Proceedings Tailings and Mine Waste 2011
Vancouver, BC, November 6 to 9, 2011

Settlement and Strength of Clay-Rich Coal Mine Spoil

David Williams

School of Civil Engineering, The University of Queensland, Brisbane, Australia

Adrian Kho

Cardno and School of Civil Engineering, The University of Queensland, Brisbane, Australia

Andrew Daley

School of Civil Engineering, The University of Queensland, Brisbane, Australia

Abstract

The settlement of clay-rich surface coal mine spoil has three components: (i) self-weight, (ii) "collapse" on wetting up, and (iii) weathering-induced settlements. Of the self-weight settlement of initially dry spoil, about 80% occurs during placement (and is "not seen"). The remaining 20% will amount to 3% or more of the height of loose-placed spoil, at a rate decreasing exponentially with time. "Collapse" settlement of spoil on wetting up is due to "corrosion cracking" at highly-stressed particle contacts. It can amount to 10% or more of the height of loosely-placed spoil. Further saturation of the spoil will fill the voids without inducing significant further collapse. Weathering-induced spoil settlement occurs over a variable timeframe depending on the durability of the spoil. It could amount to 10% or more of the height of loosely-placed spoil. The total post-placement settlement of clay-rich spoil could amount to 20 to 30% of the loose height (20 to 30 m/100 m of height). Settlement of clay-rich spoil affects its strength and compressibility under loading, and its hydraulic conductivity. Laboratory tests carried out on as-sampled and flooded scalped clay-rich spoil from Jeebropilly Coal Mine in South East Queensland, Australia, have included material characterisation and geotechnical parameter testing. The results shed some light on the settlement and strength behaviour of these materials.

Introduction

The clay-rich coal mine spoil material tested was sourced from Jeebropilly Coal Mine in South East Queensland, Australia. Jeebropilly Mine is an open pit thermal coal mine in the Jurassic age Walloon Coal Measures of the Clarence-Moreton Basin near Ipswich. The mine is owned and operated by New Hope Corporation Australia (http://www.newhopecoal.com.au/home.aspx). The mine ceased operations after 25 years of extraction in February 2007. However, the coal-washing plant at Jeebropilly continued to operate, so that coal from the nearby New Oakleigh Mine could be processed. Jeebropilly Mine was recommissioned in 2008 due to high export prices for coal. In addition to mining coal, Jeebropilly Mine has also been mined for Ca-Bentonite (Harvey & Keeling, 2002), comprising primarily montmorillonite, with trace amounts of dolomite and kaolin (Parker & Frost, 1996).

The Walloon Coal Measures occur over an interval of around 120 m comprising 43 individual seams, with an average thickness of between 0.06 m and 0.48 m, and partings of up to 2.7 m thickness. The mining method used is a multi-thin-seam operation utilising trucks, excavators and front-end loaders. Overburden is blasted or ripped by bulldozers prior to excavation.

Figure 1 shows the sequence of overburden and coal in the Jeebropilly open pit at the time of overburden sampling. The testing described in this paper was carried out on Overburden-2 material in Figure 1, which may be described as a weathered clayrock.

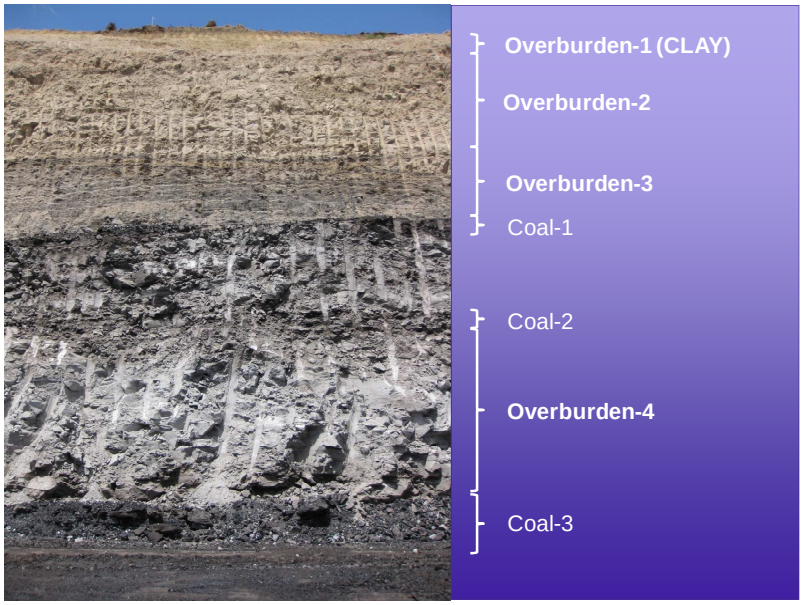


Figure 1: Sequence of overburden and coal in Jeebropilly open pit at time of sampling

Characterisation Testing Methodologies

The characterisation testing carried out on Overburden-2 material included particle size distribution analyses, specific gravity testing, gravimetric moisture content determination, Atterberg limit testing, total suction determination, electrical conductivity testing, pH testing, and Emerson crumb testing, carried out in accordance with AS 1289 where applicable.

Sampling of Overburden-2 Material

A -19 mm scalped sample of Overburden-2 material was taken from a paddock-dumped stockpile at Jeebropilly Mine, by passing the material through a 19 mm sieve into 20 l buckets. Both the material passing 19 mm and the over-size material were weighed, and photographs were taken of the all-in and +19 mm materials for subsequent estimation of their particle size distributions using the commercial software SplitDesktop (http://www.spliteng.com/split-desktop/).

Particle Size Distribution Analyses

Sieving analyses were carried out on -19 mm dry scalped samples of Overburden-2 material by: (i) dry sieving following air-drying, (ii) dry sieving following oven-drying at 60°C (rather than the conventional 105°C, to ensure no combustion of any carbonaceous material), (iii) wash sieving without dispersant, and (iv) wash sieving with dispersant.

Specific Gravity, Gravimetric Moisture Content, and Atterberg Limit Testing

Specific gravity testing was carried out on -19 mm and -2.36 mm dry scalped samples of Overburden-2 material, using a helium pycnometer to ensure acceptable penetration of fine pores. Gravimetric moisture content determinations were made on six replicate samples of -19 mm dry scalped Overburden-2 material. All gravimetric moisture content testing involved oven-drying at 60°C. The gravimetric moisture content is given by the mass of water / mass of dry solids, expressed as a percentage. Atterberg limit testing was carried out on remoulded samples of -0.425 mm dry scalped Overburden-2 material.

Total Suction, Electrical Conductivity, pH, and Emerson Crumb Testing

As-sampled total suction testing was carried out using a WP4 Dewpoint Potential Meter, which allowed samples up to 30 mm in diameter by less than 10 mm high of Overburden-2 material to be tested. Electrical conductivity and pH testing was carried out on 5 (deionised water) : 1 (solids) by mass pastes, using a WP-81 EC and pH meter. Nine replicates were tested for total suction, electrical conductivity and pH. Emerson crumb testing was carried out on typically-sized particles of Overburden-2 material.

Geotechnical Parameter Testing Methodologies

The geotechnical parameter testing carried out on Overburden-2 material included Standard compaction testing, direct shear strength testing, consolidation testing, and weathering testing.

Standard Compaction Testing

Laboratory Standard compaction testing was carried out on -19 mm scalped samples of Overburden-2 material in a 104 mm diameter compaction mould, to obtain the Standard Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the material.

Direct Shear Strength Testing

Direct shear strength testing was carried out on -2.36 mm scalped Overburden-2 material in a 60 mm size direct shear box. Single-stage testing was carried out on loosely-placed specimens at the as-sampled moisture state, under initial normal stresses of 100 kPa, 250 kPa and 500 kPa, with subsequent shearing. Prior to shearing, the settlement of the specimens under the applied normal stresses was monitored for 24 hours. Separate specimens were sheared at rates of 0.01 mm/min, 0.1 mm/min and 1 mm/min. The shear strengths were found to be largely independent of the shearing rate, since the relatively coarse-grained specimens drained faster than the applied rate of shearing, and only the results for a shearing rate of 0.1 mm/min are reported herein. Shearing was taken to about 6 mm (about 10% shear strain).

To simulate the effect of wetting up of the material, single-stage direct shear strength tests were also carried out on loosely-placed specimens placed in a bath of tap water, under initial normal stresses of 50 kPa, 100 kPa and 150 kPa, with subsequent shearing. The applied normal stress was limited by the compression of the specimens exceeding the travel of the loading arm. Prior to shearing, the compression of the specimens under the applied normal stresses was monitored for 24 hours. The specimens were sheared at a rate of 0.1 mm/min. Shearing was taken to about 9 mm (15%).

Consolidation Testing

Consolidation testing was carried out in an oedometer on -2.36 mm scalped samples of Overburden-2, using a 75 mm diameter ring. Testing was carried out on loosely-placed specimens at the as-sampled moisture state, under 24-hour increments of normal stress of 20 kPa, 40 kPa, 80 kPa, 160 kPa, 320 kPa, 480 kPa and 960 kPa, plus a single-stage test under 500 kPa normal stress. Unloading was not tested as it was intended to simulate the construction of a spoil pile to a height of about 60 m. To simulate the effect of wetting up of the material, oedometer testing was also carried out on loosely-placed specimens placed in a bath, under 24-hour increments of normal stress at the same levels as were applied to specimens at the as-sampled moisture state.

Weathering Testing

A weathering test was carried out on -19 mm scalped Overbruden-2 material, which was loosely-placed to a nominal depth of about 50 mm in a 600 mm by 600 mm by 100 mm deep Perspex tray and exposed to the weather. Surface settlements were measured periodically at nine points over the surface area, and sub-samples of the spoil were taken periodically for air-drying and sieving.

Results of Characterisation Testing

The results of the characterisation testing carried out on Overburden-2 material are summarised in the following sections.

Particle Size Distributions

The particle size distribution curves obtained for the all-in Overburden-2 material using SplitDesktop, together with the curves for -19 mm scalped material obtained by dry sieving following air-drying, dry sieving following oven-drying at 60°C, wash sieving without dispersant, and wash sieving with dispersant, are shown in Figure 2. The -19 mm scalped sample comprises about 46% of the all-in material. Figure 2 reveals the dramatic effect of wash sieving in breaking down the material. The intrinsic particle size of the weathered rock is likely fines-dominated, although it would require further mechanical and chemical breakdown of the material to reveal this.

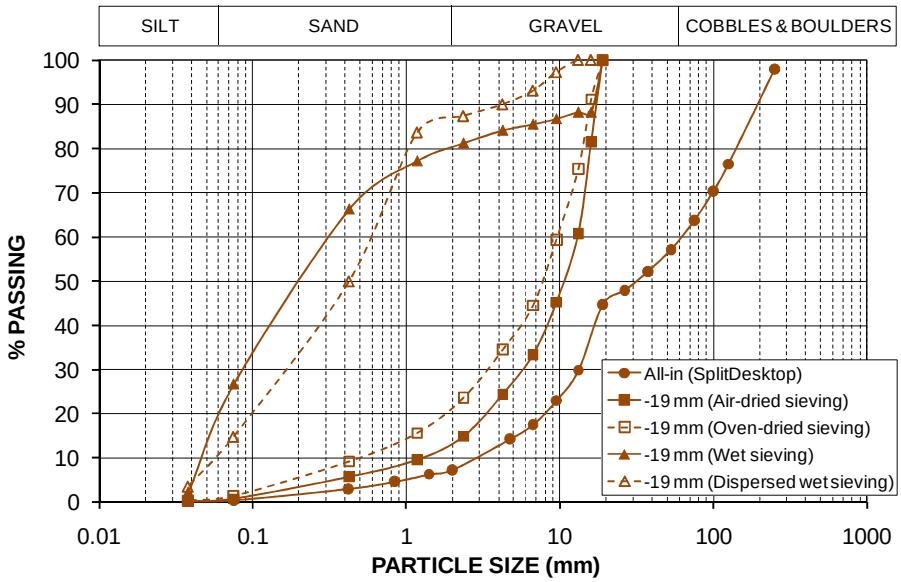


Figure 2: Particle size distributions of Overburden-2 material, as a function of pre-treatment

Specific Gravity, Gravimetric Moisture Content, and Atterberg Limits

The specific gravity of -19 mm and -2.36 mm scalped Overburden-2 material were 2.60 and 2.62, respectively. The average gravimetric moisture content of -19 mm scalped Overburden-2 material was 14.8%, the Liquid Limit was 71.0%, the Plastic Limit was 21.0% and the Plasticity Index was 50.0%. Hence, the all-in Overburden-2 material classifies under the Unified Classification System as Cobbly, Sandy GRAVEL (GW), with minor plastic fines. The -19 mm scalped sample classifies as Sandy Gravel (GW) and the -2.36 mm scalped sample classifies as a SAND (SW), both with minor plastic fines.

Total Suction, Electrical Conductivity, pH, and Emerson Class Number

The average as-sampled total suction of Overburden-2 material was 4320 kPa. The average electrical conductivity of Overburden-2 material made up to a 5 : 1 paste was 1672 µS/cm (allowing for dilution with deionised water to form the paste), and the average pH was 4.0. Based on the UDSA (1954), this electrical conductivity corresponds to an osmotic suction of about 50 kPa, implying an as-sampled matric suction of about 4270 kPa. The Overburden-2 material slaked in deionised water, and underwent some dispersion, implying an Emerson Class Number of 2.

Results of Geotechnical Parameter Testing

The results of the geotechnical parameter testing carried out on Overburden-2 material are summarised in the following sections.

Standard Compaction

The laboratory Standard compaction curve for -19 mm scalped Overburden-2 material is shown in Figure 3, from which a Maximum Dry Density (MMD) of 1.68 t/m^3 at an Optimum Moisture Content (OMC) of 13.5% (just dry of the as-sampled gravimetric moisture content) is obtained.

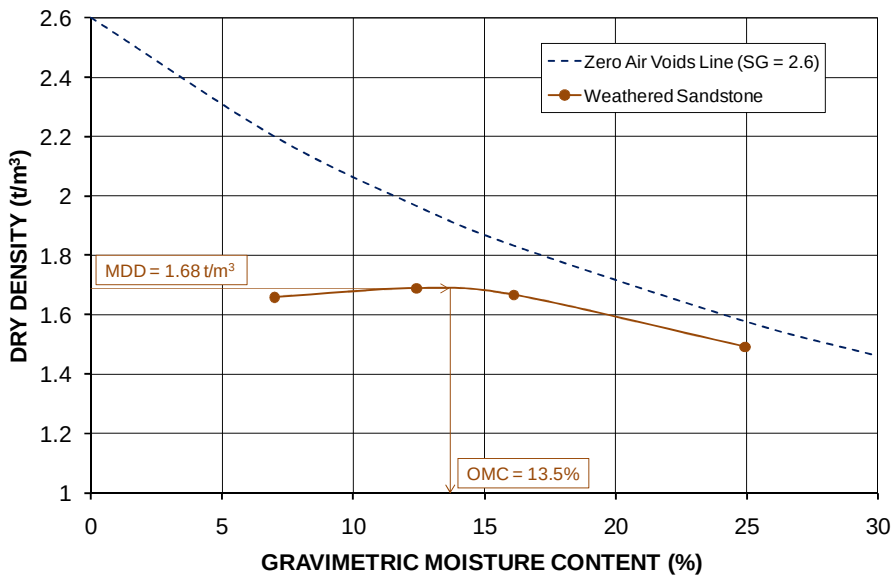


Figure 3: Standard compaction curve for -19 mm scalped Overburden-2 material

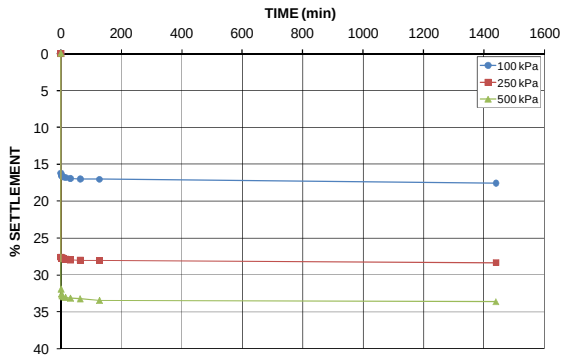
Direct Shear Strength

The results of the direct shear strength testing of loosely-placed -2.36 mm scalped Overburden-2 material, at its as-sampled moisture state and in a water bath, are shown in Figures 4 and 5, respectively. The plots shown for each case include (a) % settlement vs. time under each of the applied stresses, (b) shear stress vs. shear displacement, and (c) normal displacement vs. shear displacement. As can be seen from Figures 4(a) and 5(a), the specimens at the as-sampled moisture state settled rapidly (i.e. in a drained manner) under the applied stresses, while the specimens in a water bath settled somewhat more slowly and by a greater percentage, particularly at lower applied stress.

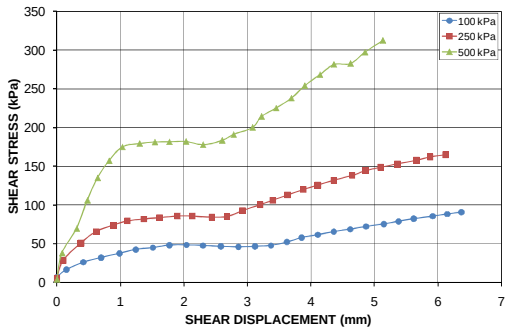
Figures 4(b) and 5(b) show that the shear stress vs. shear displacement behaviour for the two cases was reasonably similar at low shear displacement. However, there was a consistent step in the stress-strain behaviour of the specimens tested at the as-sampled moisture state, at about 3 mm shear displacement

(5% shear strain), corresponding to a consistent step in the normal displacement. The stress-strain behaviour up to about 5% shear strain was apparently dominated by the applied normal stress, accompanied by relatively little further settlement.

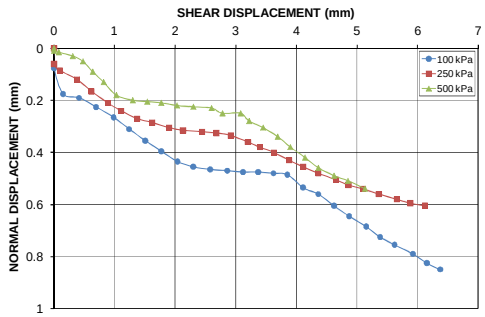
Beyond about 5% shear strain, there was a step-increase in settlement. This would cause a significant decrease in pore sizes, leading to increased matric suction and hence effective stress, and causing an increase in the measured shear stress required to further shear the specimens. This effect was not observed for the specimens in a water bath since they were essentially water-saturated, hence matric suction would have been close to zero.



(a)

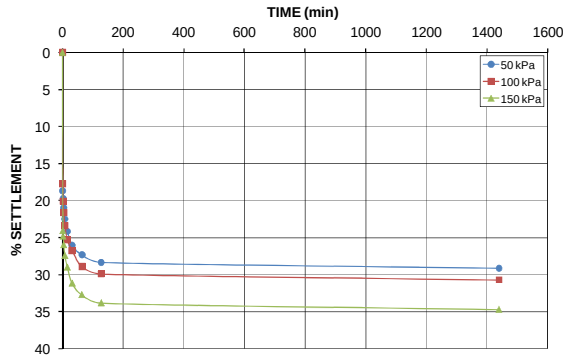


(b)

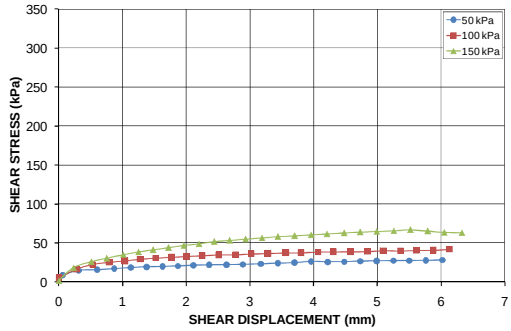


(c)

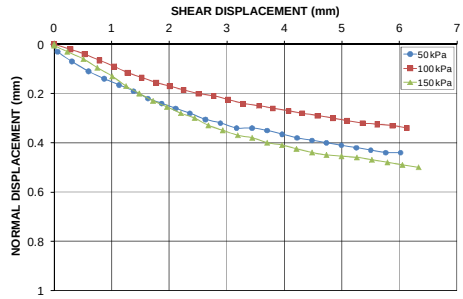
Figure 4: At as-sampled moisture state



(a)



(b)



(c)

Figure 5: In a water bath

Direct shear strengths of -2.36 mm scalped Overburden-2 material tested loose: (a) % Settlement under normal stress, (b) Shear stress vs. Shear displacement, and (c) Shear displacement vs. Normal displacement

Figure 6 compares the direct shear strength envelopes derived from the stress-strain plots in Figures 4(b) and 5(b). The plateaux in the plots for the specimens tested at the as-sampled moisture state and the peaks for the specimens tested in a water bath gave similar drained shear strength parameters, with an effective stress cohesion intercept of about 13 kPa and an effective stress friction angle of about 17.9^{o}. The final points of the plots for the specimens tested at the as-sampled moisture state gave an effective stress cohesion intercept of about 33 kPa and an effective stress friction angle of about 27.3^{o}.

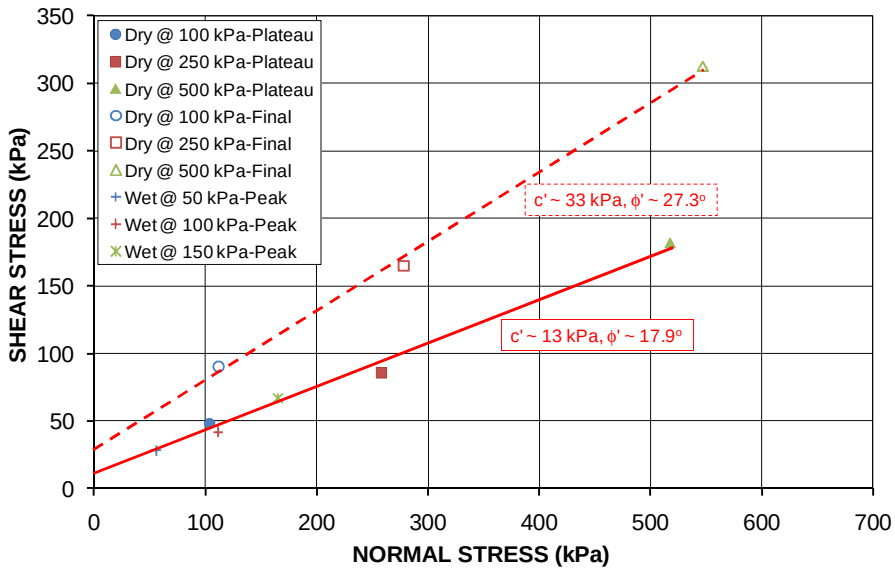


Figure 6: Comparison of direct shear strength envelopes

Tables 1 and 2 give the average dry densities, % of MDD, void ratios, and degrees of saturation, at the different stages of the tests carried out at the as-sampled moisture state and in a water bath, respectively. Saturation leads to a higher initial dry density and lower void ratio, higher loaded and final dry densities and lower loaded and final void ratios. Most of the settlement of the specimens tested at the as-sampled moisture state occurred during the initial application of the normal stress, and hence most of the increase in the degree of saturation occurred then. Similarly, most of the settlement of the specimens tested in a water bath occurred within 120 min of the application of the normal stress, and hence most of the decrease in the gravimetric moisture content occurred then, through drainage.

Table 1: Average parameters from direct shear strength tests on -2.36 mm scalped Overburden-2 material tested loose and at as-sampled moisture state

Parameter	Initial	Loaded	Plateau	Final
Average Dry Density (t/m^3)	0.859	1.176	1.194	1.214
% of MDD	51.1	70.0	71.0	72.3
Average Void Ratio	2.027	1.212	1.178	1.142
Average Degree of Saturation* (%)	19.0	31.8	32.7	33.7

* Assuming average gravimetric moisture content remains at initial 14.8%

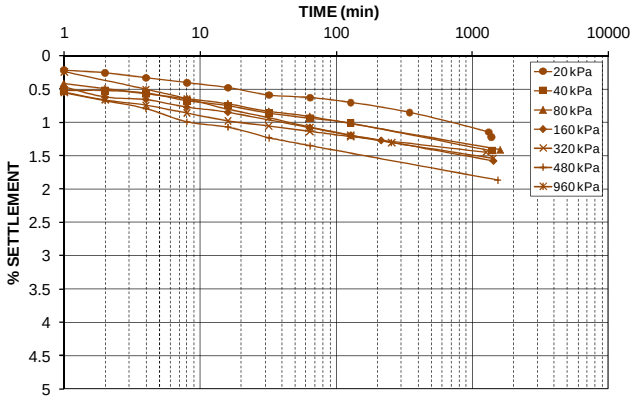
Table 2: Average parameters from direct shear strength tests on -2.36 mm scalped Overburden-2 material tested loose and in a water bath

Parameter	Initial	Loaded	Final
Average Dry Density (t/m^3)	0.914	1.337	1.364
% of MDD	54.4	79.6	81.2
Average Void Ratio	1.844	0.945	0.906
Average Gravimetric Moisture Content* (%)	70.9	36.3	34.8

* Assuming full saturation

Consolidation

The results of the individual stages of the consolidation testing of loosely-placed -2.36 mm scalped Overburden-2 material, at its as-sampled moisture state and in a water bath, are shown in Figures 7 and 8, respectively. The plots show that testing at the as-sampled moisture state resulted in about half the relative settlement compared with testing in a water bath, considered to be due to flooding-induced "collapse" settlement and weathering.



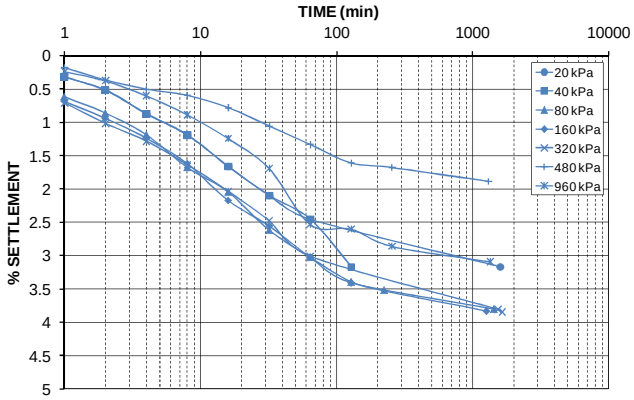


Figure 7: At as-sampled moisture state **Figure 8: In a water bath**

% Settlement vs. Time for -2.36 mm scalped Overburden-2 material tested loose

Figure 9 compares the single-stage, cumulative (to 480 kPa), and 500 kPa single-stage % Settlement vs. Time plots from testing loosely-placed -2.36 mm scalped Overburden-2 material at its as-sampled moisture state.

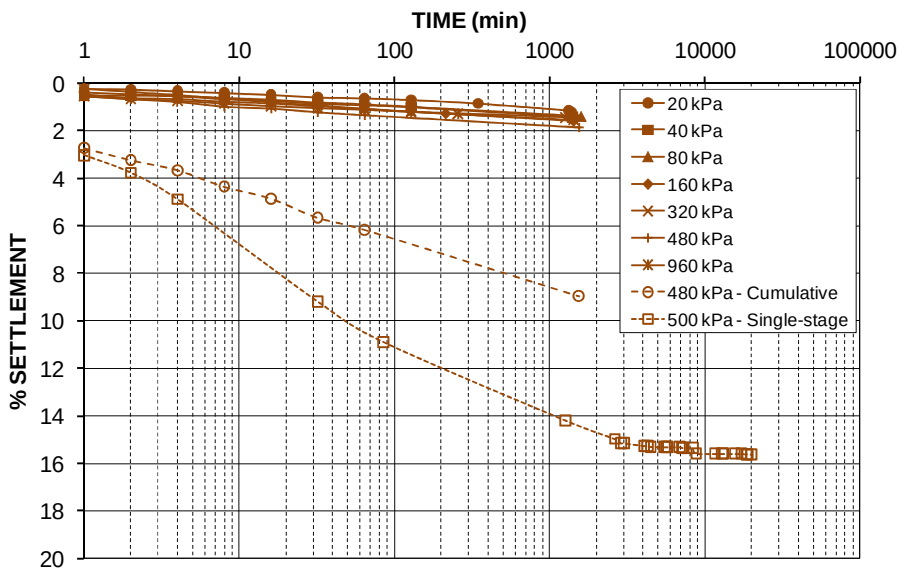


Figure 9: Comparison of single-stage and cumulative % Settlement vs. Time for -2.36 mm scalped Overburden-2 material tested loose and at as-sampled moisture state

From the 500 kPa single-stage test, the Coefficient of Consolidation c_v is calculated to be 0.94 m^2/yr. Accumulating the individual % settlements to 480 kPa indicates about 60% of the total % settlement obtained from the 500 kPa single-stage test, and hence about half the c_v value, at about 0.4 m^2/yr. Accumulating the individual % settlements is more representative of gradual field loading.

Figure 10 compares the single-stage 80 kPa applied stress test results at the as-sampled moisture state and in a water bath, with the cumulative (to 480 kPa) % Settlement vs. Time plots at the as-sampled moisture state and in a water bath, and with the single-stage 500 kPa test result. Accumulating the individual % settlements for the incremental applied stresses up to 480 kPa tested in a water bath indicates about twice the total % settlement as the 500 kPa single-stage test at the as-sampled moisture state, and hence about twice the c_v value, at about 2.0 m^2/yr.

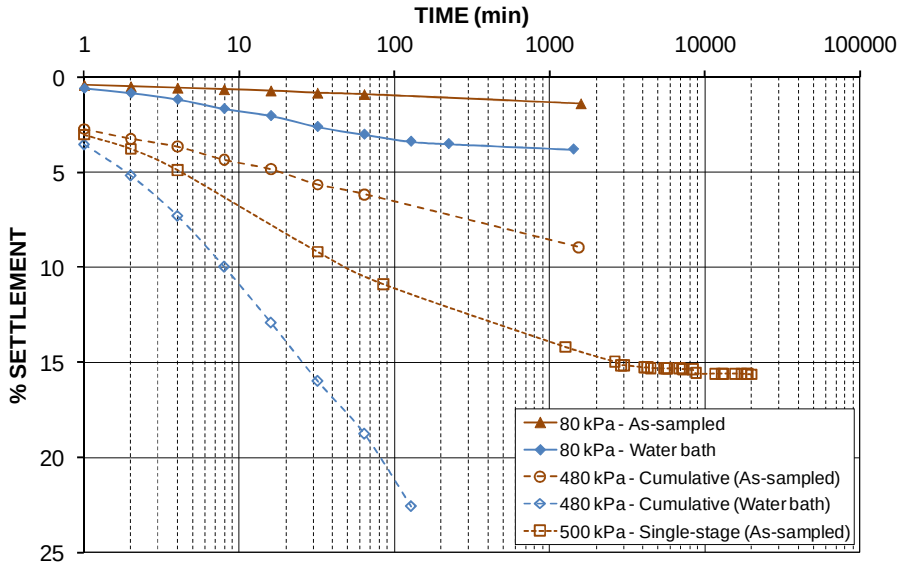


Figure 10: Comparison of 80 kPa single-stage and cumulative % Settlement vs. Time for -2.36 mm scalped Overburden-2 material tested loose and either at as-sampled moisture state or in a water bath

Figure 11 shows the consolidation plots for the tests carried out on loosely-placed -2.36 mm scalped Overburden-2 material tested either at its as-sampled moisture state or in a water bath. Also indicted in Figure 11 are the increase in dry density from 1.020 to 1.121 t/m^3 (from 61 to 67% of Maximum Dry Density) with increasing applied stress when tested at the as-sampled moisture content, increasing to 1.204 t/m^3 (72% of MDD) on flooding in a water bath, and increasing further to 1.469 t/m^3 (87% of MDD) on loading in a water bath.

The consolidation plots obtained on testing loosely-placed Overburden-2 material at the as-sampled moisture state and in a water bath are both essentially linear, representing normally consolidated conditions, as expected. The values of Compression Index C_c calculated for testing at the as-sampled moisture state and in a water bath are shown in Figure 11 as 0.115 and 0.167, respectively, confirming that the material tested in a water bath is almost twice as compressible as the material tested at its as-sampled moisture state.

Weathering

Loosely-placed -19 mm scalped Overburden-2 material was exposed to the weather for a period of 35 days, during which 112.6 mm of rainfall fell on 20 of the 35 days (ranging from 0.2 to 19.4 mm/day, with an average of 5.6 mm/day, and an average of 3.2 mm/day for the whole 35 days). Figure 12 shows the daily and cumulative rainfalls with time.

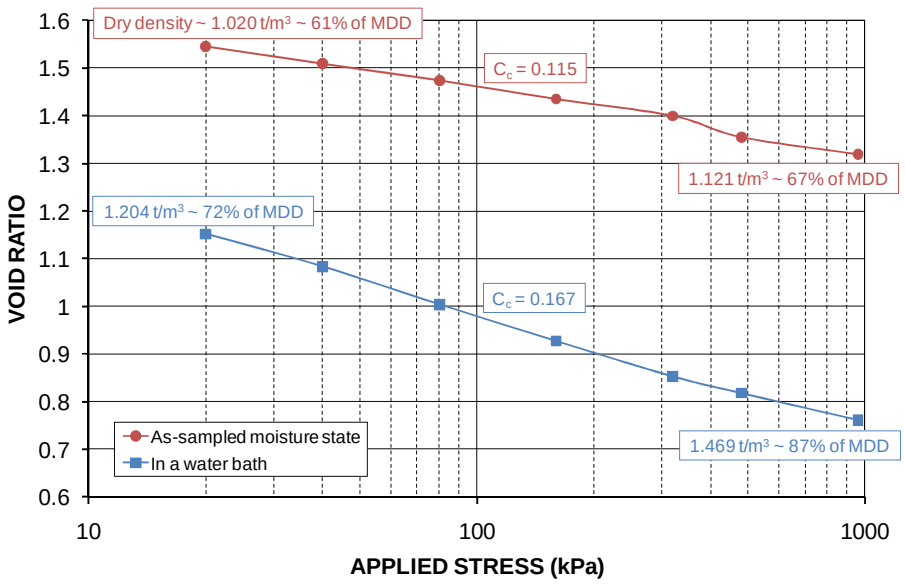


Figure 11: Comparison of Void ratio vs. Applied stress for -2.36 mm scalped Overburden-2 material tested loose and either at as-sampled moisture state or in a water bath

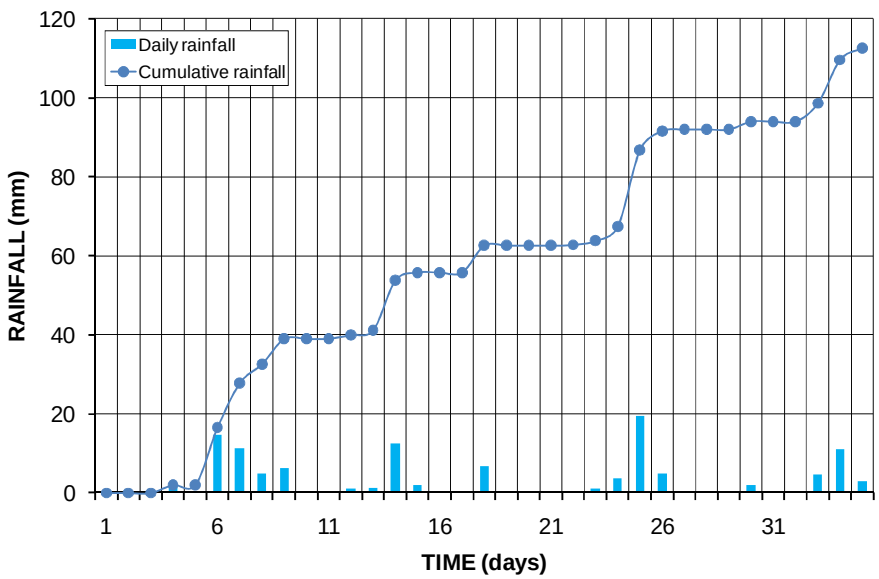


Figure 12: Daily and cumulative rainfalls during weathering test on exposed -19 mm scalped Overburden-2 material

Figure 13 shows the variation in particle size distribution on weathering over time of the exposed -19 mm scalped Overburden-2 material. Figure 14 shows photographs of the test material over time, indicating its rapid transition from a granular surface texture, through a slaked surface texture, to a desiccated surface. Figure 15 shows that the median particle size D_{50} generally decreases with cumulative rainfall, although there is some reversal, considered to be due to re-agglomeration on wetting and drying cycles. Figure 16 shows the substantial % settlement of up to 25% that the spoil undergoes on weathering, with some reversal apparent on re-agglomeration.

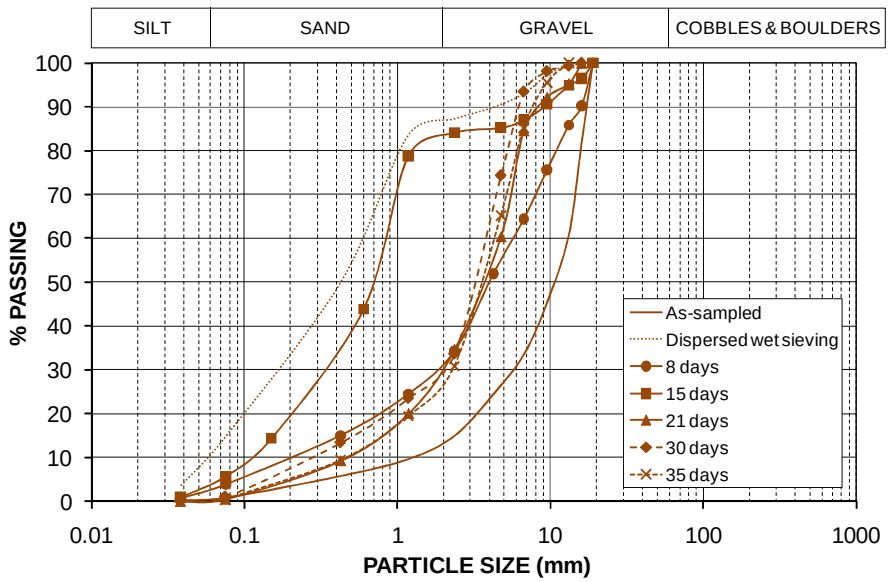
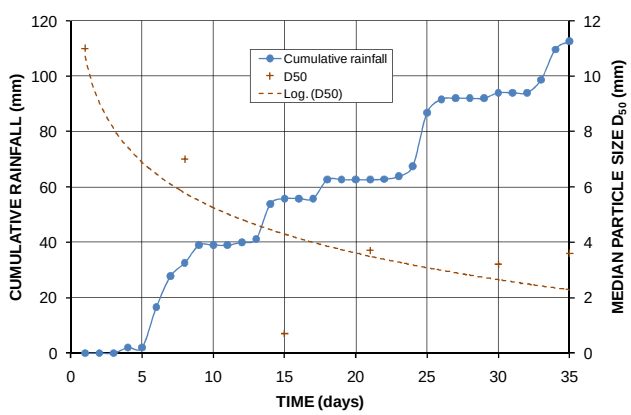


Figure 13: Variation in particle size distribution on weathering of exposed -19 mm scalped Overburden-2 material

(a) (b) (c) (d)

Figure 14: Progressive weathering of -19 mm scalped Overburden-2 material after exposure to: (a) 0 days, (b) 8 days (32.6 mm of rainfall), (c) 15 days (additional 23.2 mm of rainfall), and (d) 21 days (additional 6.8 mm of rainfall, with an additional 31.4 mm of rainfall to 35 days)



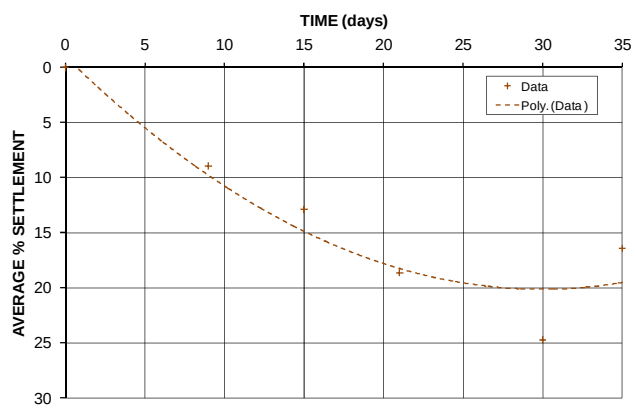


Figure 15: D_{50} vs. Cumulative rainfall **Figure 16: Average % settlement vs. Time**

On weathering of exposed -19 mm scalped Overburden-2 material

Conclusions

The results of the testing described in this paper have implications for the shear strength, and swell and settlement, of clay-rich spoil materials such as the weathered clayrock (Overburden-2) found in the upper part of the Jurassic age Walloon Coal Measures of the Clarence-Moreton Basin, at Jeebropilly Coal Mine near Ipswich, in South East Queensland, Australia. These implications are discussed below.

Implications of Test Results for Spoil Shear Strength

The shear strength behaviour of Jeebropilly Overburden-2 material at the as-sampled moisture content is similar to that on wetting up, to a shear strain of about 5%, since wetting up causes more density increase under a given applied normal stress. Up to about 5% shear strain, the stress-strain behaviour is dominated by the applied normal stress, giving an effective stress cohesion intercept of about 13 kPa and an effective stress friction angle of about 17.9^{o}. Beyond about 5% shear strain, the spoil at the as-sampled moisture content settles and undergoes a significant decrease in pore sizes leading to increased matric suction and hence effective stress. This caused an increase in the measured shear stress required to further shear the specimens. The effective stress cohesion intercept increased to about 33 kPa and the effective stress friction angle to about 27.3^{o}.

Implications of Test Results for Spoil Swell and Settlement

In situ, the Jeebropilly Overburden-2 material would be expected to have a dry density of about 2.35 t/m^3. On blasting and excavation it would swell to a dry density as low as about 0.9 t/m^3 (less than 40% of the in situ dry density and little more than 50% of the laboratory Maximum Dry Density), although this would rapidly increase to about 1.1 t/m^3 (almost 20% settlement) as the depth of spoil is built up to about 60 m (typical at Jeebropilly Coal Mine), purely due to self-weight loading and, by linear extrapolation, to perhaps 1.2 t/m^3 (25% settlement) at the base of 600 m of spoil. Wetting up alone would cause collapse settlement, leading to a dry density of about 1.2 t/m^3. Wetting up in combination with loading by 60 m depth of spoil would increase the dry density to about 1.5 t/m^3 (40% settlement), and the laboratory MDD of 1.68 t/m^3 (over 45% settlement, but still only about 70% of the in situ dry density of the original clayrock, a residual swell factor of almost 30%) would occur on wetting up and loading by about 600 m depth of spoil.

Acknowledgements

The research on which this paper is based was funded by the Australian Coal Association Research Program Project C19022. The management and staff of Jeebropilly Coal Mine, which is owned and operated by New Hope Corporation Australia, are acknowledged for providing access to the mine to take samples of the clay-rich spoil materials that were tested. Professor Williams directs the Golder Geomechanics Centre and supervised the research. Adrian Kho is employed by Consultant Cardno and is a part-time PhD student in the Centre, and Andrew Daley took part in the research under a Summer Vacation Scholarship and for his Fourth Year Thesis Project.

References

AS 1289. *Methods of Testing Soils for Engineering Purposes*. Standards Australia.

Harvey, C.C. & Keeling, J. 2002. Categorization of industrial clays of Australia and New Zealand. *Applied Clay Science*, 20 (4-5), 243-253.

Parker, R.W. & Frost, R.L. 1996. The application of drift spectroscopy to the multicomponent analysis of organic chemicals adsorbed on montmorillonite, *Clays and Clay Minerals*, 44 (1), 32-40.

USDA. (1954). *Agricultural Handbook No. 60, Diagnosis and Improvement of Saline and Alkali Soils*. L.A. Richards (ed.). United States Dept of Agriculture.