WASTE GYPSUM AS AN EMBANKMENT MATERIAL

GYPSE DE REBUT COMME REMBLAYAGE

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SYNOPSIS Phosphoric acid plants produce large tonnages of waste gypsum that are disposed of by forming dumps and hydraulic fill dams. To ensure the stability of the waste heaps, a knowledge of the mechanical properties of gypsum is required. An investigation of these properties is described and data are given on the permeability, consolidation and shear strength characteristics of waste gypsum.

INTRODUCTION

Phosphoric acid is an important ingredient in the manufacture of chemical fertilizer. In the <u>wet</u> process of phosphoric acid manufacture, apatite rock is reacted with sulphuric acid to produce a slurry of phosphoric acid and gypsum. After filtering off the phosphoric acid, the wet gypsum is left as a waste product requiring disposal. Disposal involves the handling and transporting of large volumes of material, as a typical phosphoric acid plant produces 30,000 to 40,000 tons of wet gypsum per month.

In South Africa, gypsum is being disposed of by dry dumping or by forming enclosed hydraulic fill dams similar to those used for the disposal of gold mine tailings.*

The pore fluid of the gypsum is highly poisonous as it contains up to 3000 p.p.m. of fluorine. To minimize pollution of the groundwater, each dump or dam is entirely contained within a pond or basin lined with impervious material such as plastic sheeting or rolled fat clay.

One of the dry gypsum dumps has been planned for an eventual height of 46 metres at a slope of 44°, while one of the dams is planned for a similar height and will eventually contain some 7.5 million tons of gypsum.

These dumps and dams pose an important and formidable stability problem as they are constructed of a material with largely unknown mechanical properties. A slide in the slopes of a dump or a breach in the wall of a dam could spill poisonous material outside the bounds of the impervious lined area and result in dangerous pollution.

The object of this paper is to describe some of the physical and mechanical properties of gypsum when used as an embankment material. The gypsum has been tested, as if it were a soil and, as far as possible, standard laboratory and <u>in situ</u> testing procedures have been used. Unless otherwise stated, all tests were performed on undisturbed specimens of gypsum taken from a gypsum dump by means of 76 mm. diameter thin-walled open-drive sample tubes.

PRECAUTIONS TAKEN IN THE TESTING OF WASTE GYPSUM

The pore fluid of a gypsum dump or dam consists of a dilute aqueous solution of phosphoric, sulphuric and hydrofluoric acids and various salts. In addition, gypsum is itself sparingly soluble in water. It is possible that any dilution of the pore fluid (e.g. by mixing with distilled water) may alter the physical properties of the gypsum.

Also, if a triaxial cell containing a gypsum specimen is filled with distilled or tap water, an osmotic gradient will develop across the latex membrane between the gypsum and the cell water. This may influence the behaviour of the specimen.

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* Donaldson (1965) describes the construction of gold mine tailings dams.

Osmotic effects due to differences in dissolved air content are known to affect triaxial strength and volume change measurements on unsaturated soils (Blight, 1967).

To prevent errors due to this cause, pore fluid was collected from a well in a gypsum dump and this fluid was used in all tests involving the mixing of gypsum. Triaxial cells and associated pressure tubes were filled with the fluid, as were the water reservoirs of shear boxes and oedometers.

PARTICLE SIZE AND PLASTICITY

The gypsum formed during phosphoric acid production consists of needle-like monoclinic crystals, the crystal size being carefully controlled to give suitable filtering rates. A wet sieve analysis gives the following particle size distribution:

Sieve No.:	% By weight passing :
100	98 to 100
200	75 to 85
400	50 to 60

The material therefore consists mainly of silt-size particles.

The gypsum is non-plastic by the standard Atterberg tests.

EFFECTIVE STRESS BEHAVIOUR

The mechanical behaviour of soils is governed by the principle of effective stress according to which changes in the shear strength and volume of a soil are a function of the difference between the total stress σ and the pore pressure u . The effective stress for a saturated soil may be written, for all practical purposes as :

$$\bar{\sigma} = \sigma - u \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (1)$$

Before conventional soil mechanics tests on gypsum can be interpreted and before the stability of gypsum slopes can be analysed, it must be established whether or not the engineering properties of gypsum are controlled by the principle of effective stress.

Figure 1A compares measurements of volumetric strain made on two identical specimens of gypsum consolidating under isotropic stress in triaxial cells. One specimen was consolidated to zero (gauge) pore pressure, while the other was consolidated to a pore pressure of 3.51 kg/cm^2. The difference between the cell pressure and the pore pressure was the same in each case. It is clear from Figure 1A that, allowing for experimental error, the volume change of the two specimens was controlled by the stress difference ($\sigma - u$).

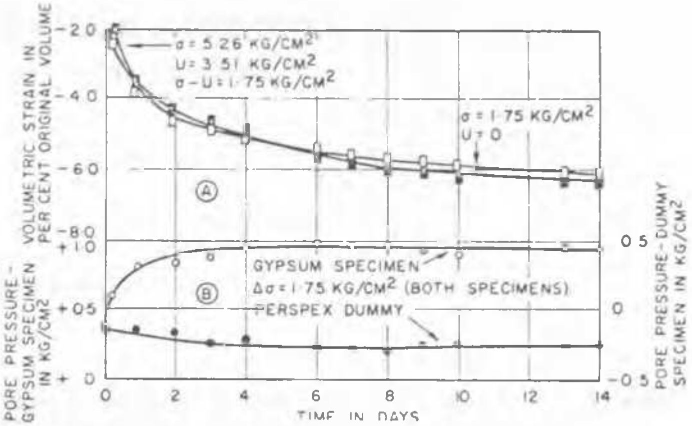

Figure 1 (a) Long-term consolidation of two gypsum specimens

(b) Pore pressure changes under undrained conditions

It will be seen later (Figure 3) that the volume change shown in Figure 1A consists of secondary consolidation which is probably caused by readjustment of the gypsum crystals under load. A similar phenomenon affects pore pressures under undrained conditions. Changes in pore pressure in a gypsum specimen loaded under undrained conditions are shown in Figure 1B. For comparison, similar changes, measured on a perspex dummy specimen of the same dimensions, and set up in the same way, have been superimposed on Figure 1B. The latter data show that the pore pressure and volume changes measured in the gypsum specimens were real changes and were not due merely to membrane leakage.

Figure 1 also shows that the secondary changes in volume and pore pressure appear to terminate and do not run counter to the effective stress principle.

Figure 2 compares drained triaxial compression tests, with a time to failure of 8 hours, on a pair of gypsum specimens. In specimen (a) the pore water pressure u was maintained at zero (gauge). In specimen (b) a pore pressure of 7.04 kg/cm^2 was maintained. The effective confining stress (σ_3 - u) was in each case equal to 3.52 kg/cm^2. There was very little difference in the stress strain curves for the two specimens although the specimen with zero pore pressure failed on a series of visible planes, while that with a raised pore pressure failed by bulging. The volume change curves showed little difference until the specimens started to dilate. The specimen with a raised pore pressure dilated more, and the rate of dilation showed little sign of decreasing with increasing axial strain. It is thought that cavitation, due to negative pressure in the drainage system of the specimen with nominally zero pore pressure, was responsible for the measured differences in dilation of the two specimens. Unrelieved negative pore pressures may also account for part of the strength difference of the specimens. It may be concluded from the data of Figure 1 and 2 that, for all practical purposes, changes of the strength and volume of gypsum are controlled by the principle of effective stress.

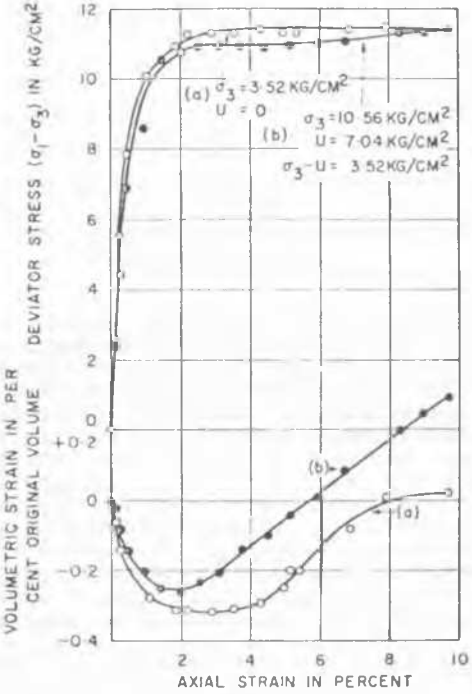

Figure 2 Behaviour of gypsum in drained triaxial compression

CONSOLIDATION CHARACTERISTICS

Figure 3 shows a set of time-consolidation curves for gypsum specimens consolidating under isotropic stress in triaxial cells. The specimens were 38 mm. in diameter, 76 mm. long, and were consolidating with single-end drainage. The increment in effective stress for each specimen has been shown on Figure 3, in which a square-root time scale has been used.

There is no initial linear portion of the time-consolidation curve and, within the time-span of Figure 3, a horizontal asymptote is not approached. Figure 1A shows that volume change in this size of specimen does not terminate until about 14 days after the application of a stress change.

The coefficient of consolidation of the gypsum, c_v, was calculated as follows: A chord was drawn to the initial steep portion of the consolidation curve. A tangent to the later part of the curve was extrapolated to intersect the chord. The point of intersection was taken as t_{100} in the equation :

$$c_v = \frac{\pi \quad h^2}{t_{100}} \quad \ldots \quad \ldots \quad \ldots \qquad (2)$$

(Bishop and Henkel, 1962. h = 38 mm.)

On this basis, the average coefficient of consolidation of gypsum is c_v = 0.3 cm²/sec. Constant head permeability tests show a permeability coefficient k = 2 x 10^{-5} cm/sec ($^{c}v/_{k}$ = 1.5 x 10^4 cm). Measurements on gold mine tailings, a ground quartzite with a similar particle size distribution, show a coefficient of consolidation c_v = 0.1 cm²/sec and a permeability coefficient k = 1 x 10^{-5} cm/sec ($^{c}v/_{k}$ = 1 x 10^4cm). Gold mine tailings have no secondary consolidation characteristics. Since the ratio $^{c}v/k$ is similar for the two materials, the ^{c}v - values obtained for gypsum are probably representative of the primary consolidation of the material.

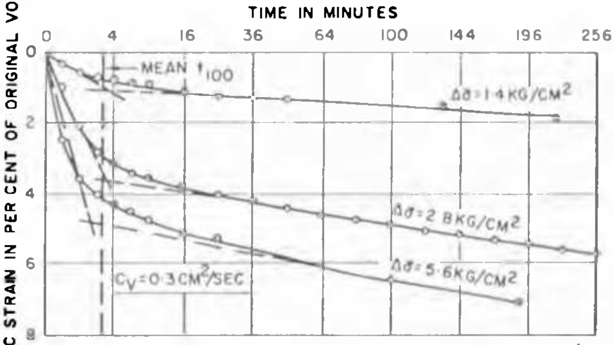

Figure 3 Time-consolidation curves for gypsum

Figure 4 shows oedometer test curves relating consolidated density and water content to consolidating stress. The loading period for each stress increment was 3 days. According to Figure 1A, the curves of Figure 4 represent about 80 per cent of full consolidation. The consolidation curves for gypsum are similar in shape to those for gold mine tailings (see Donaldson, 1965). The only notable feature is the very high water content (relative to oven dryness) that the gypsum retains.

STRENGTH CHARACTERISTICS IN LABORATORY TESTS.

Typical axial stress/axial strain and volumetric strain/axial strain curves for the drained triaxial compression of gypsum are shown in Figure 2. Figure 5 summarizes failure stresses measured in a number of laboratory shear tests.

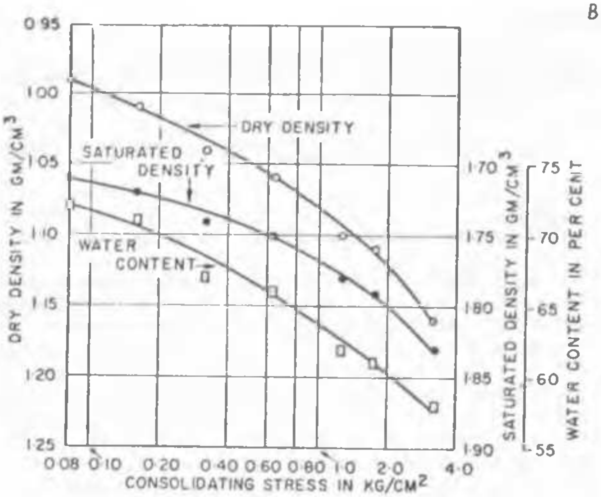

Figure 4 Stress-consolidation curves for gypsum

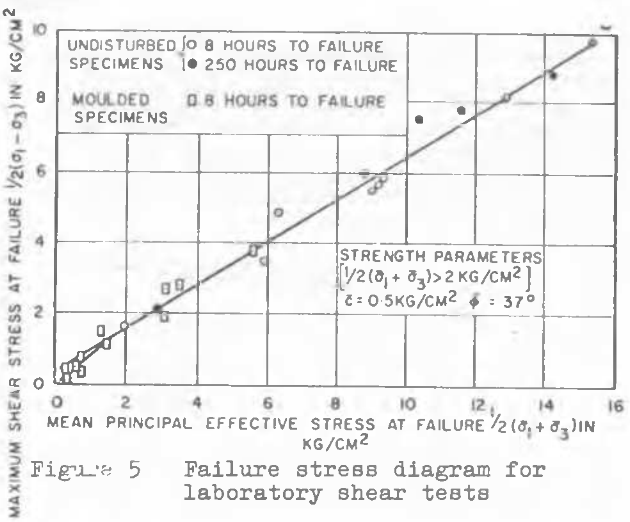

Figure 5 Failure stress diagram for laboratory shear tests

Drained triaxial compression tests on undisturbed specimens were carried out in two series. In the first series, specimens were consolidated for 2 days and failed in 8 hours. In the second series a 2-day consolidation period was followed by failure in 250 hours. (10½ days). Failure stresses did not appear to be affected by the difference in time to failure. The strength envelope for tests on undisturbed specimens may be described by the equation :

$$\tau_f = (0.5 + \bar{\sigma} \tan 37^\circ)\ \text{kg/cm}^2 \quad .. \quad (3)$$

In addition to the triaxial tests, a series of shear box tests was carried out on specimens moulded at a water content of 75 per cent. Failure stresses in the shear box tests agreed with failure stresses for the triaxial tests. The failure line for tests at low consolidation stresses appears to curve down to give a cohesion intercept of zero.

STRENGTH CHARACTERISTICS IN IN SITU TESTS

The results of a number of in situ vane shear tests made in a gypsum dump are shown in Figure 6. At the time of the tests, the dump was 5 metres in height, and to avoid puncturing the plastic lining on which the gypsum rests, the maximum depth of the vane tests was limited to 4½ metres. The technique used in the vane tests was similar to that described by Blight (1967), and the time to failure was adjusted so that the fully drained shear strength was measured (Blight 1968).

The gypsum had been placed "dry" at a water content of 65 to 70 per cent. After spreading in layers ½ metre thick, the gypsum was compacted by crawler tractor and truck traffic. The water table in the dump was at a depth of 2.1 metres.

Figure 6 shows that compacted gypsum is a material of high undisturbed strength with a moderate sensitivity (sensitivity ratio 3 to 6). The strength profile predicted from the results of laboratory shear tests almost coincides with the profile of minimum remoulded strength. This strength profile was calculated on the assumption that the effective stress on the failure surface was equal to the effective overburden stress. Although the laboratory shear tests were carried out on carefully sampled and prepared 'undisturbed' specimens, laboratory strengths do not appear to be closely related to in situ undisturbed strengths. This discrepancy was at first thought to be due to the combined effect of large horizontal stresses in the compacted gypsum and the unfavourable proportions of the standard vane. The standard vane, with a height equal to twice its diameter, gives a weighting of 86 per cent to the shear strength on vertical planes in a soil and only 14 per cent to that on horizontal planes. If horizontal stresses in a fill differ appreciably from vertical stresses, strength measurements made with a standard vane cannot agree with strength predictions from laboratory tests. Subsequent tests using vanes of various shapes, have shown, however, that the strength of gypsum in situ is isotropic. Tests have also shown that the strength of gypsum is highly sensitive to over consolidation. Gypsum with an over consolidation ratio of 15 is 1.5 times stronger than the normally consolidated material. It is probable that the high in situ strengths are indicative of over consolidation by compaction.

Figure 7 shows in situ vane strength measurements made in gypsum that was end-tipped in lifts of approximately 3 metres. The only compaction applied to the gypsum

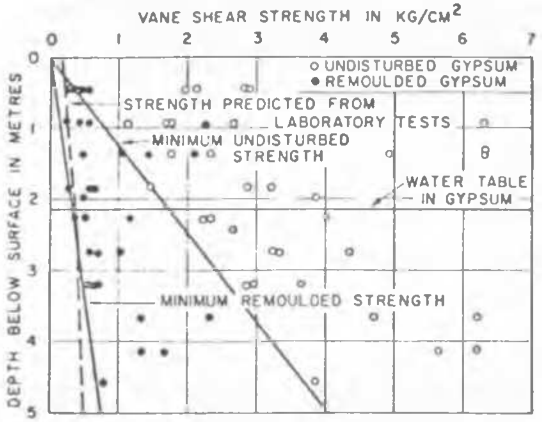

Figure 6 In situ vane shear tests on compacted gypsum

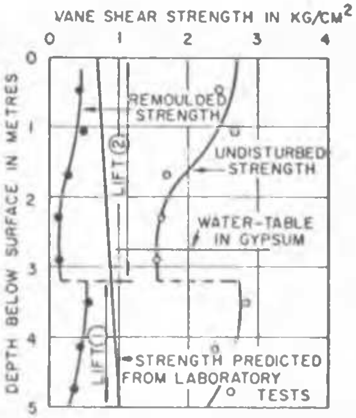

Figure 7 In situ vane shear tests on gypsum end-tipped in 3 metre lifts

was one or two passes of a crawler tractor with a track pressure of 0.45 kg/cm^2. The influence of the compaction is clearly visible in the strength profile. Even with this minimal compaction, undisturbed in situ vane strengths are far larger than predicted strengths.

DESIGN OF GYPSUM SLOPES

The slopes of the gypsum dump mentioned in the introduction were designed by the conventional slip circle method. Because of the discrepancy between strengths measured in the field and in the laboratory, the design was based on the laboratory strength parameters. On this basis a dump 46 metres high, with slopes of 44° has a calculated factor of safety of 1.35. The dump has been instrumented with standpipe piezometers that are being extended as the height of gypsum increases. Additional strength measurements will be made from time to time.

The final design of the slopes for the hydraulic fill gypsum dam has been deferred until a sufficient depth of gypsum has accumulated to enable in situ strength measurements to be made. An initial slope angle of 30° is being used.

CONCLUDING SUMMARY

(a) Waste gypsum from phosphoric acid plants is non-plastic and consists of silt-size crystals.

(b) The strength and volume change behaviour of gypsum appears to conform to the principle of effective stress, although a large proportion of the consolidation volume change has a secondary nature.

(c) The coefficients of consolidation and permeability of gypsum are given by :

$$c_v = 0.3 \text{ cm}^2/\text{sec}$$

$$k = 2 \times 10^{-5} \text{ cm/sec}$$

(d) Laboratory tests on undisturbed specimens of compacted gypsum lead to the following strength equation :

$$\tau_f = (0.5 + \bar{\sigma} \tan 37^\circ) \text{ kg/cm}^2$$

(e) In situ drained vane shear tests show that compacted gypsum is a material of high undisturbed strength, having a sensitivity ratio of 3 to 6.

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