Essential Readings in Light Metals: Alumina and Bauxite.
Edited by Don Donaldson and Benny E. Raahauge.

CORRELATION OF RED MUD CONSOLIDATION WITH ITS SOIL PROPERTIES

John M. Stinson
Aluminum Company of America
Alcoa Technical Center
Alcoa Center, PA 15069

Consolidation tests of red muds from various bauxites allow the prediction of the extent of settlement in a mud lake and the rate of consolidation. Differences in the consolidation properties have been shown to correlate with the moisture contents at which the various muds change from a liquid to a plastic state, as indicated by the Atterberg Liquid and Plastic Limits.

Introduction

A one-dimensional consolidation test measures the rate and magnitude of the volume reduction of a soil when it is placed under a compressive load. The reduction in volume is caused by the sustained application of a load and is principally due to the squeezing out of water from the void spaces of the soil. It is accompanied by a transfer of the load from the soil water to the soil solids.

Description of Experimental Procedure

Our tests on the consolidation properties of red muds are based on ASTM Standard D 2435-70, One-Dimensional Consolidation Properties of Soils, with a variation required in the manner in which the mud is placed in the apparatus. The consolidometer, shown in Figure 1, consists of a cylindrical steel tube, 21 square centimetres in internal cross-sectional area, which provides lateral support of the red mud sample. Circles of filter paper and porous stone discs placed at each end of the tube retain the mud solids, yet allow free drainage of the water. Loads of 25 to 400 kilopascals are applied to the top of each mud sample by means of a series of steel weights. Each additional weight is chosen so that the total load is doubled. The change in mud volume is determined by measuring the mud thickness within the consolidometer tube with a depth gage.

Since red mud is typically discharged to a mud lake as a relatively dilute slurry from which the mud solids rapidly settle, it is desired to measure consolidation properties starting with mud at a high moisture content. At this condition, red mud is too weak to be handled in the conventional procedure used in testing soils. Our modified procedure for placing the red mud in the consolidometer tube involves pouring a thick slurry into the tube in a manner to avoid trapping air bubbles, gently tamping level, and applying a seating pressure of 2.4 kilopascals. The sample is kept saturated with water by adjusting the drain line.

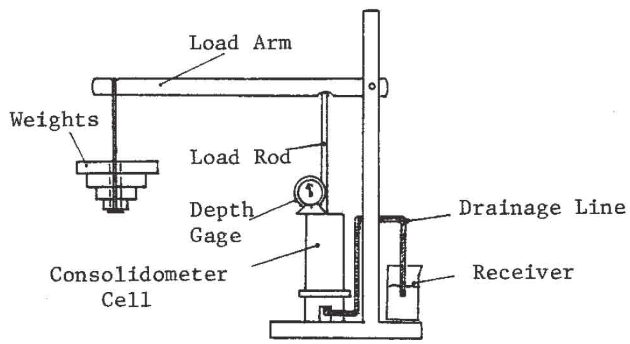
Test Results

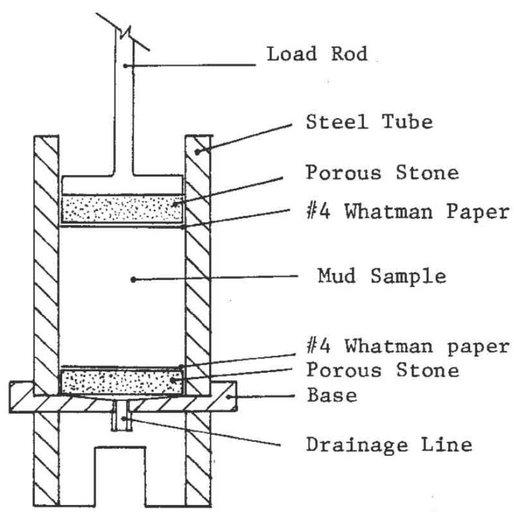
From the mud volume measured at time intervals for each load pressure, and the measured final mud moisture content and specific gravity of the mud solids and water, plots of mud void ratio versus time, such as Figure 2, are obtained. The readings at each load pressure are continued until the slope of the void ratio change with time becomes linear. Due to the relatively slow response of red muds, especially at the higher load pressures, some loads were applied for over 10,000 minutes.

Red muds from four bauxites were tested. These bauxites, from Jamaica, West Africa, Australia and Brazil, were chosen to represent the range of bauxite types processed by Alcoa. Table I presents properties of these muds. While red muds are generally composed of the same minerals, the relative proportions and, therefore, the chemical compositions vary widely. The consolidation properties are expected to be dependent upon the mineral and chemical species which make-up that mud, however, other factors appear to play important roles. It will be shown that the Jamaican and Brazilian muds, which are quite similar in mineral and chemical composition, exhibit extremely different consolidation characteristics.

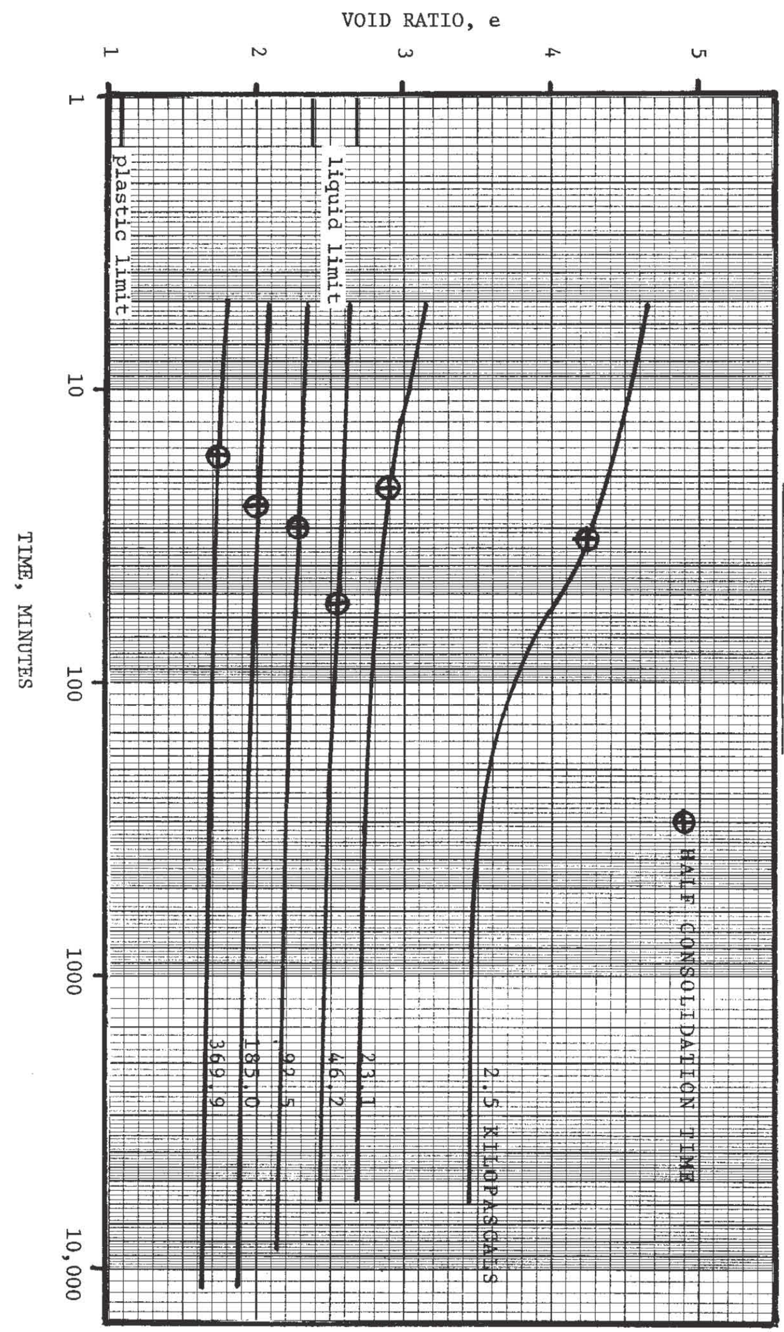
For treatment of the data, we follow the methods of Salem and Krizek[1] who measured consolidation characteristics of clay-like dredging wastes. Four properties are determined: the consolidation index, the coefficient

FIGURE 1. CONSOLIDOMETER





CROSS-SECTIONAL VIEW OF CONSOLIDOMETER CELL



VOID RATIO VERSUS TIME

FIGURE 2.

TABLE I. PROPERTIES OF THE RED MUDS

	Mud Type			
	Jamaican	West African	Australian	Brazilian
Chemical Analysis, %				
Fe_2O_3	32	12	29	37
TiO_2	5	13	2	4
SiO_2	7	8	25	16
Al_2O_3	20	39	27	21
Na_2O	9	3	3	11
CaO	7	7	4	1
LOI	18	16	10	10
Mineral Analysis:				
major	Hematite, Goethite DSP	Boehmite, Quartz	Quartz, Hematite Goethite	DSP, Hematite
minor	Boehmite	DSP, Hematite, Goethite Anatase	DSP	Goethite, Anatase
Surface Area m^2/gram	22	19	13-17	14
Specific Gravity	2.9-3.0	2.9-3.0	2.7-2.8	2.6
Atterberg Limits, % Moisture				
Liquid Limit (LL)	87.1 ± 5.2	76.3 ± 1.8	41.3 ± 0.7	42.8 ± 0.8
Plastic Limit (PL)	35.4 ± 2.0	45.2 ± 1.6	34.1 ± 1.1	32.9 ± 1.4
Plastic Index	51.7 ± 7.2	31.1 ± 3.4	7.2 ± 1.8	9.9 ± 2.2

of volume compressibility, the coefficient of consolidation and the coefficient of permeability.

The consolidation index (expressed by the symbol C_c) relates the eventual mud density, or void ratio, to each load pressure. The index is the slope of the best straight line when void ratio is plotted versus the logarithm of pressure. For each mud, equations were determined by least square fits to the data. These equations are in the form

$$e = e_o - C_c \text{ (log P)} \quad (1)$$

where e is the ultimate void ratio obtained for each load pressure, P, Cc is the consolidation index, and e_o is an intercept, or void ratio when the load pressure is one.

The coefficient of volume compressibility (expressed by the symbol m_v) describes the compression of a layer per unit of original thickness due to a given unit increase in pressure. It is defined by the equation

$$m_v = a_v/(1 + e_o) \quad (2)$$

where $a_v = \Delta e/\Delta P$, e_o is the initial void ratio at the initial applied pressure, and Δe and ΔP are the change in void ratio due to the change in pressure. As a mud consolidates, the change in void ratio for each additional increase in pressure is less. The coefficient of volume compressibility is, therefore, a function of pressure and for each mud, equations were determined by least squares fit. These equations are in the form

$$\log m_v = m_v' \text{ (log P)} + \log m_{v_o} \quad (3)$$

where m_v is the coefficient, P is pressure, m_v' is the slope, and m_{v_o} is an intercept at P = 1.

The coefficient of consolidation (expressed by the symbol C_v) describes the rate of consolidation. This coefficient is defined by the equation

$$C_v = T \cdot h^2/t_u \quad (4)$$

where h is the drainage path length, t_u is the time required for a given degree of consolidation, u, and T is a time factor which relates to the degree of consolidation. Consolidation to 50% is chosen, so t_{50} is the time for half the consolidation to occur and the time factor is 0.197. The rate of consolidation is a function of the pressure, however, the relationship is not linear. At load pressures near 50 to 100 kilopascals, the rate decreases sharply, then increases again as pressure is further increased.

Since the changes in mud volume during consolidation are principally due to the expulsion of water from the mud mass, the theory of consolidation holds that volume change should be related to the permeability of the mud. Permeability describes the rate of water discharge under laminar flow conditions through a unit cross-sectional area of porous mud under a unit hydraulic gradient. The coefficient of permeability (expressed by the symbol k) is defined by the equation

$$k = 0.1\, C_v \times m_v \times \gamma_L \tag{5}$$

where C_v is the coefficient of consolidation, m_v is the coefficient of volume compressibility and γ_L is the unit weight of water. The permeability is commonly expressed as a function of void ratio and least squares equations were fit to the data for each mud. These equations are in the form

$$\log k = k' (\bar{e}) + \log k_o \tag{6}$$

where $\bar{e}$ is the average void ratio, k' is the slope, and k_o the intercept at a void ratio of zero.

Use of Consolidation Characteristics of Red Muds

The consolidation characteristics determined for a mud assist in predicting the long term behavior of a mud lake disposal area. Generally, red mud in a mud lake is subjected to a load due to its own weight. When saturated with water, as red mud usually is, the buoyant action of the water reduces the effective load of the mud solids, and drainage is usually only from the upper surface.

From the relationship of void ratio to pressure, it is possible to determine the eventual density that a red mud will attain. The settlement, or reduction in volume, due to consolidation can be obtained by the equation

$$S = H \left(\frac{C_c}{1 + e_o}\right) \log \left(\frac{P + \Delta P}{P}\right) \tag{7}$$

where S is the settlement distance, H is the initial mud depth, e_o is the initial void ratio corresponding to an initial pressure, P, ΔP is an increase in load pressure, and C_c is the consolidation index.

The time required for half this settlement can be estimated from the coefficient of consolidation by the equation

$$t_{50} = \frac{0.197\, h^2}{C_v} \tag{8}$$

This equation is a rearrangement of equation (4) used to calculate the coefficient of consolidation. The drainage path distance, h, is the initial mud depth in most mud lakes, but, the use of underdrains would reduce this distance by half and the consolidation time by one-fourth.

Prediction of Consolidation Characteristics

Due to the slow response of red muds at the higher pressure loads, consolidation tests are time-consuming, taking as long as thirty days to complete. A means to correlate consolidation behavior with other mud properties was sought, to avoid this time-consuming process and to better understand the reasons for variations in characteristics among different red muds. In our tests, the Jamaican mud initially retains a large amount of water and consolidates slowly, but, the change in volume during consolidation is large. At the other extreme is the Brazilian mud which retains much less water, consolidates quickly, and undergoes less volume change since less water must be squeezed from the mud mass. Between these two muds in behavior are the West African mud and the Australian mud.

Surface area is one property of the muds which follows the consolidation behavior. A high surface area mud retains more water and consolidates slowly with large volume changes. Surface area is certainly indicative of the types of minerals present in the mud, but, exact correlations have not been made at this time.

Atterberg Limits have proven to be a means to quantify the effect of moisture content on the characteristics of a soil. These arbitrary limits define the water content at which the mud changes from a liquid state to a plastic state and from a plastic state to a rigid state. Atterberg Limits are determined by the methods of ASTM Standard D 423, Test for Liquid Limit of Soils, and Standard D 424, Test for Plastic Limit and Plasticity Index of Soils.

By definition, liquid limit is the water content at which a block of soil, cut by a groove of standard dimensions, will flow together (12.7 mm) under an impact of 25 blows. Plastic limit is the water content at which a soil will just begin to crumble when rolled into a thread approximately 3.2 mm in diameter. In both cases, the water content is expressed as a percentage of the water weight to weight of dry solids. The liquid limits of the four red muds correspond closely to the surface areas. The plastic limits are identical for three of the four muds.

It has been possible to correlate the liquid limits of the four muds to their consolidation characteristics. Linear equations, shown in Figure 3, were determined by least squares fit to relate liquid limit (LL) to the slope and intercept coefficients of the equations previously developed. For the coefficient of consolidation, although an equation relating the coefficient to pressure was not developed, it was possible to relate the minimum value of the coefficient to the liquid limit.

In Figures 4 through 7 are shown the predicted consolidation properties of each mud compared to the measured properties. The predicted void ratios differ from the measured values by an average of 5 percent. The predicted coefficients of volume compressibility differ by an average of 7 percent. The predicted coefficients of permeability differ by only 11 percent for the Jamaican and West African mud and average 26 percent for all the muds considered together. Finally, the predicted minimum coefficients of consolidation differ by an average of 20 percent from the measured values. The shape of the coefficient of consolidation curve is also related to the Atterberg Limits. The sudden decrease in consolidation rate at load pressures between 50 and 100 kilopascals coincides with consolidation of the muds to their liquid limits. As the plastic limits are approached, the rates increase back to the initial values.

The predicted settlement of Jamaican and Australian red muds has been compared to settlement measured in mud lake simulation tests[2]. Red mud which initially was at thirty-five percent solids consolidated in our column test under its own weight. The predicted changes in mud density, calculated from equation (7), and shown by the straight lines in Figure 8, agree well with the changes in mud density measured at difference depths in the mud columns.

FIGURE 3

CORRELATION EQUATIONS

Void Ratio: $e = e_o - C_c\ (\log P)$

where $e_o = 0.0433\ (LL) + 0.148$

$C_c = 0.0151\ (LL) - 0.370$

Coefficient of Volume Compressibility:

$\log m_v = m_v'\ (\log P) + \log m_{v_o}$

where $m_v' = 0.00354\ (LL) - 1.312$

$m_{v_o} = 0.00128\ (LL) + 0.0771$

Coefficient of Consolidation, minimum value:

$\log C_v = -0.0231\ (LL) - 1.909$

Coefficient of Permeability:

$\log k = k'\ (\bar{e}) + \log k_o$

where $k' = 4.100 - 0.0338\ (LL)$

$\log k_o = 0.0142\ (LL) - 11.348$

FIGURE 4

Predicted Void Ratio

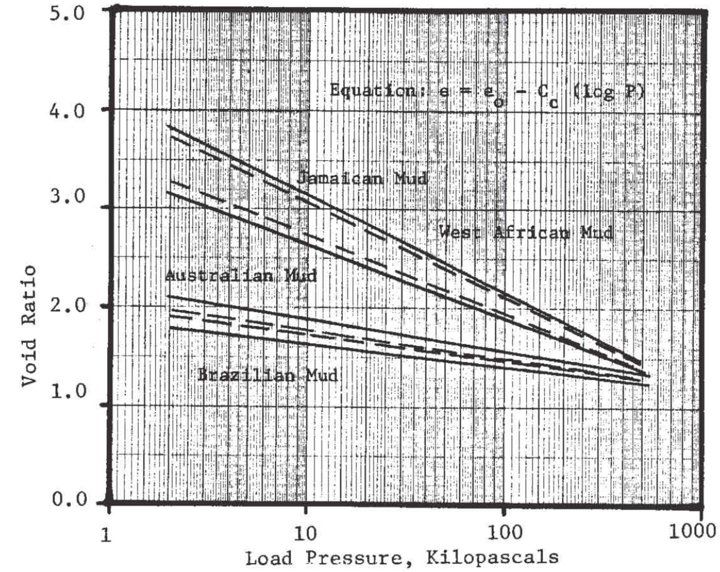


FIGURE 5

Predicted Coefficient of Volume Compressibility

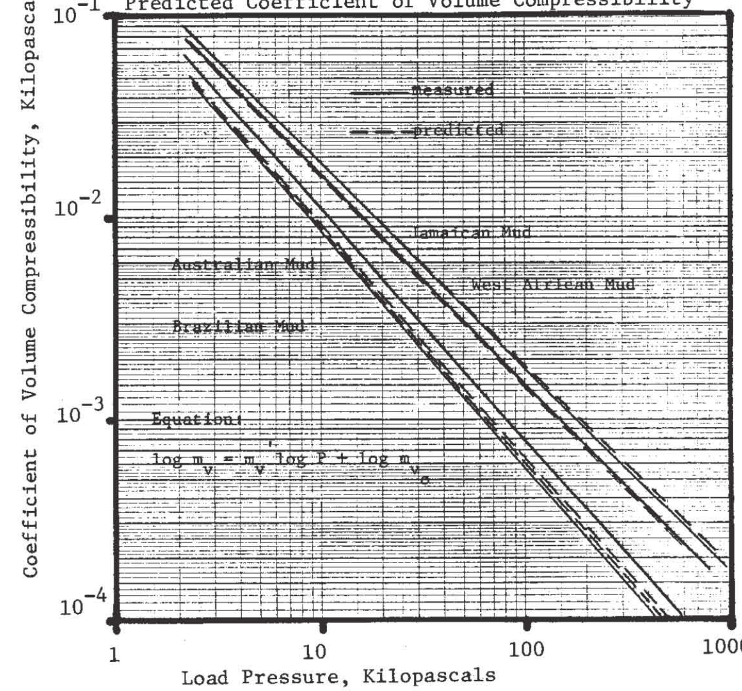


FIGURE 6

PREDICTED COEFFICIENT OF PERMEABILITY

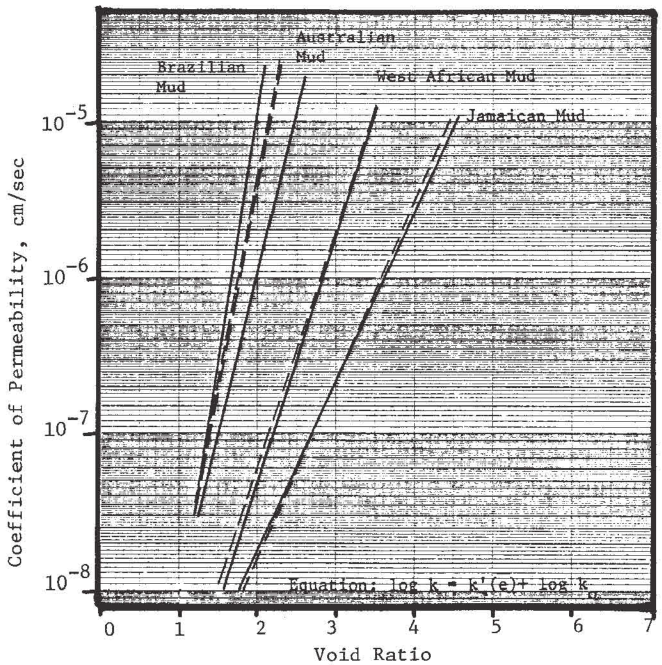


FIGURE 7

Predicted Coefficient of Consolidation

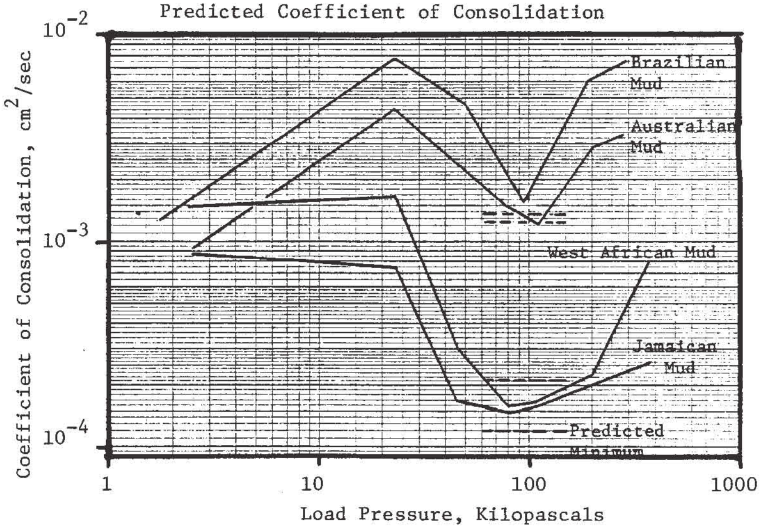
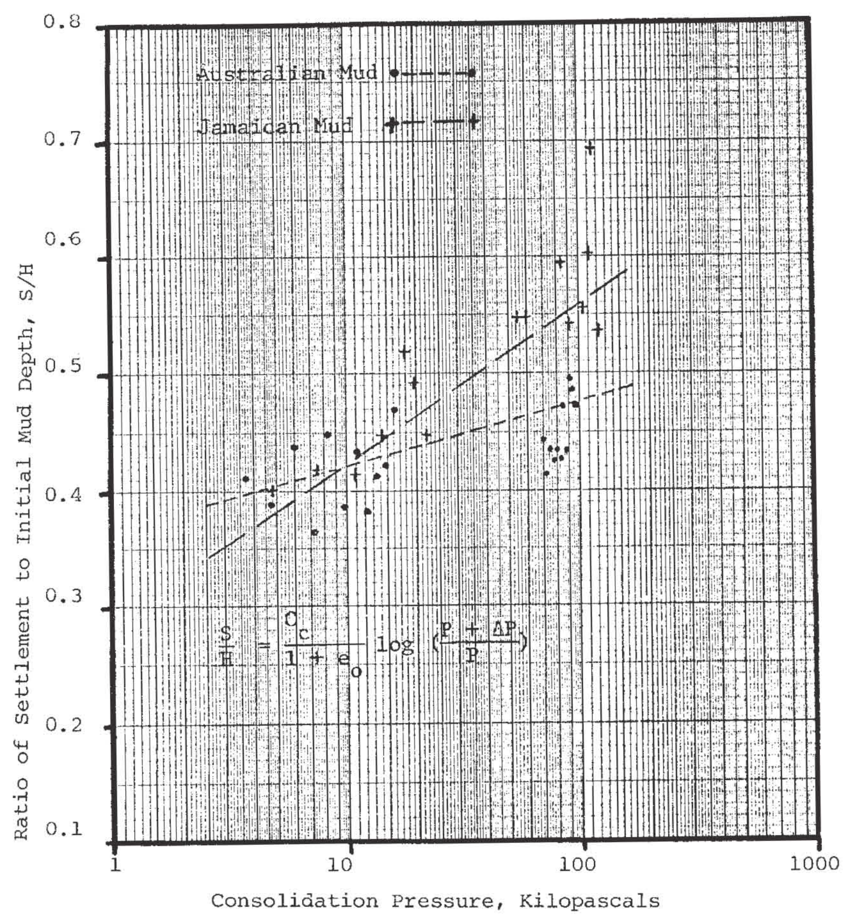


FIGURE 8

COMPARISON OF MUD SETTLEMENT TO PREDICTED VALUES



Conclusion

While consolidation behavior of red muds is probably controlled by interactions between the mud particle surfaces and the water in the mud mass and is dependent upon the types of minerals present in the mud and their surface areas, the Atterberg Limits provide a rapid and relatively simple method to determine the overall effect. From the Atterberg Limits, the consolidation properties can be predicted with an accuracy that approaches the accuracy of the Atterberg Limits determination.

References

1. A. M. Salem and R. J. Krizek, "Consolidation Characteristics of Dredging Slurries," Journal of the Waterways, Harbors and Coastal Engineering Division, WW4 (November 1973) pp. 439-457.

2. J. M. Stinson, "Red Mud Lake Simulation," paper presented at TMS-AIME Meeting, New Orleans, LA, Feb. 1979.