Bulking and settlement of weakly-cemented and cemented coal mine spoil

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ABSTRACT

Despite its importance to mine planning, very few coal mine operators routinely and accurately measure the net bulking of spoil from their mines. With increasing environmental restrictions and space constraints being imposed on mine sites, a better understanding of the net bulking of spoil is important, as it affects volume storage requirements both in-pit and, more importantly, out-of-pit. Laboratory compression tests have been undertaken on scalped (to a given maximum size to allow testing) spoil specimens to estimate the self-weight and collapse settlement of coal mine spoil. Degradation testing was carried out by exposing scalped spoil to the weather and monitoring its degradation and settlement. The results of these tests were used as input into a predictive tool for estimating the net bulking of coal mine spoil. This paper focuses on the laboratory testing program of two spoil types, representing the range from uncemented to cemented coal mine spoil, and presents an estimate of their net bulking based on the predictive tool.

Keywords: bulking factor, coal mine spoil, collapse settlement, degradation, self-weight settlement.

1 INTRODUCTION

The net bulking of coal mine spoil is the ratio of spoil volume in place compared to that of the overburden *in situ* and is derived from its initial bulking and subsequent settlement under self-weight loading, collapse on wetting-up and material degradation. With coal mine pits in Eastern Australia projected to reach depths of as much as 500 m, and associated spoil piles heights of up to 600 m, accurate estimation of the net bulking of the spoil becomes increasingly important as it directly affects volume storage requirements and thus the economics of deep open pit coal mining. Bulking factors depend on the excavation methods employed and the open pit geometry (and associated spoil pile heights), but are mainly influenced by overburden geology, spoil pile height and climate. Williams (2012) found that fresh, durable rock is likely to bulk more on excavation and to settle and flatten less than more soil-like spoil types. Bulking factors typically range from 1.00 to 1.40 (based on data from Ofoegbu et al. 2008) for open pit mining. Miekle and Fincham (1999) suggested values of 1.15 to 1.25 for shale and 1.25 to 1.40 for sandstone overburden. Heit (2011) reported an average bulking factor of 1.11 (ranging from 1.01 to 1.98) for the Callide Open Cut Coal Mine (Anglo American) in the Callide Basin of Central Queensland, Australia, while values of 1.10 to 1.25 are typical for the Bowen Basin further north in Central Queensland (BMA, 2008; BMA, 2009).

2 LABORATORY TESTING METHODOLOGY AND RESULTS

The research on which this paper is based was funded through Australian Coal Association Research Program (ACARP) Project C19022 on bulking and subsequent settlement and geotechnical stability of high coal mine spoil piles. Several mine sites were visited: Jeebropilly (New Hope Coal) in the Ipswich Coalfields of South-East Queensland, and Mt Owen (Xstrata), Mt Arthur (BHP Billiton) and Hunter Valley Operations (Rio Tinto) in the Hunter Valley Coalfields of New South Wales. During the site visits, the spoiling methods were observed, and representative samples of the spoil materials were collected for laboratory testing. Of the 18 different spoil types that were identified, two spoil types were given particular attention as they represented the range from weakly-cemented (prone to breaking down) to cemented (durable) coal mine spoil. These spoil materials were Jeebropilly weathered rock that was observed to pond rainfall, disperse and degrade on wetting and drying, and fresh Mt Arthur sandstone which has proven to be durable, as evidenced by its use in drains.

2.1 Spoil Sampling

It is necessary for spoil material to be scalped to obtain smaller particle sizes for laboratory testing. The sampling procedure is detailed in Williams (2012) and involved the passing of the spoil materials through a 19 mm sieve, and weighing the +19 mm and -19 mm fractions. The unscalped spoil materials were photographed for estimation of their particle size distribution using the method outlined in Kho and Williams (2012). The -19 mm scalped samples were collected for subsequent laboratory testing.

2.2 Characterisation Testing

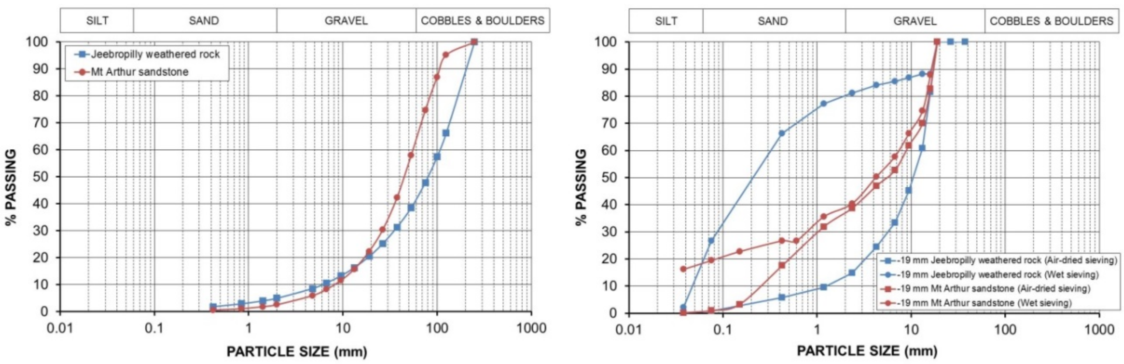
A range of laboratory characterisation tests was undertaken on scalped spoil samples, generally in accordance with AS 1289. The range of tests undertaken and a summary of the results are presented in Table 1. The detailed testing methodology was reported in Williams (2012).

Table 1: Results of laboratory characterisation testing of scalped spoil samples

Spoil Material	Grav. Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity	Max. Dry Density (t/m^3)	Optimum Moisture Content (%)	Slake Durability Index (%)*
Jeebropilly weathered rock	15	71	21	50	2.60	1.52	19	64
Mt Arthur sandstone	3	26	23	4	2.79	1.96	12	91

*Tested on -19 mm particles

Figure 1(a) shows the “all-in” particle size distribution (PSD) curves of the Jeebropilly weathered rock and Mt Arthur sandstone spoil samples obtained using Split Desktop (Split Engineering, 2011) analysis. Figure 1(a) indicates that both spoil types exhibit similar blasted and dumped PSDs, which can be classified using the Unified Soil Classification (AS 1289) as Sandy Cobbly GRAVEL. However, their respective behaviours were observed to be very different upon wetting-up as part of sample preparation and testing. Particle size distribution (PSD) curves for both spoil samples sieved under dry (air-dried) and wet conditions are shown in Figure 1(b), in which the weakly-cemented Jeebropilly spoil was observed to break down significantly on wet sieving. Conversely, limited breakdown on wet sieving was observed for the Mt Arthur sandstone.



(a) (b)

Figure 1. (a) PSD results obtained from: (a) Split Desktop analysis of the “all-in” spoil materials, and (b) Air-dried and wet sieving of the scalped -19 mm samples.

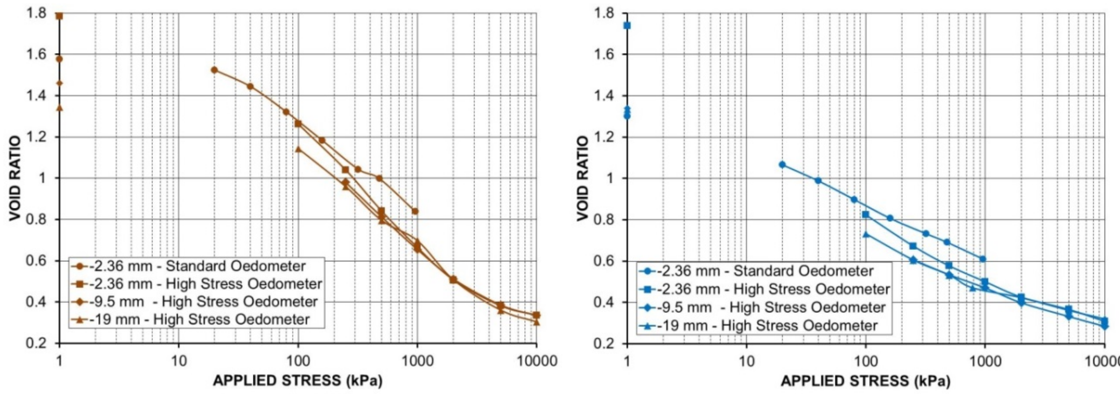
2.3 Compression Testing

Laboratory compression testing was undertaken in two different apparatus; a standard oedometer with a 76 mm diameter by a nominal 20 mm high specimen capable of loading up to 1,000 kPa, and the

150 mm diameter by a nominal 100 mm high, high stress oedometer (HSO) manufactured by Universitat Politècnica de Catalunya, Barcelona, capable of loading to 10 MPa. The specimens for the 76 mm diameter oedometer were scalped to -2.36 mm, while specimens for the HSO were scalped to -19 mm, -9.5 mm and -2.36 mm. All tests were undertaken broadly in accordance with AS1289.5.1.1, with the following modifications:

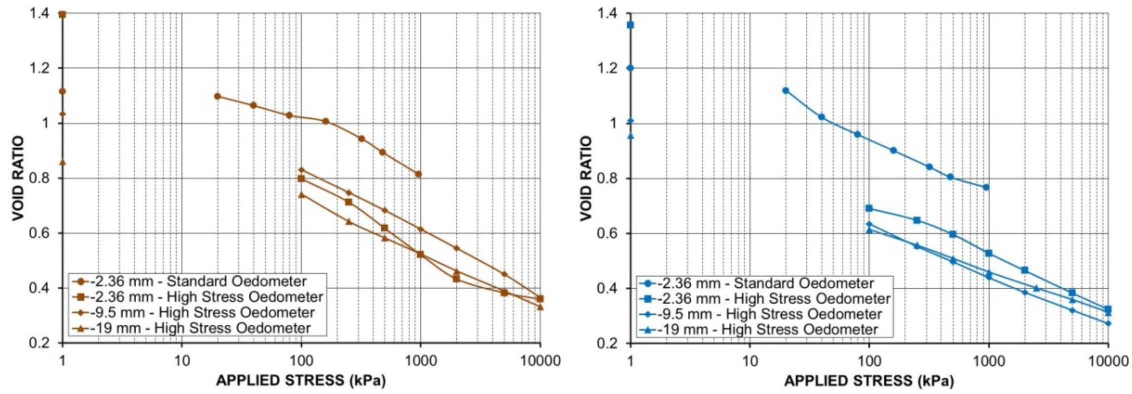
- Specimens were tested at their as-sampled gravimetric moisture content (termed “dry”) and in a water bath (termed “wet”; simulating the worst case of saturation of the spoil).
- Specimens were placed loose to simulate the loose-dumped state of the spoil in the field.

The compression test results were presented and discussed in Williams and Kho (2014), and a summary is presented in Figures 2 to 4. Figures 2 and 3 show the effect of maximum particle size on the compression behaviour of both spoil types when tested under wet and dry conditions. The results show minimal difference in terms of compression behaviour between specimens scalped to -2.36 mm, -9.5 mm and -19 mm, suggesting that the compression behaviour would be similar for field-sized materials. Additionally, the deviation in the compression curves between the Standard oedometer and the HSO is attributed to the inherent differences in apparatus stiffness. Figure 4 compares the results of the -2.36 mm tests, carried out in both test apparatus, for the spoil specimens tested under dry and wet conditions. Figure 4(a) highlights the effects of wetting-up on the Jeebropilly weathered rock, causing significant amounts of collapse settlement. In contrast, wetting-up was observed in Figure 4(b) to have minimal effect on the compression curves for the Mt Arthur sandstone.



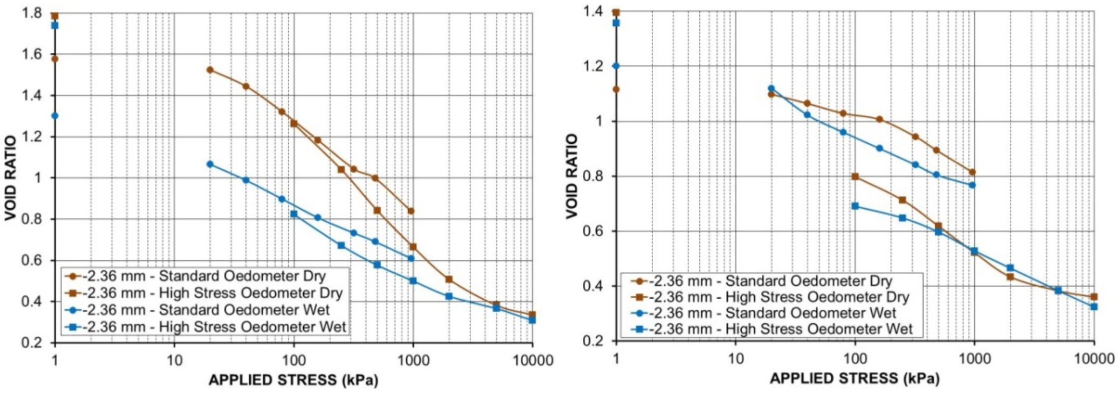
(a) *(b)*

Figure 2. Compression test results for Jeebropilly weathered rock scalped to -19 mm, -9.5 mm and -2.36 mm: (a) under dry conditions, (b) in a water bath



(a) *(b)*

Figure 3. Compression test results for Mt Arthur sandstone scalped to -19 mm, -9.5 mm and -2.36 mm: (a) under dry conditions, (b) in a water bath



(a) *(b)*

Figure 4. Comparison of the dry and wet test results for -2.36 mm scalped spoil samples (a)Jeebropilly weathered rock (b) Mt Arthur sandstone

Despite the variation in compression behaviour of the two different spoil specimens, the final void ratio, at 10 MPa applied stress, was in a narrow range between 0.3 and 0.35 for both spoil materials, which corresponds to a narrow range of dry density between 1.95 t/m^3 and 2.1 t/m^3. This suggests that the height of the spoil pile has a greater effect on the compressibility of coal mine spoil than the spoil type and its moisture state.

2.4 Degradation Testing

Both the Jeebropilly weathered rock and Mt Arthur sandstone spoil samples were subjected to degradation testing, using a test method that was developed as part of the ACARP C19022 Project. The full test procedure is detailed in Williams (2012) and involved placing the test specimens in purpose-built Perspex trays measuring 600 mm by 600 mm by 150 mm high, which were drained at the base, and filling them with -19 mm scalped spoil specimens to nominal initial heights of 25 mm. The trays were left out on the roof of the Geomechanics Laboratory of The University of Queensland for about 1 month each and were subjected to ambient rainfall and desiccation cycles. Once a week, height measurements were taken from nine points across the surface and sub-samples were taken for air-dried sieving.

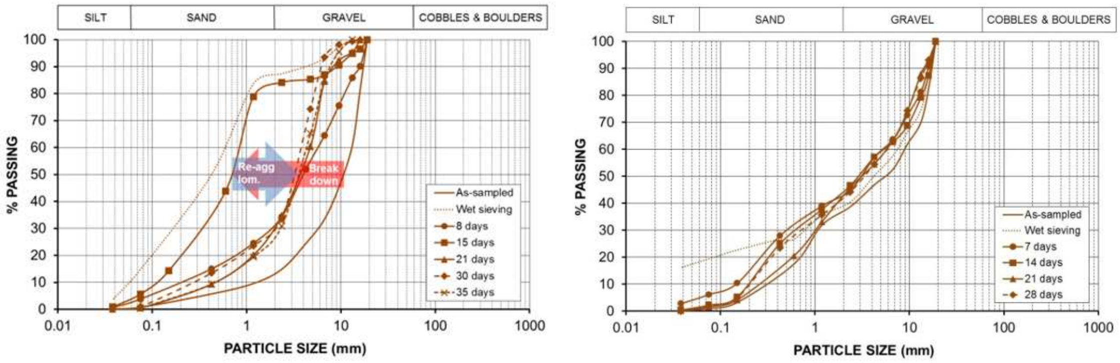
Figure 5 compares the state of the Jeebropilly weathered rock spoil during various stages of the test. The test specimen was observed to slake and disperse on wetting-up before re-agglomerating and cracking on drying. The corresponding photos for the Mt Arthur sandstone spoil are shown in Figure 6, where the only difference observed over time was the fines being washed down to the bottom of the tray. The PSD curves of sub-samples collected during the tests are presented in Figure 7. Major particle breakdown was observed for the Jeebropilly weathered rock spoil in the first two weeks before re-agglomeration, while the PSD curves of the Mt Arthur sandstone spoil was fairly consistent throughout the entire test. Throughout the test, the Jeebropilly weathered rock spoil showed maximum settlement of about 25% relative to its initial height, while the Mt Arthur sandstone settled significantly less with settlements in the order of 5% of its initial height.

Day 1 | Day 8 (+32.6 mm rain) | Day 15 (+23.2 mm rain) | 21 days (+6.8 mm rain)

Figure 5. Condition of Jeebropilly weathered rock spoil at various stages of degradation testing

Day 1 | Day 7 (+4.0 mm rain) | Day 14 (+39.2 mm rain) | Day 21 (+47.8 mm rain)

Figure 6. Condition of Mt Arthur sandstone spoil at various stages of degradation testing



(a) *(b)*

Figure 7. Variation in PSD on degradation of exposed -19 mm scalped (a) Jeebropilly weathered rock spoil, and (b) Mt Arthur sandstone spoil

3 SPOIL SETTLEMENT PREDICTION TOOL

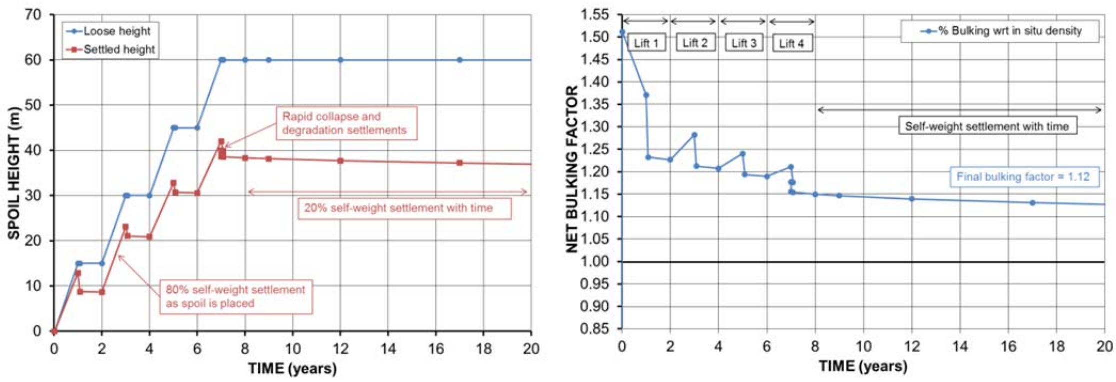
Using the laboratory test results from the ACARP C19022 Project, a spreadsheet based prediction tool was developed to estimate coal mine spoil settlement and final net bulking. The prediction tool allows the user to specify spoil pile lift heights and spoil types (up to 5 different lifts and spoil types), the rate of construction including pauses between construction of lifts, and rainfall infiltration or equivalent groundwater recharge. The prediction tool is based on a layer of spoil (termed a "lift") being placed and compressed by the weight of subsequent lifts. The spoil undergoes instantaneous self-weight settlement as it is being placed with the remaining self-weight settlement experienced in accordance with the compression rate (c_v) allocated. The total settlement is the sum of the self-weight settlement, the collapse settlement on wetting-up and the degradation-induced settlement at a particular point in time. Due to the observed non-linear behaviour of spoil behaviour under compression, settlement was estimated using a logarithmic relationship between settlement (*% of height = ln[applied stress] + a constant*) and applied stress of each spoil type based on laboratory oedometer tests. Other assumptions made in the prediction tool are:

- 80% of self-weight occurs during placement (i.e. post-construction settlement = 20%) as suggested by Williams (2012). This can be adjusted in the inputs to suit site conditions.
- Self-weight settlement = settlement from dry test.Collapse settlement = settlement from the wet test subtracting the settlement from the dry test (self-weight settlement).
- Degradation settlement occurs only at the surface of the spoil pile to a depth of 5m or 5% of spoil height. This can be adjusted in the inputs to suit site conditions.
- Trigger rainfall for collapse settlement is 60 mm/month (i.e. collapse is not considered for rainfall inputs of less than 60 mm/month) based on site observations and laboratory dry and wet testing results. This can be adjusted in the inputs to suit site conditions.
- Spoil is assumed to be placed loose, at an initial unit weight that is estimated from laboratory oedometer test results.
- Collapse and degradation-induced settlements are assumed to occur linearly over a month.

A scenario was created assuming construction of a spoil pile consisting of four lifts of equal height, with each lift taking 1 year to build and a pause of 1 year before the start of the subsequent lift. Throughout the construction, it was assumed that the rainfall was greater than 60 mm/month, appropriate to the relatively wet climate of the site. Jeebropilly weathered rock spoil was modelled for a representative spoil pile height of 60 m, while Mt Arthur sandstone spoil was modelled for a representative spoil pile height of 200 m. These represent current typical spoil pile heights in the Ipswich Coalfields and Hunter Valley Coalfields, respectively.

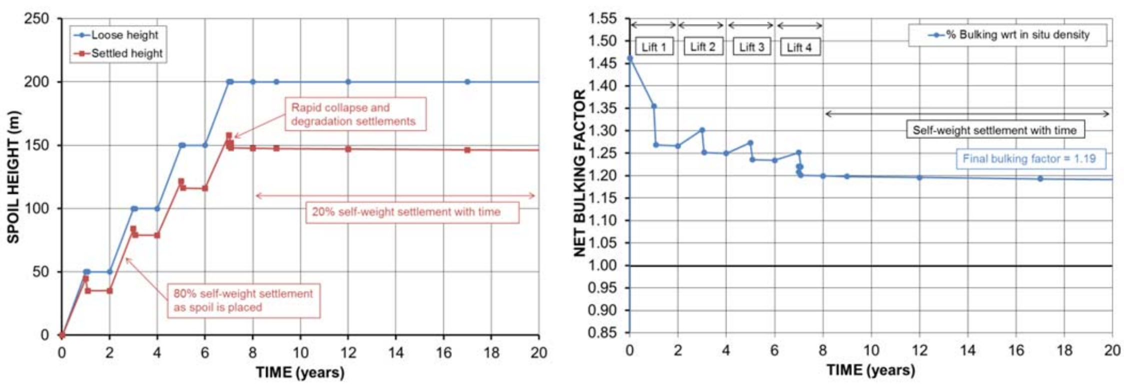
Figure 8(a) shows the estimated settlement and corresponding spoil heights with time for a 60 m high spoil pile consisting of Jeebropilly weathered rock spoil. Figure 8(b) shows the calculated net bulking factor of the spoil material based on this scenario. The 60 m high spoil pile was estimated to settle to 36 m height over 20 years, which is equivalent to a net bulking factor of 1.12. Figures 9(a) and 9(b) show the same plots but for a 200 m high spoil pile consisting of Mt Arthur sandstone spoil. For this more durable spoil type, the 200 m high spoil pile was estimated to settle to 148 m over the same 20 years, corresponding to a net bulking factor of 1.19.

Both spoil types were then modelled for heights of 600 m, representing the upper range of anticipated spoil pile heights. Figures 10(a) and 10 (b) show the change in spoil heights and net bulking factors with time for a 600 m high spoil pile consisting of Jeebropilly weathered rock spoil. The 600 m high spoil pile was estimated to settle to 325 m over 20 years, which is equivalent to a net bulking factor of 1.07. These plots are replicated for the Mt Arthur sandstone spoil constructed to the same 600 m height, in Figures 11 (a) and 11(b), which show a settled spoil height of 410 m over 20 years, corresponding to a net bulking factor of 1.14.



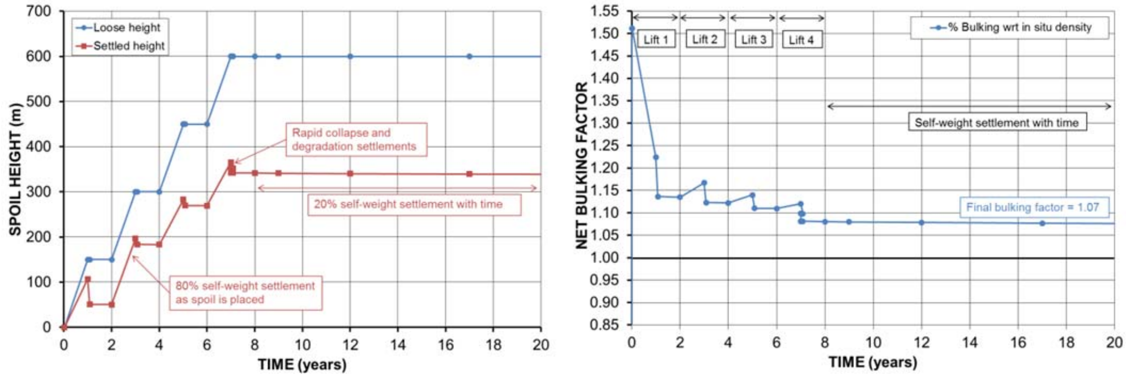
(a) *(b)*

Figure 8. Prediction tool outputs for a 60 m high spoil pile consisting of Jeebropilly weathered rock spoil: (a) Spoil height versus time, and (b) Net bulking factor versus time



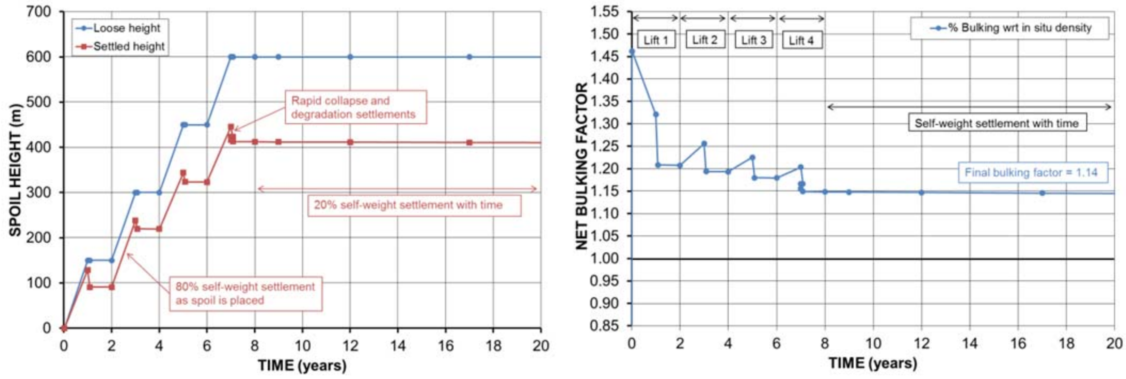
(a) *(b)*

Figure 9. Prediction tool outputs for a 200 m high spoil pile consisting of Mt Arthur sandstone spoil: (a) Spoil height versus time, and (b) Net bulking factor versus time



(a) *(b)*

Figure 10. Prediction tool outputs for a 600 m high spoil pile consisting of Jeebropilly weathered rock spoil: (a) Spoil height versus time, and (b) Net bulking factor versus time



(a) *(b)*

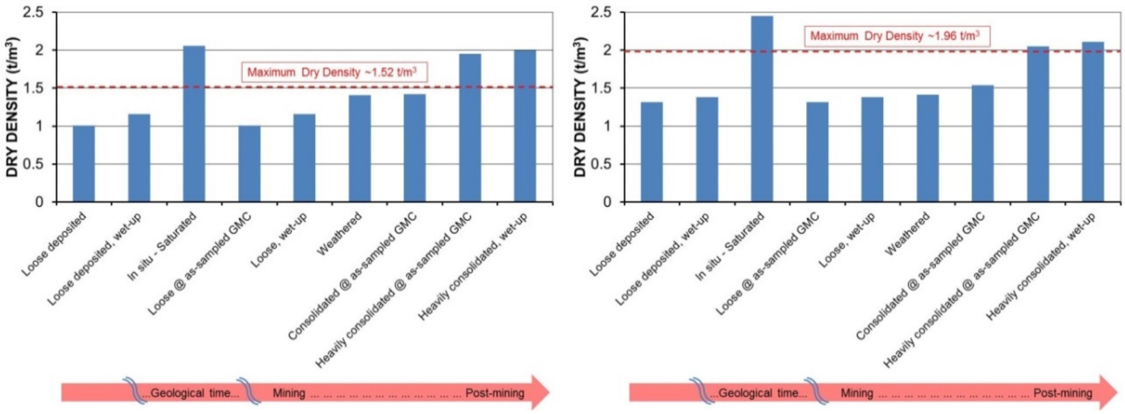
Figure 11. Prediction tool outputs for a 600 m high spoil pile consisting of Mt Arthur sandstone spoil: (a) Spoil height versus time, and (b) Net bulking factor versus time

4 DISCUSSION

The calculated net bulking factors for the range of spoil pile heights modelled fall within the range of 1.07 to 1.19, which compare well with those previously reported in the literature that are generally between 1.10 and 1.25 for open cut coal mine spoil.

The outputs of the spoil settlement calculator indicate that the weakly-cemented Jeebropilly weathered rock spoil initially bulked up more but also settled significantly more than the cemented Mt Arthur sandstone spoil. Comparing the settlement behaviour of both spoil types, the settlement rate at lower stresses for the Jeebropilly weathered rock spoil was observed to be greater. However, as the applied stresses increased, the inverse was observed. This is attributed to the lower crushing stress of the weaker spoil subsequent to the development of a stable skeleton at lower stress.

Using the results of the prediction tool, the evolution of dry density through geological time and the mining process has been illustrated for both the Jeebropilly weathered rock spoil and Mt Arthur sandstone spoil in Figures 13(a) and 13(b), respectively. Both spoil materials showed final heavily consolidated, wetted-up dry densities greater than their respective maximum dry densities. For the Jeebropilly weathered rock spoil, it is shown that the heavily consolidated, wetted-up spoil material achieved a dry density approaching that at its *in situ* state. For the Mt Arthur sandstone spoil however, the difference in dry density between the final heavily consolidated, wetted-up spoil material and its *in situ* state was still quite significant, indicating a higher net bulking factor.



(a) *(b)*

Figure 12. Evolution of dry density through time: (a) Jeebropilly weathered rock spoil, and (b) Mt Arthur sandstone spoil

5 CONCLUSION

The paper covered the effects of different settlement mechanisms on weakly-cemented and cemented coal mine spoil, which represent the lower and upper bounds in terms of spoil durability. Additionally, a spoil settlement prediction tool was introduced and validated against data from the literature. Overall, the results show that weaker spoil types tend to initially bulk-up more but also settle more compared to more durable spoil, due to their greater propensity for particle breakage. The prediction tool estimated that final net bulking factors for coal mine spoils range between 1.07 and 1.14 at 600 m spoil height, which corresponds to % settlements of between 32 and 46% of the initial height. For a 600 m high spoil pile this equates to a difference in height of about 85 m between weak and durable spoil, highlighting the need for accurate volume estimation for high coal mine spoil piles.

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