Compressibility of neutralized phosphogypsum

Compressibilité du phosphogypse neutralisé

B. P. WRENCH, Steffen, Robertson and Kirsten, Johannesburg, South Africa
G. E. BLIGHT, University of Witwatersrand, Johannesburg, South Africa

SYNOPSIS Phosphogypsum tailings is a by product of the fertilizer industry. A large tailings impoundment has been formed of phosphogypsum neutralized by the addition of lime. This paper describes a field and laboratory study to determine the compressibility parameters of the material. The tests show the phosphogypsum to be highly compressible and to display considerable secondary compression.

INTRODUCTION

In 1984 a phosphoric acid plant was established at Richards Bay on the east coast of Natal, South Africa. The town has developed rapidly because of the recent construction of a deep water harbour. Further harbour related and industrial development is planned which must take account of extensive mangrove marshes around the harbour. Reclamation of large areas of swamp has already been accomplished by the use of hydraulic fill recovered during dredging for the harbour. Further development of the marsh lands is however being delayed by a shortage of fill materials.

The phosphoric acid factory is located close to the harbour and potential sites for the tailings impoundment were therefore limited. A site was chosen for the impoundment in a low lying marsh on the northern boundary of the harbour. The site is underlain by up to 30m of interbedded soft clays and sands. Following evaluation of the environmental impact of the facility it was decided to neutralize the phosphogypsum at the factory by the addition of lime prior to its placement on the impoundment. The impoundment is constructed by the upstream method of construction.

The owners of the land were anxious to evaluate the suitability of the neutralized phosphogypsum as a light weight landfill to reclaim the site for possible future development. A study was conducted to investigate the geotechnical properties of the phosphogypsum with particular reference to the load deformation characteristics. A test site was established on the surface of the impoundment and the compaction, hydraulic conductivity, compressibility and shear strength characteristics evaluated both in the field and in the laboratory. This paper presents the results of the tests to determine the compressibility characteristics of the neutralized phosphogypsum.

MATERIAL PROPERTIES

Phosphoric acid is produced at the factory by treating phosphatic ore with sulphuric acid to yield orthophosphoric acid, calcium sulphate and hydrofluoric acid. The orthophosphoric acid is removed by filtration and the remaining products form the phosphogypsum tailings. Over 95% by weight of this product is dihydrate phosphogypsum ($Ca\ SO_4.2H_2O$) and the remaining constituents comprise hydrofluosilicic acid, phosphoric acid and complex fluorine based products. The waste is strongly acidic and presents potential problems for disposal, both in the primary handling of the material and in subsequent secondary or resultant effects. The problems associated with disposal of phosphogypsum waste have been discussed by Wissa & Fuleihan (1980) and Smith & Wrench (1984). At Richards Bay, lime is added to neutralize the tailings and the pH of the product is controlled to between 7,0 and 8,0.

The shape of the dihydrate calcium sulphate crystals is controlled in the factory. These are plank shaped with an average length to width ratio of between 5 and 9. When placed hydraulically the crystals are sorted such that the long axis of the crystals is nearly always horizonal. Electron microscope photomicrographs have been used to investigate the structure of the tailings.

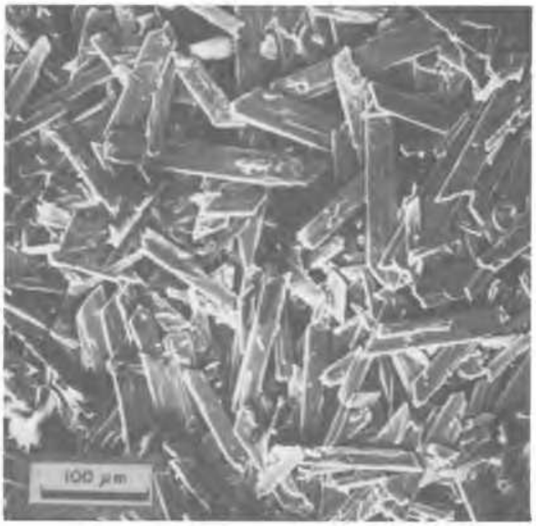

Figure 1: Photomicrograph of neutralized phosphogypsum

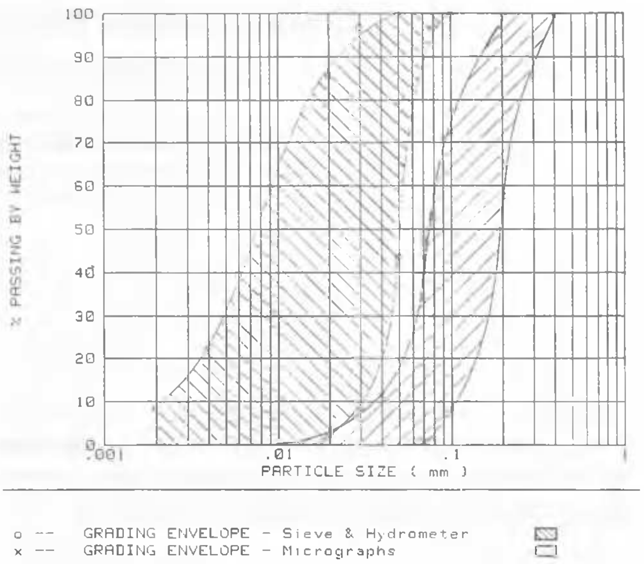

Figure 2: Grading envelopes for Richards Bay phosphogypsum

An example of a photomicrograph of the phosphogypsum from the factory is presented in Figure 1.

Tests on acid phosphogypsum (Blight 1969, Vick 1977) have shown that the product is highly compressible and displays appreciable secondary compression. Experience from the construction of acid phosphogypsum impoundments has shown that the material consolidates rapidly. Similar characteristics were observed on the neutralized phosphogypsum impoundment.

From tests carried out by the authors it is apparent that conventional grading and hydrometer tests give grading envelopes that are too fine. An alternative method of establishing the particle size distribution for the tailings was therefore developed using the photomicrographs. Grading envelopes for the neutralized phosphogypsum from Richards Bay obtained by this method and by conventional sieve and hydrometer methods are presented in Figure 2.

The specific gravity of the phosphogypsum varies between 2,27 and 2,40 depending on the percentage of other minerals and waste products in the tailings. The in situ dry density of the surface phosphogypsum on the impoundment varies from 700 to 900kg/m^3 and the initial void ratio between 1,60 and 2,30.

Field and laboratory tests have shown the horizontal permeability of the surface phosphogypsum to vary between 300 to 2000 m/year, and vertical permeability varying between 30 to 100 m/year. During consolidation the vertical permeability reduces with reducing void ratio.

Gypsum is soluble in fresh and sea water. Solubility increases for higher total dissolved solids in the water and saturation is obtained at a concentration of approximately 0.3 percent by weight.

TESTING PROGRAMME

The consolidation properties of neutralized phosphogypsum were investigated by field and laboratory testing. The test programme comprised short and long term consolidation tests in the laboratory and long term static plate bearing tests on the surface of the impoundment. Details of the tests are presented below.

Laboratory Testing

Twenty one consolidation tests were carried out in the laboratory on undisturbed block samples of phosphogypsum recovered from the impoundment. All samples were tested vertically i.e. with the crystals orientated perpendicular to the applied load. Tests were carried out on 75mm diameter samples and conventional one dimensional consolidation test equipment was used.

Both the primary and secondary compression characteristics were measured. A suite of ten tests were carried out with incremental loading from 10kPa to 1600kPa. Load durations varying from 12hrs to 7 days were used. Secondary compression effects were measured in eleven tests where compression under constant load was measured for up to 100 days. Typical curves of void ratio versus pressure and void ratio versus time are presented in Figure 3. Tests were carried out on both unsaturated and saturated materials.

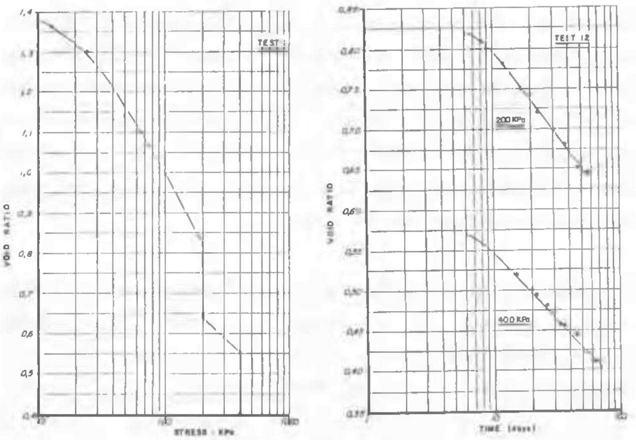

Figure 3: Typical laboratory consolidation results

Field Testing

In situ testing was carried out on the impoundment at a paddock underlain by approximately 6 metres of phosphogypsum. As part of the test programme in situ compaction of the paddock was undertaken using a light roller. On completion of this work a 150mm layer of ash was placed and compacted over part of the compacted area. The compressibility of the phosphogypsum at the test paddock was measured using three identical loading frames. The frames were square with rigid steel plates of equal area located at each corner. Two of these plates were square with sides 500mm long and two were rectangular measuring 350 by 820mm. The frames were constructed on the test paddock and the plates were embedded 20mm into the phosphogypsum. The first frame was located wholly on the uncompacted phosphogypsum, the second on compacted phosphogypsum and the third on ash overlying the compacted phosphogypsum. Settlement sensors were installed at four plates to record settlements at various depths below the plates. The sensors comprised steel rods fixed in prebored holes in the phosphogypsum at depths of 250, 500 and 1000mm vertically below the plates. A photograph of one of the frames is presented in Figure 4.

Figure 4: Photograph of Loading Frame

Load was applied by kentledge comprising concrete blocks. An initial loading of 48kPa was applied to the plates and settlements of each plate were measured at regular intervals for 268 days. These measurements were made using an optical level mounted on a stable plinth buried into the phosphogypsum. A second load increment was then applied to the frames. Different load increment ratios were applied to each frame resulting in plate bearing pressures of 64, 72 & 96kPa respectively. The resulting additional settlements were measured for a further 886 days. Plots of settlement versus time for one of the plates founded on the uncompacted phosphogypsum and the corresponding settlement sensor readings are given in Figure 5.

COMPRESSION PARAMETERS

The study has provided both primary and secondary compression characteristics of the neutralized phosphogypsum.

The void ratio versus log pressure curves show that the neutralized phosphogypsum has similar consolidation characteristics to normally consolidated clays. Values of the coefficient of consolidation (c_v) and compression index (C_c) were computed from the test results. These coefficients describe the primary compression of the phosphogypsum. The time settlement curves obtained

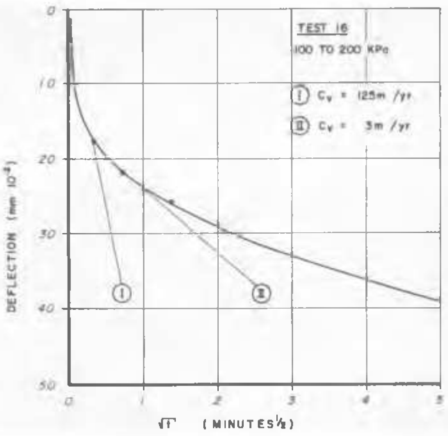

Figure 5: Settlement record for one plate

in the laboratory are similar to the Type III curves defined by Leonards and Girault (1961). Primary consolidation occured rapidly and the subsequent secondary compression was large. It is known that for Type III curves the Terzaghi consolidation equation does not adequately describe the rate of pore water pressure dissipation. The results of eighteen time settlement measurements were used to evaluate c_v for the phosphogypsum samples. The log time method proposed by Casagrande (1938) was found to be inappropriate since the rate of displacement did not reduce with increasing time thereby making it impossible to identify the end of the primary consolidation phase. The square root of time method proposed by Taylor (1948) was then used. Plots of sample deformation

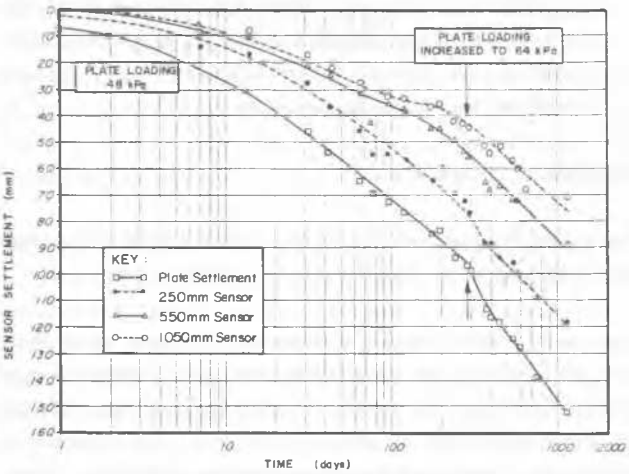

Figure 6: Typical laboratory time-settlement plot

versus square root of time were prepared. Analysis of these plots was difficult since a straight line portion of the curve was not obtained in the early stages of consolidation. A typical plot is presented in Figure 6 and shows very large initial displacements followed by a conventional decay curve. It is probable that primary consolidation of phosphogypsum is not only controlled by dissipation of excess pore water pressures but also includes short term elasto-plastic deformation of the crystals themselves.

Analysis made using secants from the start of the consolidation curve show c_v ranging between 30 to 200 m^2/year. Using tangents over the linear range of the curves yields values from 1 to 3 m^2/year. These may be compared with values of c_v of 1000m^2/year obtained by Blight (1969) for acid phosphogypsum and greater than $6.10^5 m^2$/year obtained by Morasky et al (1980).

Compression indexes were calculated from the consolidometer loading curves. In common with normally consolidated clays these show peak values of C_c near the "critical" pressure (Mesri and Godlewski 1977). Typical plots of C_c versus effective applied pressure are presented in Figure 7. Maximum values of C_c from the tests vary from 0,7 to 1,4. It was expected that C_c would increase for the longer load durations. This trend was not always evident and the variations are probably due to differences in initial density and void ratio of the test samples.

Secondary compression parameters were calculated from both the laboratory consolidation tests and the field plate tests. The secondary compression index ($C\alpha = \Delta e / \Delta \log t$) and secondary compression ratio ($S\alpha = [\Delta s/So]/\Delta \log t$) were computed from the results as applicable.

Laboratory tests on clays reported by Mesri & Godlewski (1977) show that $C\alpha$ is not constant for a given material but reaches a peak at the critical pressure. A similar trend was observed for the laboratory tests results on phosphogypsum. $C\alpha$ values of 0,07 were recorded at a consolidating pressure of 25kPa increasing to a maximum of between 0,18 and 0,22 at an effective pressure of 400kPa. These peak values correspond to secondary compression ratios of 0,07 to 0,14.

Secondary compression ratios were calculated for the plate loading tests. The ratios were similar for the plates founded on the compacted and uncompacted phospho-

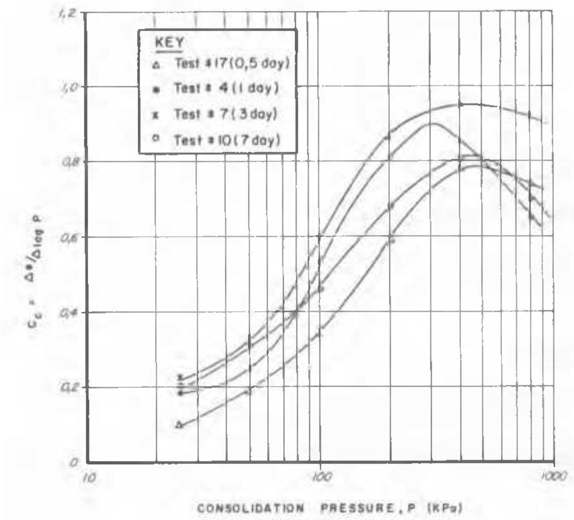

Figure 7: C_c vs Consolidation pressure

gypsum and values of Sα ranging from 0,06 to 0,07 were obtained for the 48kPa loading. The ratio increased for the second load increment to 0,08 and 0,12 for the plates loaded to 64 and 96kPa respectively. These values are similar to those obtained from the laboratory consolidation tests. A plot of secondary compression ratios computed for the laboratory and field tests against consolidation pressure is shown in Figure 8. Mesri and Godlewski (1977) have shown that the ratio $C\alpha/C_c$

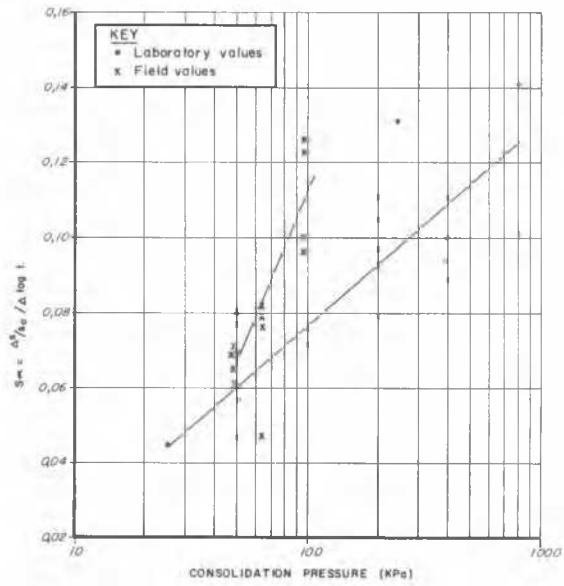

Figure 8: Secondary Compression ratios vs consolidation pressure

is approximately constant for most normally consolidated clays and peats. Analyses of many test results showed the ratio to lie within a range of 0,025 to 0,10 with the higher values corresponding to organic soils. The ratio did not exceed 0,1 for all of the natural soils considered. The results of the laboratory tests show the ratio to vary within the range 0,15 to 0,20 for neutralized phosphogypsum. This result reflects the great importance of secondary compression in the consolidation of phosphogypsum.

Electron micrographs were made of phosphogypsum samples at the end of the long duration load tests in the laboratory. A typical micrograph is presented in Figure 9. It is of interest to note the presence of much additional fine phosphogypsum. The origin of this material is uncertain but probably results from partial breakage of crystals and secondary crystallisation.

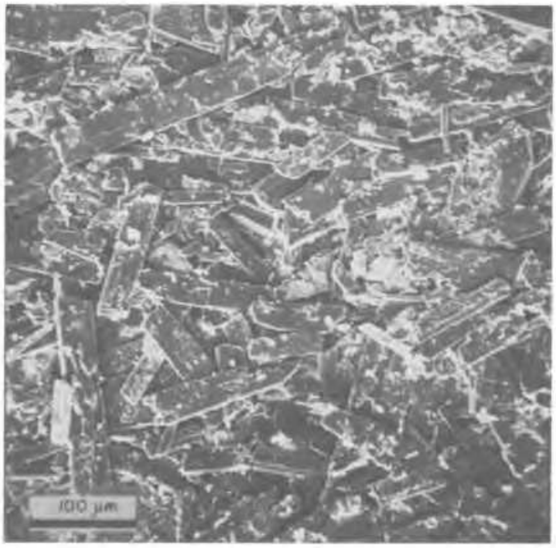

Figure 9: Photomicrograph of phosphogypsum after laboratory consolidation

CONCLUSIONS

The tests show that the neutralized phosphogypsum is highly compressible and displays appreciable secondary compression. The mechanism of secondary compression in the material is not understood but is probably greatly influenced by creep of the long calcium sulphate crystals. The angularity of the crystals also probably results in high inter-crystal contact stresses.

The tests results have been used to derive consolidation models of the neutralized phosphogypsum at the impoundment. These models are of the form both of a family of void ratio pressure curves as proposed by Bjerrum (1967) and of a rheological model based on the theory presented by Gibson and Lo (1961).

REFERENCES

Bjerrum L (1967) "Engineering Geology of Normally Consolidated Marine Clays as Related to Settlement of Buildings" Geotechnique, Vol 17 pp 2 - 36.

Blight, G E (1969) "Waste Gypsum as an Embankment Material", Proc. 7th Int Conf SM & FI, Mexico pp 39 - 43.

Casagrande A (1938) "Notes of Soil Mechanics" Harvard University (unpublished).

Gibson & Lo (1961) "A Theory of Consolidation for Soils Exhibiting Secondary Compression". Norges Geoteckniske Institutt, Publication no 41.

Leonards G A & Girault P (1961) "A Study of the One Dimensional Consolidation Test" Proc. 5th Int. Conf SM and FE Vol 1 pp 213 - 218.

Morrasky T, Ingra T, Larrimore L, Garlanger J (1980) "Evaluation of Gyspum Waste Disposal by Stacking" Proc. Symp on Flue Gas Desulfurization, Houston, Energy/Environment Agencies Report.

Mesri G and Godlewski P (1977) "Time and Stress Compressibility Interrelationship" Journal of the Soil Mechanics & Foundations Division, ASCE Vol 103, No GT5 pp 417 - 430.

Smith A and Wrench B (1984) "Aspects of Environmental Control of Phosphogypsum Waste Disposal" 8th Regional Conf. for Africa, Int. Soc SM & FE, Harare 1984.

Taylor (1948) "Fundamentals of Soil Mechanics" Wiley, New York.

Vick S (1977) "Rehabilitation of a gypsum tailings embankment", Solid Waste Materials 1977 pp 697 - 714.

Wissa A and Fuleihan (1980) "Control of Groundwater Contamination from Phosphogypsum Disposal Sites" Proc. Int Symp on Phosphogypsum, Floride Inst of Phosphate Research 1980 pp 482 - 539.