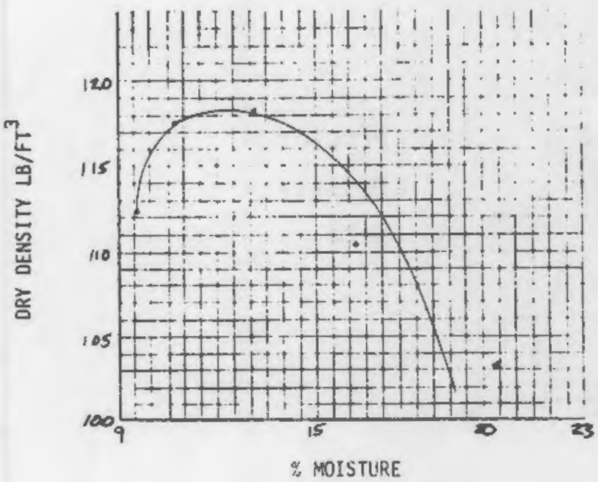
Proctor Density Data



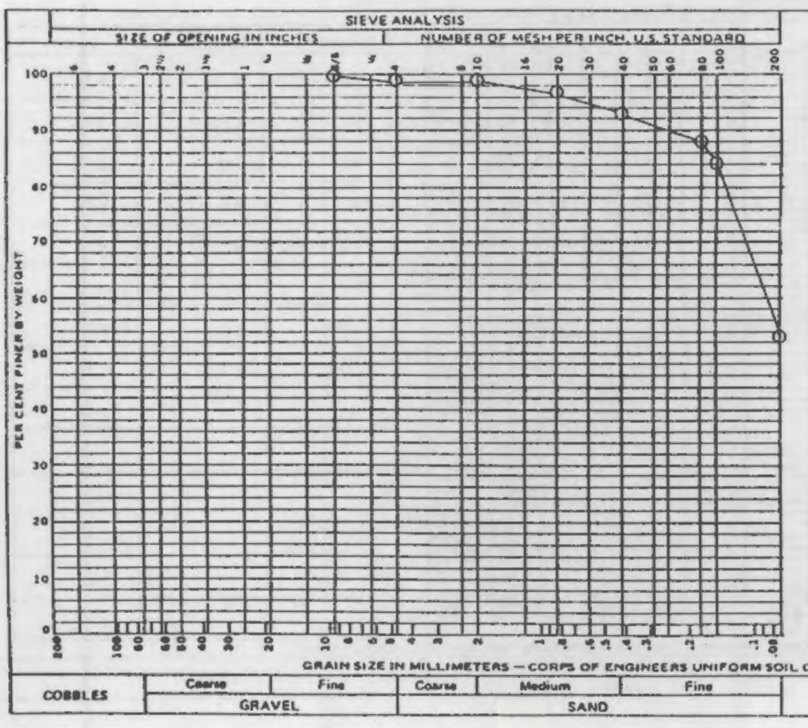
Sieve	%passing	Spec.
3/8	N/A	N/A
#4	N/A	N/A
#10	100	N/A
#20	91	N/A
#40	79	N/A
#80	68	N/A
#100	63	N/A
#200	43	N/A

Appendix

Sample Number: 8 - A
Contractor Soil Classification: Overburden
Engineering Soil Classification: Inorganic Silt - Inorganic Clay
Proctor Maximum Density lb./ft^3: 118.5
Optimum Moisture %: 12.5
Liquid Limit: 24
Plastic Limit: 20
Plasticity Index: 4
Specific Gravity, g/cm^3 2.66



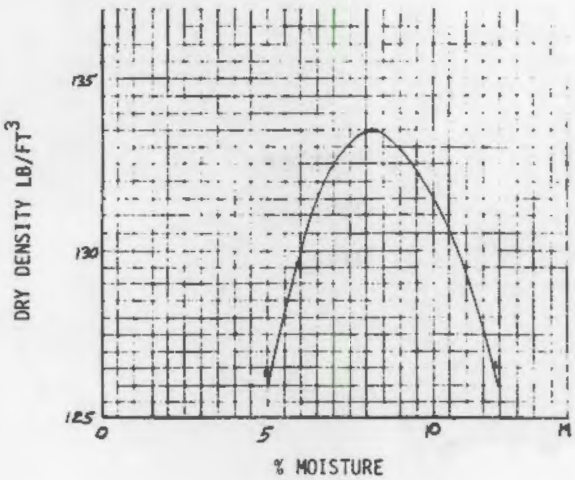
Proctor Density Data



Sieve	%passing	Spec.
3/8	100	N/A
#4	99	N/A
#10	99	N/A
#20	97	N/A
#40	93	N/A
#80	88	N/A
#100	84	N/A
#200	53.6	N/A

Appendix

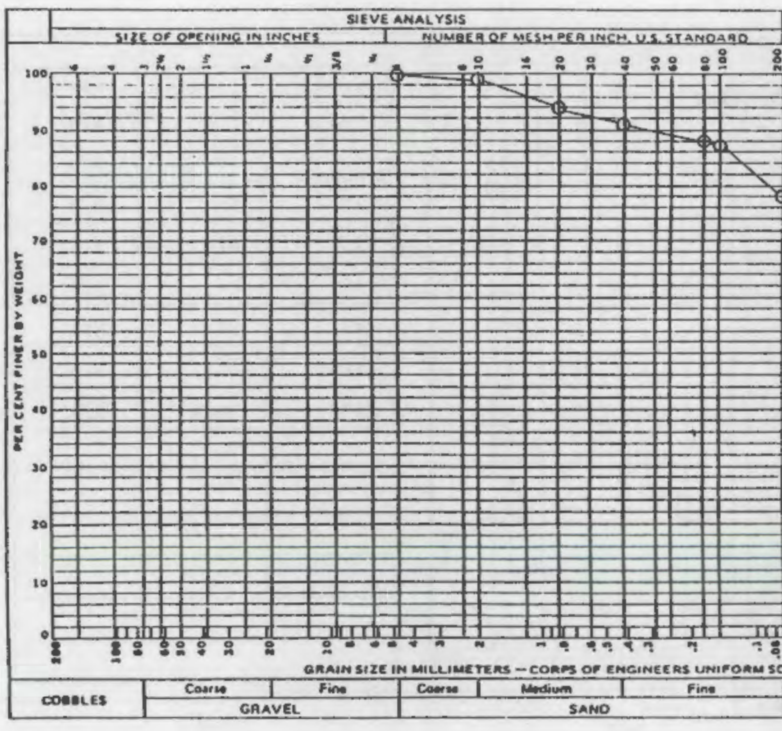
Sample Number: 8 - B
Contractor Soil Classification: Mudstone
Engineering Soil Classification: Silty Sand
Proctor Maximum Density lb./ft^3: 133.5
Optimum Moisture %: 8.1
Liquid Limit: 24
Plastic Limit: 21
Plasticity Index: 3
Specific Gravity, g/cm^3 2.73



Proctor

Density

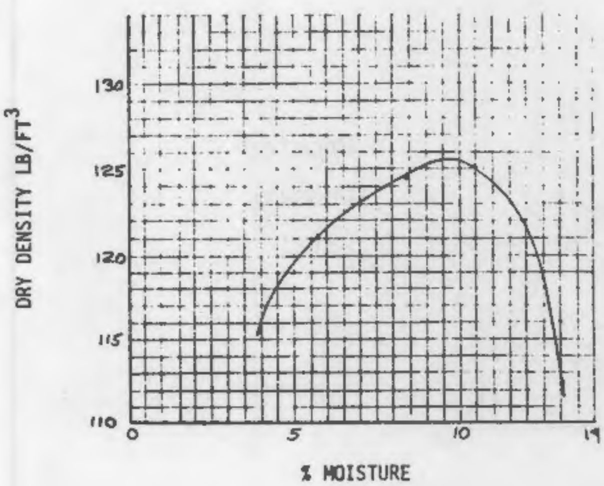
Data



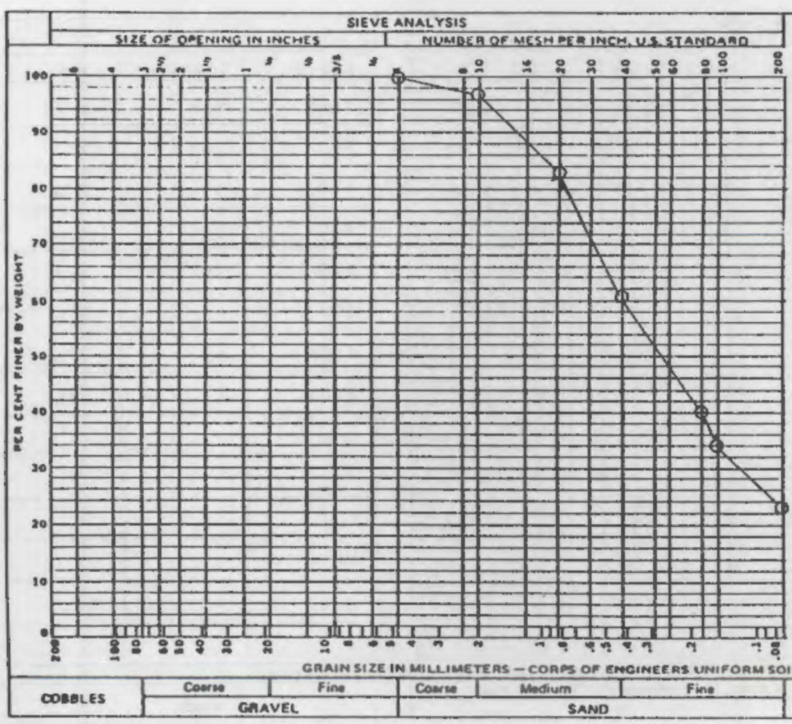
Sieve	%passing	Spec.
3/8	N/A	N/A
#4	100	N/A
#10	99	N/A
#20	94	N/A
#40	91	N/A
#80	88	N/A
#100	87	N/A
#200	79.2	N/A

Appendix

Sample Number: 9 - A
Contractor Soil Classification: Overburden
Engineering Soil Classification: Clayey Sand
Proctor Maximum Density lb./ft^3: 125.5
Optimum Moisture %: 9.7
Liquid Limit: NP
Plastic Limit: NP
Plasticity Index: NP
Specific Gravity, g/cm^3: 2.80



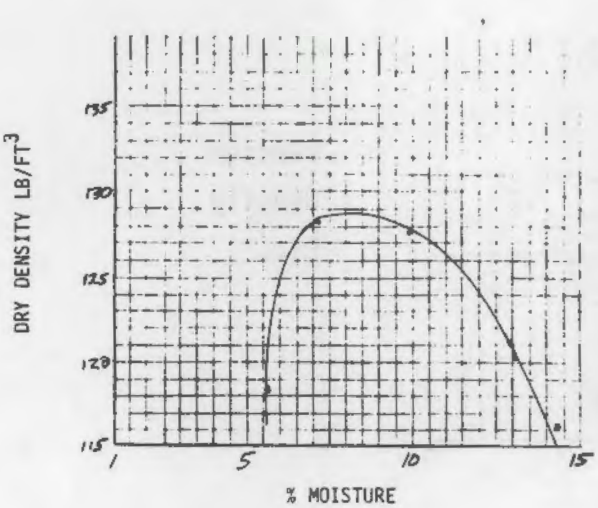
Proctor Density Data



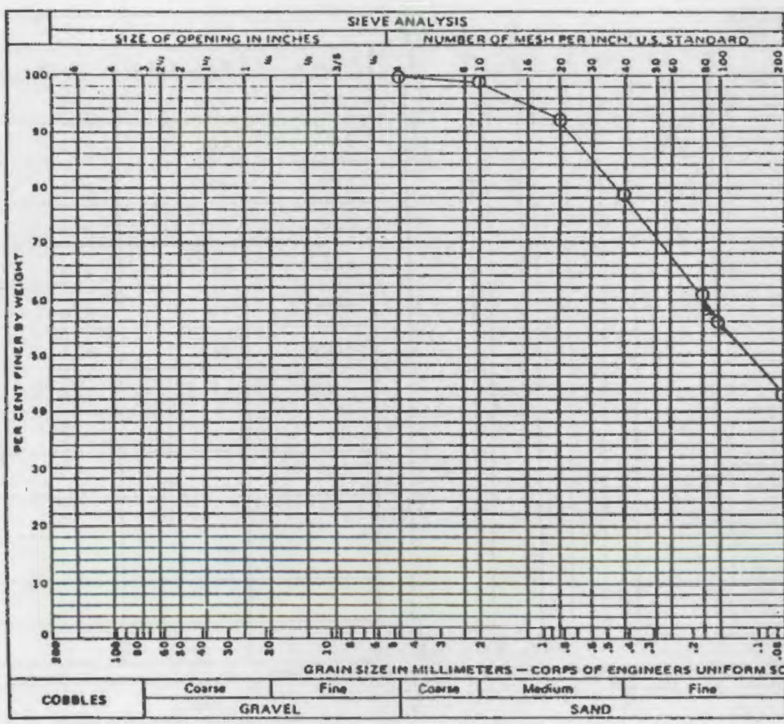
Sieve	%passing	Spec.
3/8	N/A	N/A
#4	100	N/A
#10	97	N/A
#20	83	N/A
#40	61	N/A
#80	40	N/A
#100	36	N/A
#200	23.3	N/A

Appendix

Sample Number:	9 - B
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	128.8
Optimum Moisture %:	8.4
Liquid Limit:	29
Plastic Limit:	18
Plasticity Index:	11
Specific Gravity, g/cm^3	2.69



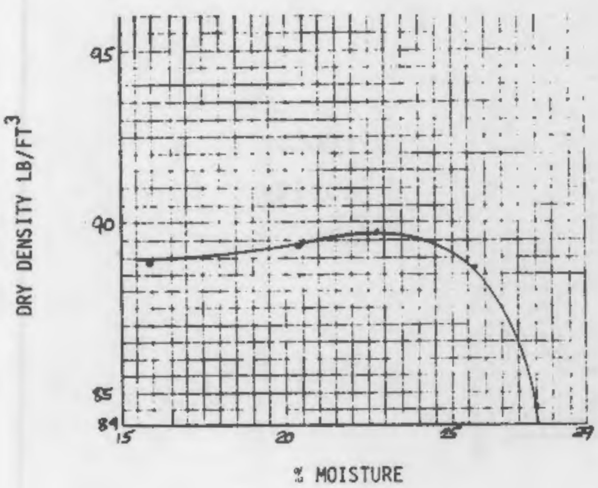
Proctor
Density
Data



Sieve	%passing	Spec.
3/8	N/A	N/A
#4	100	N/A
#10	99	N/A
#20	92	N/A
#40	79	N/A
#80	61	N/A
#100	56	N/A
#200	43.0	N/A

Appendix

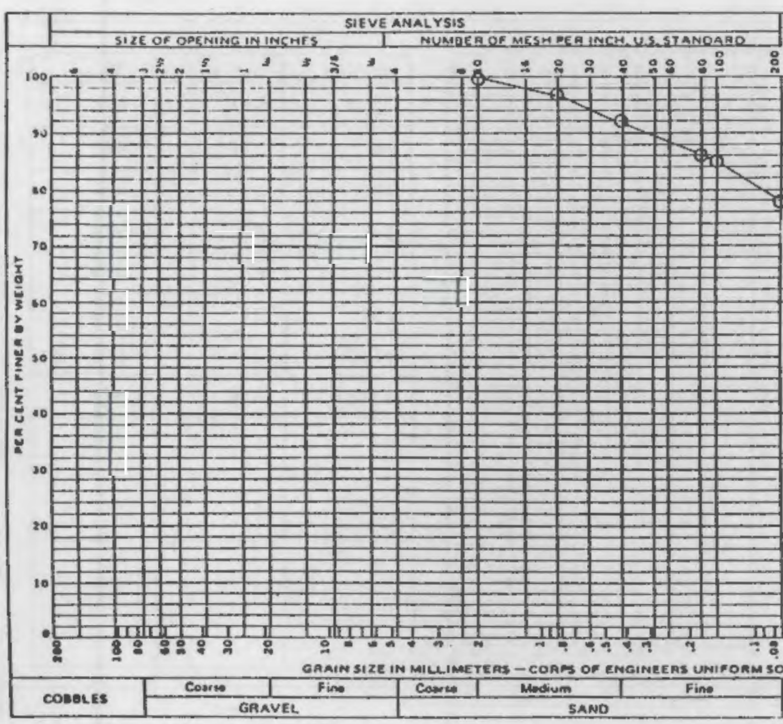
Sample Number:	9 - C
Contractor Soil Classification:	Shale
Engineering Soil Classification:	Inorganic Silt, low plasticity
Proctor Maximum Density lb./ft^3:	89.8
Optimum Moisture %:	22.7
Liquid Limit:	38
Plastic Limit:	30
Plasticity Index:	8
Specific Gravity, g/cm^3	2.33



Proctor

Density

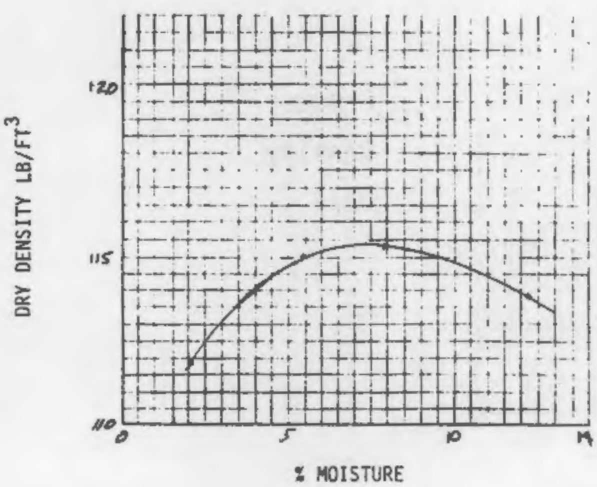
Data



Sieve	%passing	Spec.
3/8	N/A	N/A
#4	N/A	N/A
#10	100	N/A
#20	97	N/A
#40	92	N/A
#80	86	N/A
#100	85	N/A
#200	78.7	N/A

Appendix

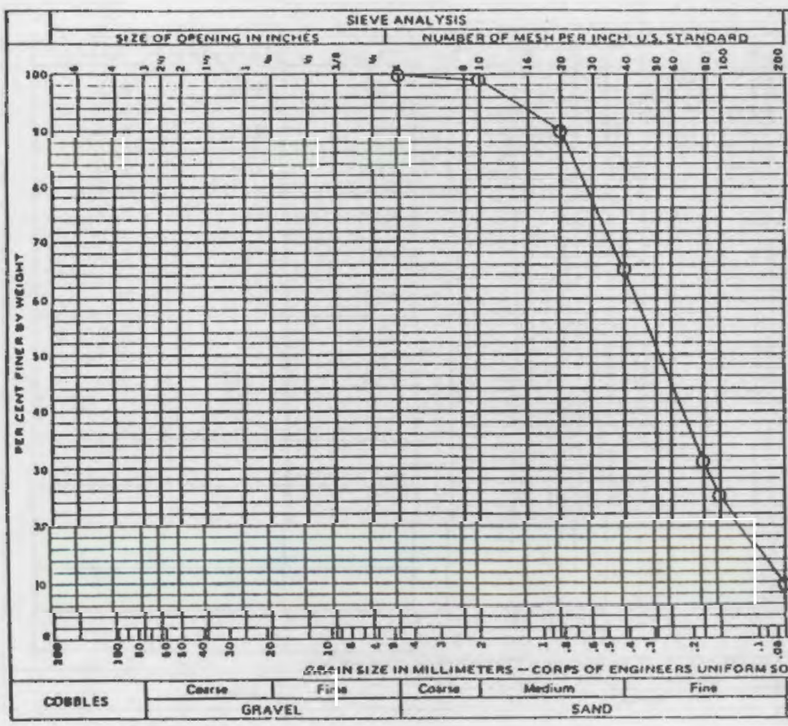
Sample Number:	10 - A
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	115.3
Optimum Moisture %:	7.0
Liquid Limit:	NP
Plastic Limit:	NP
Plasticity Index:	NP
Specific Gravity, g/cm^3	2.63



Proctor

Density

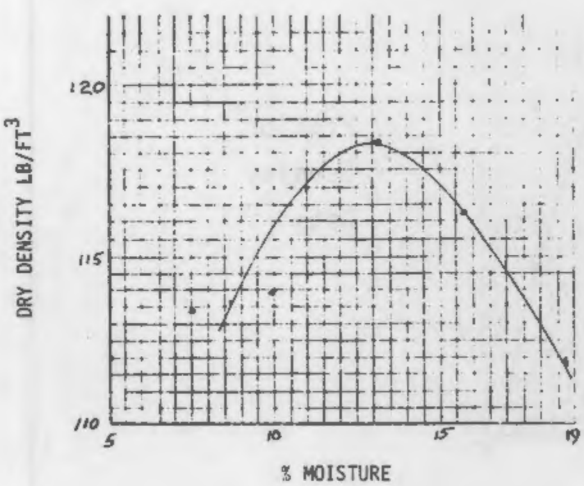
Data



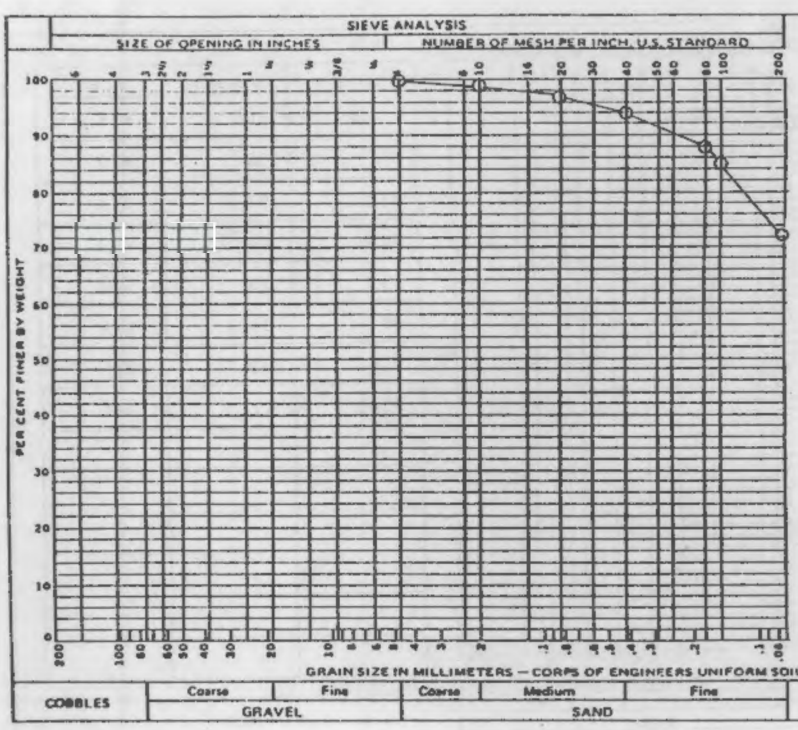
Sieve	%passing	Spec.
3/8	N/A	N/A
#4	100	N/A
#10	99	N/A
#20	90	N/A
#40	65	N/A
#80	31	N/A
#100	25	N/A
#200	9.4	N/A

Appendix

Sample Number:	10 - B
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Inorganic Clay, low plasticity
Proctor Maximum Density lb./ft^3:	118.5
Optimum Moisture %:	11.7
Liquid Limit:	34
Plastic Limit:	20
Plasticity Index:	14
Specific Gravity, g/cm^3	2.76



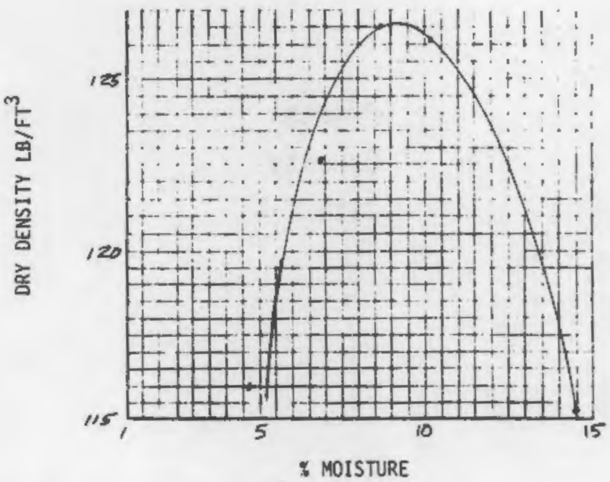
Proctor Density Data



Sieve	%passing	Spec.
3/8	N/A	N/A
#4	100	N/A
#10	99	N/A
#20	97	N/A
#40	94	N/A
#80	88	N/A
#100	85	N/A
#200	72.2	N/A

Appendix

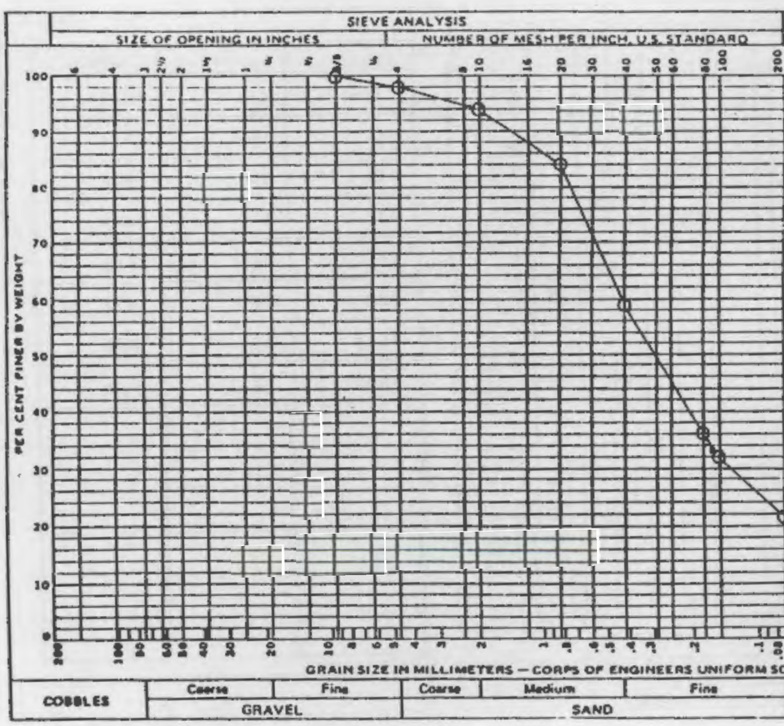
Sample Number:	10 - C
Contractor Soil Classification:	Topsoil
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	126.7
Optimum Moisture %:	9.2
Liquid Limit:	NP
Plastic Limit:	NP
Plasticity Index:	NP
Specific Gravity, g/cm^3	2.72



Proctor

Density

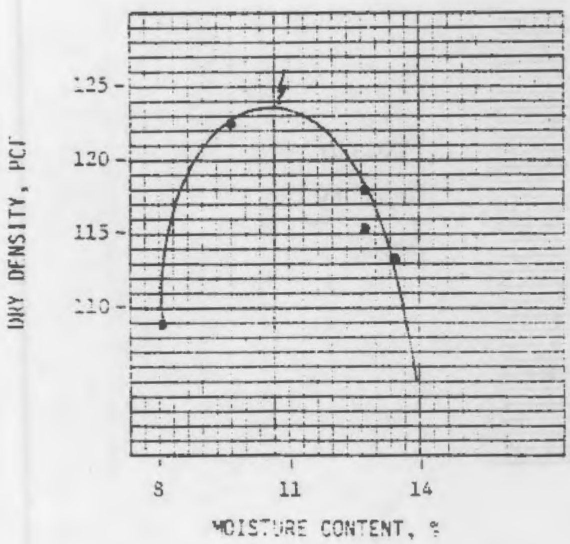
Data



Sieve	%passing	Spec.
3/8	100	N/A
#4	98	N/A
#10	94	N/A
#20	84	N/A
#40	59	N/A
#80	36	N/A
#100	32	N/A
#200	21.6	N/A

Appendix

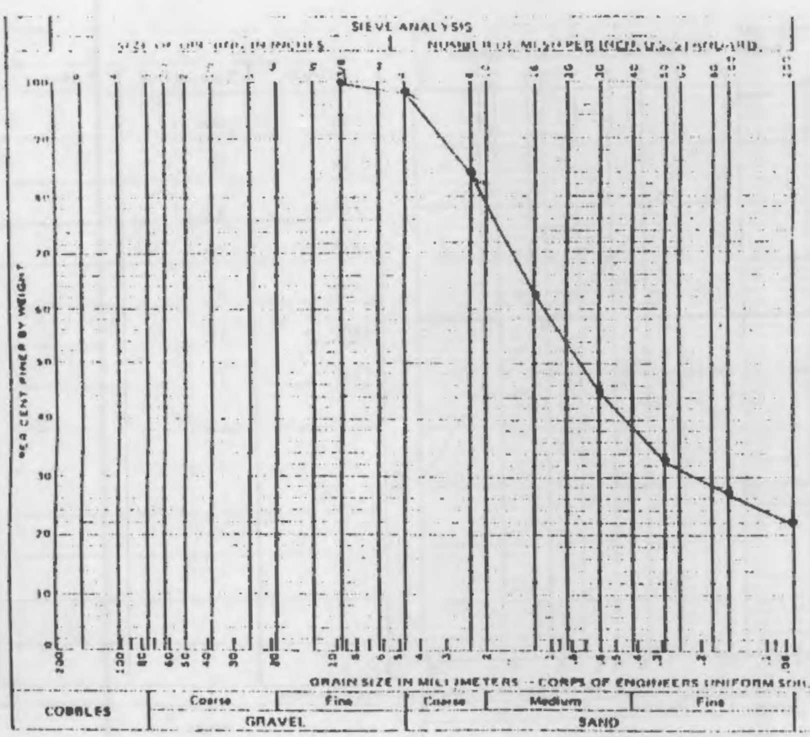
Sample Number:	11 - A
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	123.3
Optimum Moisture %:	10.6
Liquid Limit:	46
Plastic Limit:	24
Plasticity Index:	22
Specific Gravity, g/cm^3	2.69



Proctor

Density

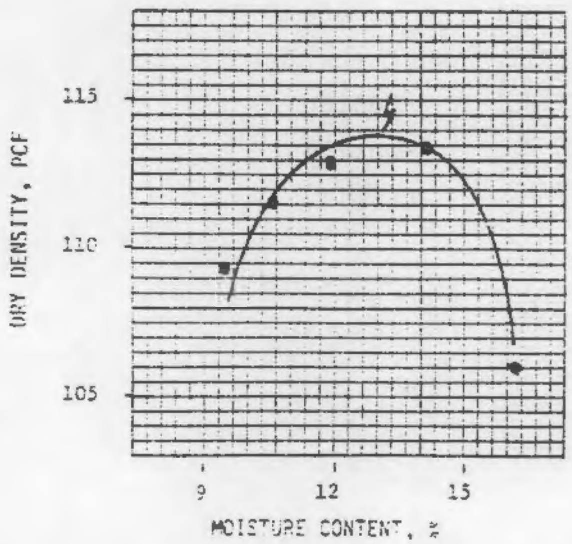
Data



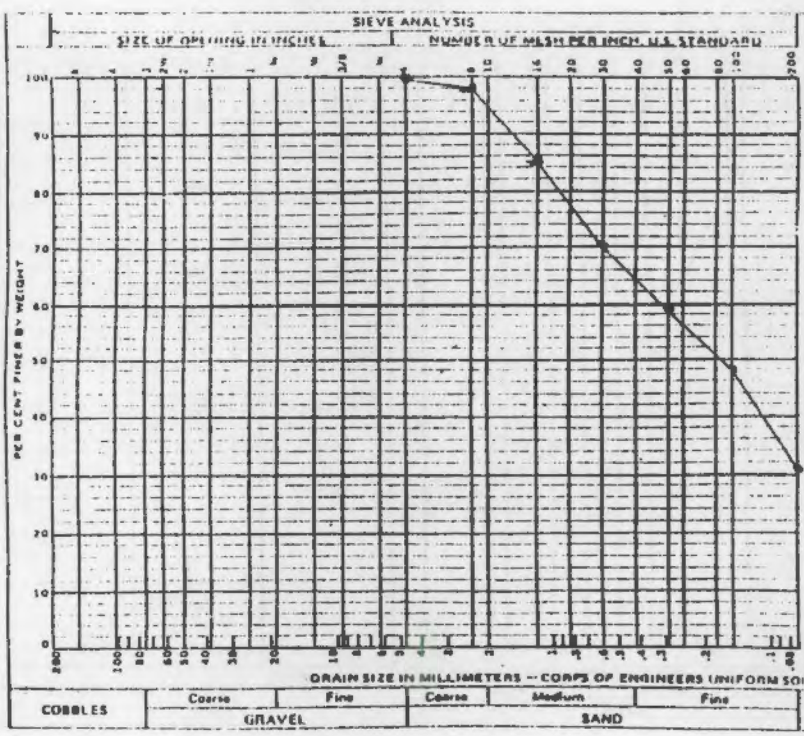
Sieve	%passing	Spec.
3/8"	100	
#4	98	
#8	84	
#16	62	
#30	45	
#50	33	
#100	27	
#200	22	

Appendix

Sample Number:	11 - B
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	113.8
Optimum Moisture %:	13.0
Liquid Limit:	31
Plastic Limit:	23
Plasticity Index:	8
Specific Gravity, g/cm^3	2.69



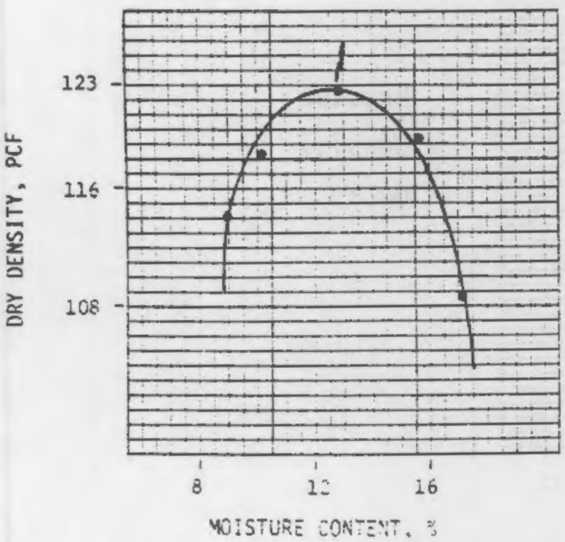
Proctor Density Data



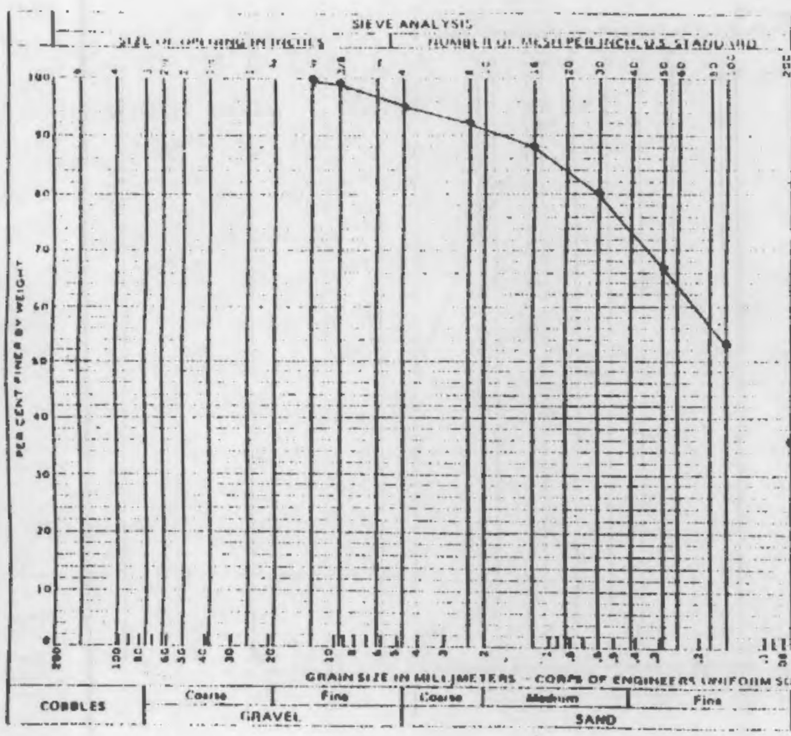
Sieve	%passing	Spec.
#4	100	
#8	98	
#16	85	
#30	70	
#50	59	
#100	48	
#200	31	

Appendix

Sample Number:	12 - A
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	122.6
Optimum Moisture %:	12.9
Liquid Limit:	27
Plastic Limit:	19
Plasticity Index:	8
Specific Gravity, g/cm^3	2.63



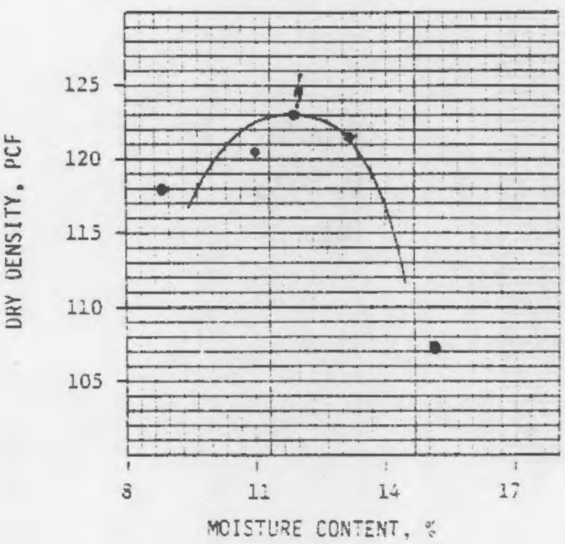
Proctor Density Data



Sieve	%passing	Spec.
1/2"	100	
3/8"	99	
#4	95	
#8	92	
#16	88	
#30	80	
#50	67	
#100	53	
#200	36	

Appendix

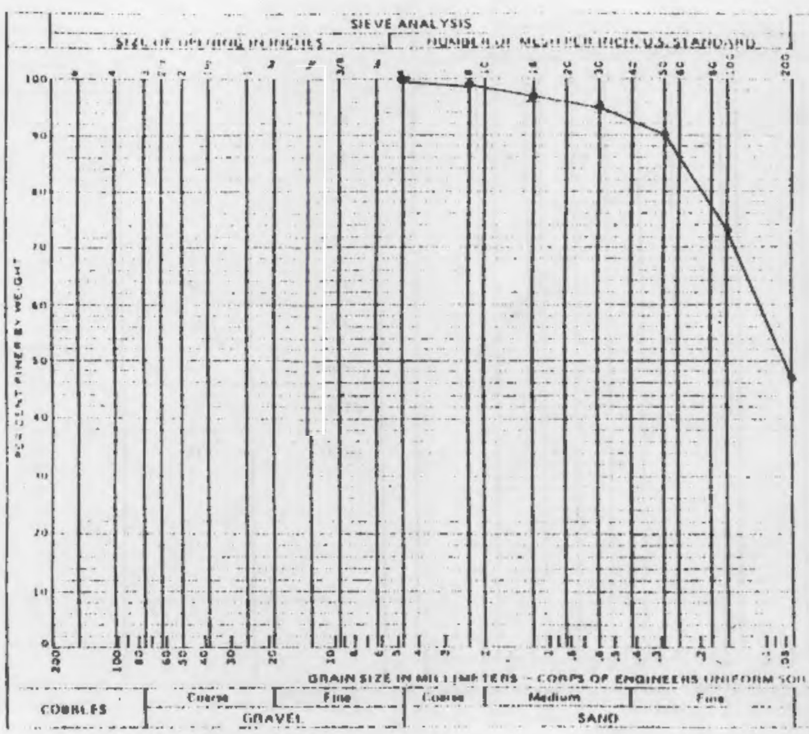
Sample Number:	12 - B
Contractor Soil Classification:	Clay
Engineering Soil Classification:	Silty Sand - Clayey Sand
Proctor Maximum Density lb./ft^3:	123.2
Optimum Moisture %:	11.8
Liquid Limit:	29
Plastic Limit:	22
Plasticity Index:	7
Specific Gravity, g/cm^3	2.69



Proctor

Density

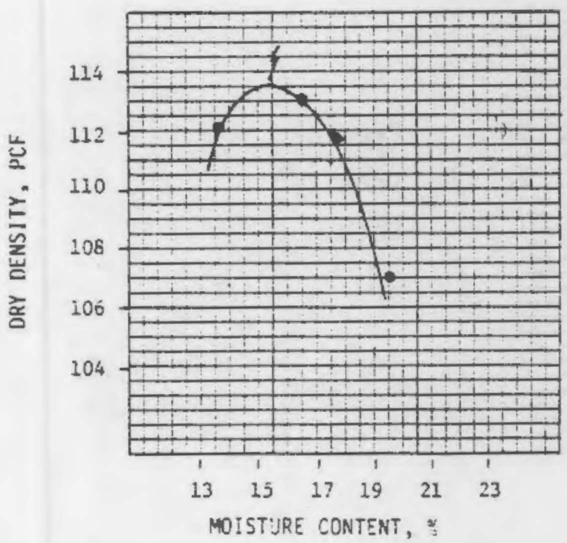
Data



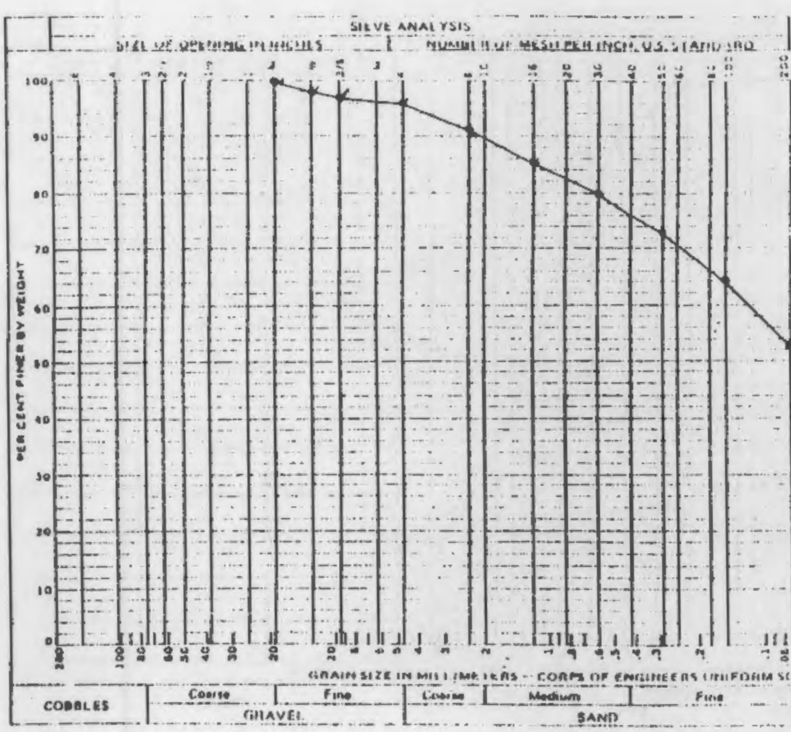
Sieve	%passing	Spec.
#4	100	
#8	99	
#16	97	
#30	95	
#50	90	
#100	73	
#200	47	

Appendix

Sample Number: 13 - A
Contractor Soil Classification: Shale
Engineering Soil Classification: Inorganic Clay, low plasticity
Proctor Maximum Density lb./ft^3: 113.6
Optimum Moisture %: 15.5
Liquid Limit: 46
Plastic Limit: 22
Plasticity Index: 24
Specific Gravity, g/cm^3 2.68



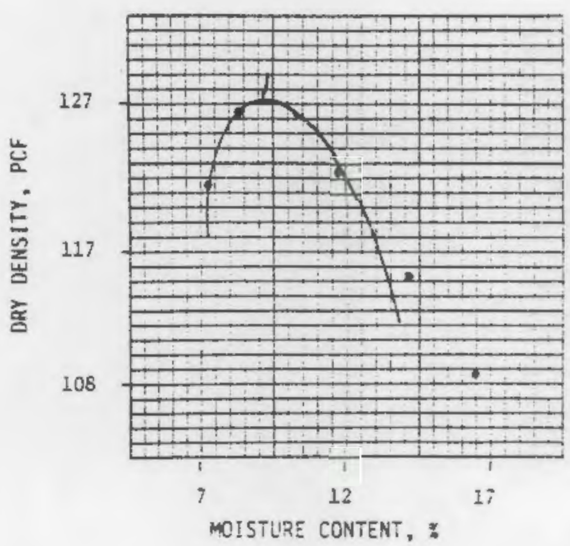
Proctor Density Data



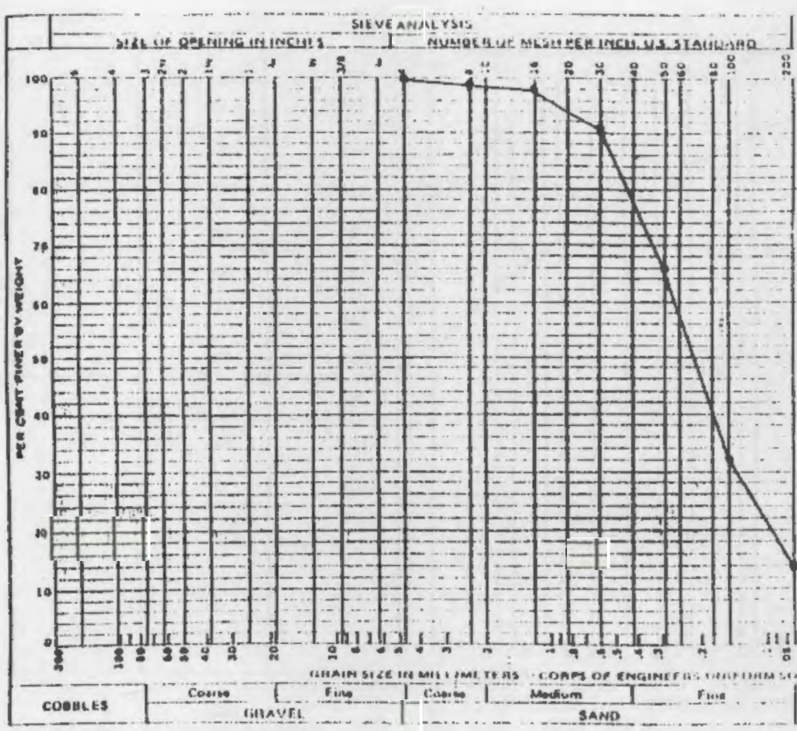
Sieve	%passing	Spec.
3/4"	100	
1/2"	98	
3/8"	97	
#4	96	
#8	91	
#16	85	
#30	80	
#50	73	
#100	64	
#200	53	

Appendix

Sample Number: 14 - A
Contractor Soil Classification: Overburden
Engineering Soil Classification: Silty Sand
Proctor Maximum Density lb./ft^3: 127.2
Optimum Moisture %: 9.5
Liquid Limit: NP
Plastic Limit: NP
Plasticity Index: NP
Specific Gravity, g/cm^3 2.66



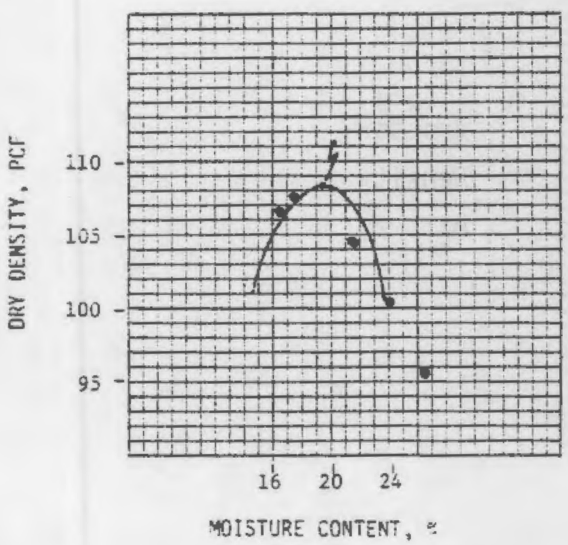
Proctor Density Data



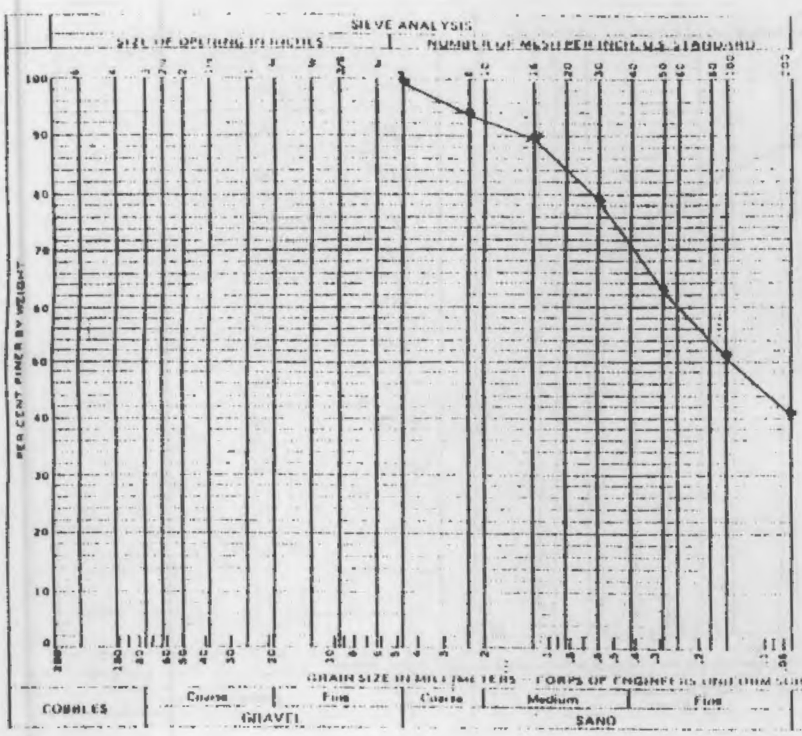
Sieve	%passing	Spec
#4	100	
#8	99	
#16	98	
#30	91	
#50	66	
#100	32	
#200	14	

Appendix

Sample Number:	14 - B
Contractor Soil Classification:	Shale
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	108.5
Optimum Moisture %:	19.5
Liquid Limit:	49
Plastic Limit:	33
Plasticity Index:	16
Specific Gravity, g/cm^3	2.74



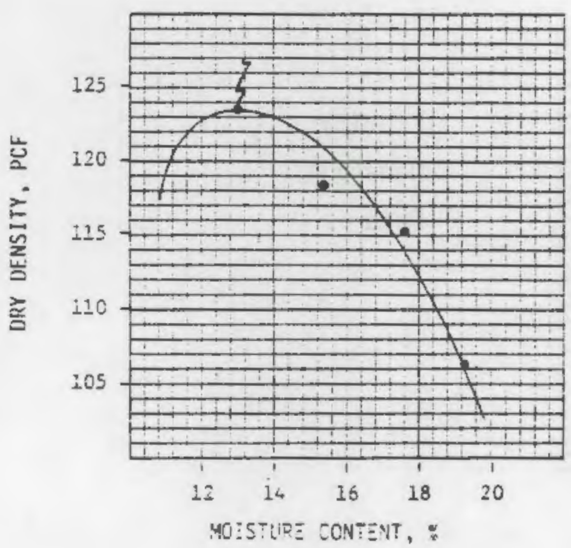
Proctor Density Data



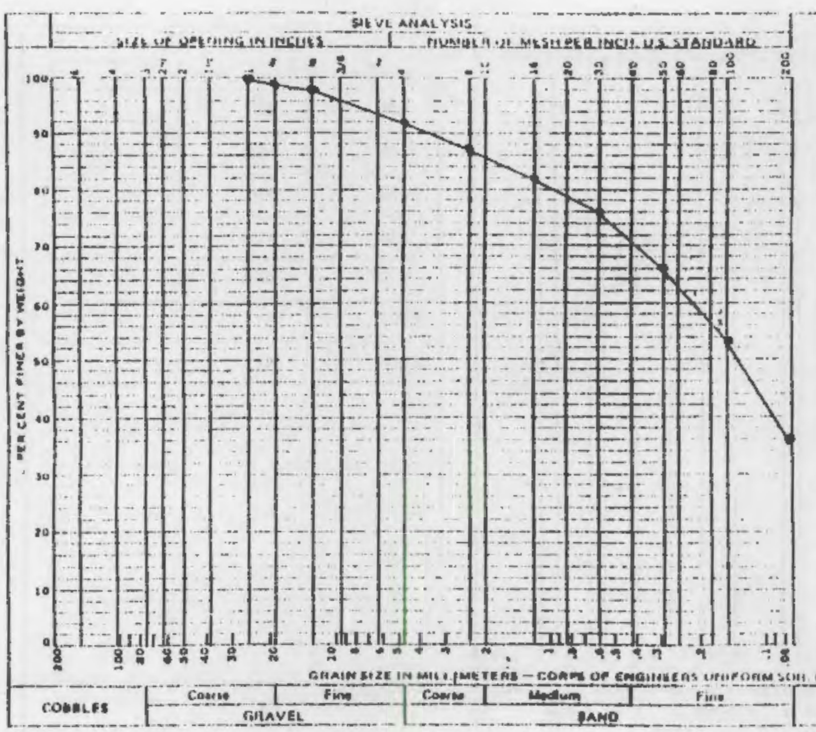
Sieve	%passing	Spec.
#4	100	
#8	94	
#16	90	
#30	79	
#50	63	
#100	51	
#200	41	

Appendix

Sample Number:	14 - C
Contractor Soil Classification:	Shale
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	123.4
Optimum Moisture %:	13.2
Liquid Limit:	32
Plastic Limit:	19
Plasticity Index:	13
Specific Gravity, g/cm^3	2.70



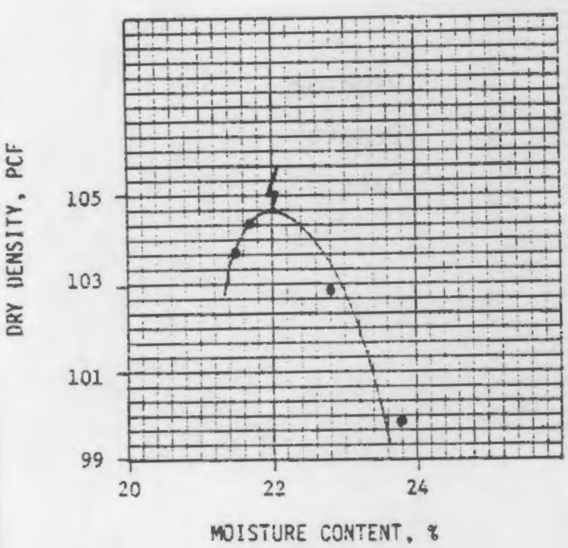
Proctor Density Data



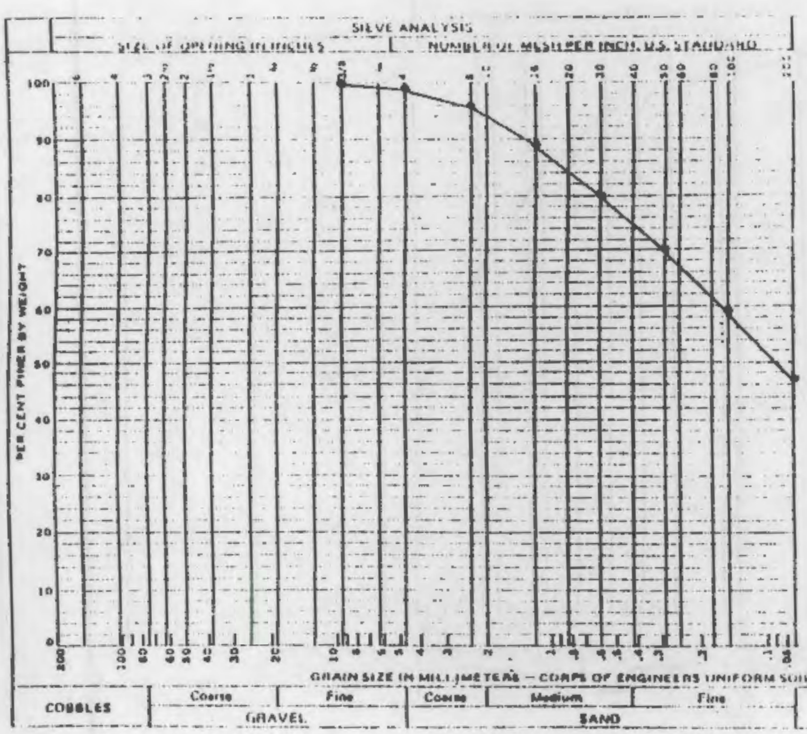
Sieve	%passing	Spec.
1"	100	
3/4"	99	
1/2"	98	
#4	92	
#8	87	
#16	82	
#30	76	
#50	66	
#100	53	
#200	36	

Appendix

Sample Number:	15 - A
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Silty Sand
Proctor Maximum Density lb./ft^3:	104.6
Optimum Moisture %:	22.0
Liquid Limit:	74
Plastic Limit:	37
Plasticity Index:	37
Specific Gravity, g/cm^3	2.55



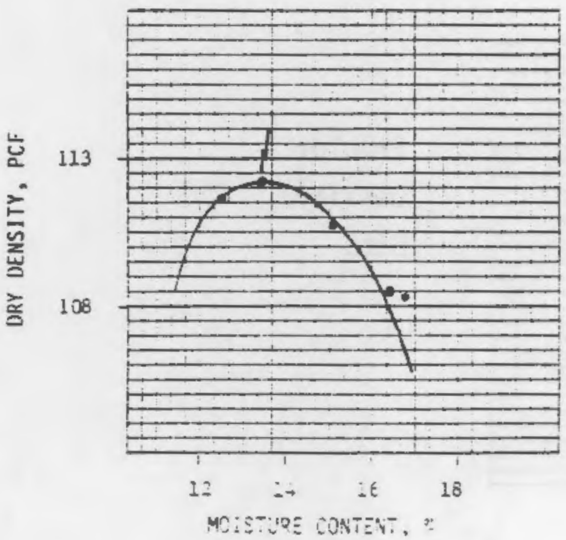
Proctor Density Data



Sieve	%passing	Spec.
3/8"	100	
#4	99	
#8	96	
#16	89	
#30	80	
#50	70	
#100	59	
#200	47	

Appendix

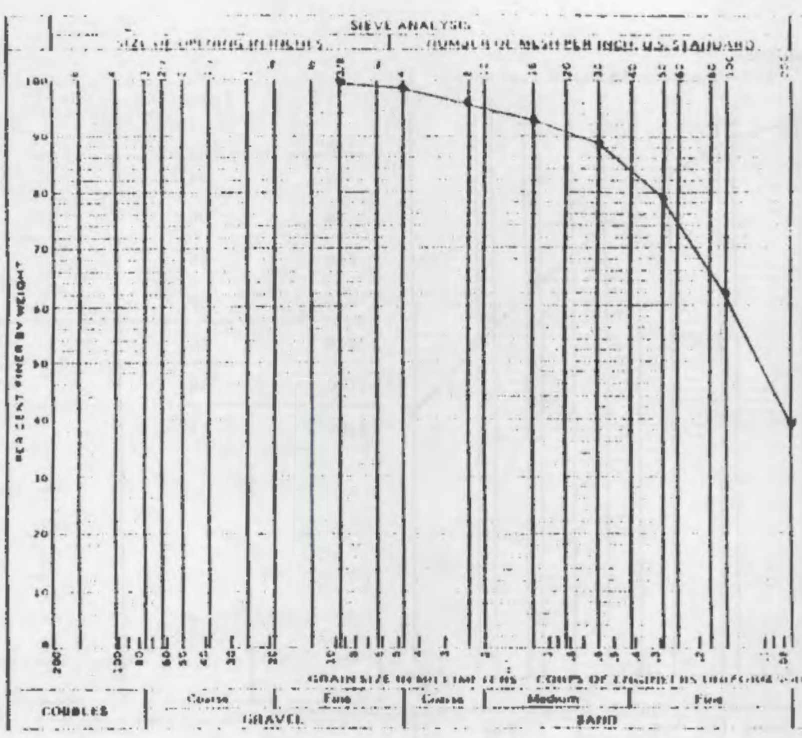
Sample Number:	15 - B
Contractor Soil Classification:	Overburden
Engineering Soil Classification:	Clayey Sand
Proctor Maximum Density lb./ft^3:	112.3
Optimum Moisture %:	13.5
Liquid Limit:	43
Plastic Limit:	25
Plasticity Index:	18
Specific Gravity, g/cm^3	2.54



Proctor

Density

Data



Sieve	%passing	Spec.
1/8"	100	
#4	99	
#8	96	
#16	93	
#30	89	
#50	79	
#100	62	
#200	39	

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Diffusion coefficients were measured for radon in 34 soils that had been identified by uranium mill personnel as candidate soils for covering their tailings piles in order to reduce radon emission. The coefficients referred to diffusion in the total pore space of the soils. They were measured by a steady-state method using soil columns compacted to greater than 8D% of their Proctor maximum packing densities, but with moisture contents generally less than would be expected at a tailings site. An empirical equation was used to extrapolate measured coefficients to values expected at soil-moisture contents representative of tailings sites in the western United States. Extrapolated values for silty sands and clayey sands ranged from 0.004 to D.06 cm^2/s. Values for inorganic silts and clays ranged from 0.001 to 0.02 cm^2/s.

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