Bearing capacity of open-cut coal-mine backfill materials

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Surface mining is common practice in most countries that produce black coal. The operations are subject to increasingly stringent regulations and requirements aimed at reducing the environmental impact and creating stable, self-sustaining land that can be put to productive use in the long term. In most cases the rehabilitated land is eventually used for agriculture. In populated areas, however, it is increasingly being put to recreational, industrial or residential use. The problems reported in the use of rehabilitated lands are mostly due to excessive or differential settlement and to inadequate bearing capacity.

The rocks constituting the overburden dominate the materials used for the backfilling of open-pits. They are disturbed and altered by the sequence of mining and backfilling operations and environmental processes, and their geotechnical properties consequently change. Knowledge of the mechanical behaviour of these materials is a prerequisite for understanding the likely mechanism of settlement and for any analytical, quantitative and predictive study of rehabilitated land. This knowledge is also essential for the success of any future construction of buildings, roads or other structures on the reclaimed land.

The main subjects of the investigation described here were the compressibility and bearing capacity of open-cut coal-mine backfill of different ages. Laboratory tests were used to determine basic strength and deformation properties of sandstone and claystone, the most common open-cut coal-mine backfill materials. *In-situ* plate bearing tests were carried out to assess the ability of backfill material to support load. By conducting these tests on four backfills of different ages the relationship between the bearing capacity and age of the backfill was also investigated.

Literature review

The data on the mechanical properties of backfill materials reported in the literature are very limited. Several attempts, based mainly on field measurements, have been made to address settlement in backfilled open-cut coal mines,[1–11] but there have been few attempts at developing a procedure to predict the settlements. A range of measured settlements of between 0.3 and 7% of the backfill height has been reported under dry conditions, with further settlement of 1–4% of the backfill height on inundation by a rising groundwater level. Creep or consolidation settlement may continue for more than ten years, at a more or less uniform rate.[9] The theories suggested to explain the mechanism of settlement in backfills ascribe it to: the reorientation of the particles; the weakening of inter-particle bonds due to the effect of moisture; the weathering (swell/slake) of backfill material with a high clay content; and/or the transport of fine particles from the top to lower layers.

The attempts to explain the mechanisms of the backfill settlement reported in the literature ignore some important factors. These include the nature of the backfill material, the placement method and the geometry of the void. Furthermore, none of the published theories distinguishes between the different types of settlement in backfills, which results in a poor understanding of the mechanisms of backfill settlement.

The number of publications dealing with the bearing capacity of the backfilled land is even smaller. Kilkenny[1] suggested that if the relative compaction of the backfill were greater than 90% of the maximum density for cohesionless materials or greater than about 95% of the maximum density for standard compaction of cohesive materials, the bearing capacity of the backfill could be accepted as adequate for building purposes. It was also suggested that building could start immediately if the backfill were compacted to greater than 85% of the solid dry density (specific gravity) of the rock. Excessive settlements were, however, identified as the major problem for construction on backfill. Where backfill was more than 30 m deep a minimum period of 12 years was generally suggested before development commenced.

Gilbert and Knipe[12] conducted a series of standard penetration tests, finding that in most areas the backfill investigated was capable of supporting applied pressures of 50–70 kN/m^2 safely. All of the backfilling operations, however, were carried out by scrapers with loaded masses of up to 60 t. Raft and ground slab footings were considered. Foundation settlements under stresses of less than 50 kN/m^2 applied at the surface were found to be small. The authors believed that the principal risk of differential settlement was posed by self-weight induced settlement of the backfill.

Site of investigation

Jeebropilly colliery, the site for the present study, is one of the major open-cut mines in the Walloon district of the Ipswich Coalfields in southeast Queensland, Australia. Backfilling materials consist mainly of sandstone, mudstone and claystone, with about 2% non-recoverable coal. The quantities and qualities of the spoil materials depend on the stratigraphic level from which they are excavated.

The mining method employed at Jeebropilly colliery is bench mining with hydraulic excavators, large front-end loaders being used to scoop the coal into 77- to 120-t rear-dumptrucks. The open-cut excavations reach depths of 40–60 m. Open-cut working takes place on a succession of several major blocks. Each block is backfilled, after removal of the coal, with the waste rock from the next. Unlike backfill placed by dragline, the Jeebropilly backfill material is somewhat compacted after dumping by the earthmoving equipment that passes over it. The compaction is, however, limited to the surface of the backfill and is not systematic. The backfilled area is eventually recontoured and covered by a layer of 20–40 cm of topsoil prior to revegetation.

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Laboratory test results

The materials used in the study were sandstone and claystone, representing, respectively, the extremes of very stiff and very soft backfill materials found in coal-mine overburden spoil. The samples were collected from freshly blasted overburden at Jeebropilly colliery.

Laboratory compression tests were carried out on the samples to quantify all of the components of backfill settlement. Specimens 50 mm high × 150 mm in diameter and 80 mm high × 250 mm in diameter were prepared in two Rowe cells of different sizes. Particle sizes were limited to a maximum of 19 mm by scalping. All specimens were placed in the cells at their moisture content as sampled and were compacted to densities of 1.6 t/m^3 and 1.4 t/m^3 for sandstone and claystone, respectively. These densities were based on the results of field density measurements by the sand-replacement method in fresh backfill placed in the pit by end-tipping.

In the first test series sandstone and claystone specimens were prepared and subjected to incremental series of vertical stresses of 50, 100, 200, 400 and 800 kN/m^2. This test series was aimed at determining the one-dimensional stress–strain behaviour of the materials under the moisture conditions as sampled.

In the second test series specimens of both sandstone and claystone, prepared at their as-sampled moisture content and density, were individually compressed under a constant vertical stress until an equilibrium state was reached (usually after 24 h) and were then flooded with water. Short-term collapse settlements due to the effects of the water were measured for specimens at applied vertical stresses of 50, 100, 200 and 400 kN/m^2 for the sandstone and 50, 100, 200, 400 and 800 kN/m^2 for the claystone. A rapid crushing effect was observed after the initial application of a given vertical stress. Settlement continued for a short time before the material reached an equilibrium state under the moisture conditions as sampled. A similar effect was observed after the specimens were flooded. The collapse settlement was a relatively short-term phenomenon and was followed by longer-term consolidation settlement.

The averages of the settlements observed in the two test series at the moisture content as sampled were used to obtain the stress–strain curves for the moisture condition as placed. The collapse settlements obtained from the second test series were then added to the as-placed stress–strain curves to obtain the stress–strain relationship for each material when saturated. The stress–strain behaviour of both materials is typical of that of granular material under one-dimensional conditions (Fig. 1). This is marked by non-linearity at low stress levels followed by linear behaviour at higher stresses, under which the tangent modulus remains constant with increasing stress. For both materials almost half of the compression occurs at vertical stresses of less than 200 kN/m^2.

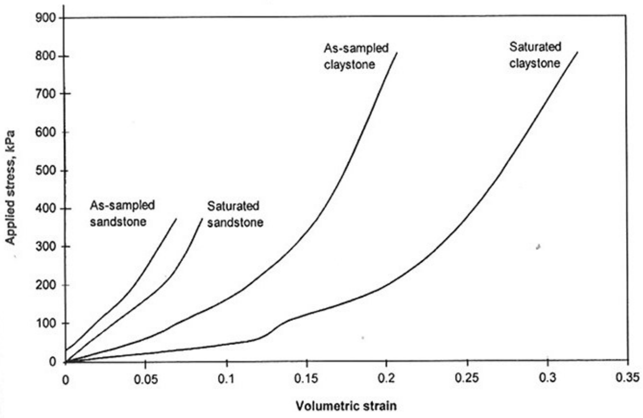

Fig. 1 Stress–strain relationship for as-sampled and saturated sandstone and claystone

In the third test series the specimens were compacted and then saturated, before being consolidated under a series of incremental vertical stresses. Consolidation and hydraulic properties, including long-term creep settlements, were obtained by this means.

The three test series were aimed at simulating the range of likely settlement mechanisms occurring in the field, which comprise self-weight settlement under the moisture conditions as placed, collapse settlement on inundation and consolidation settlement.

Fig. 2 shows the relationships between the inundation-induced collapse settlement and the applied stress for both the sandstone and the claystone. It reveals an initial sharp increase in collapse settlement with increasing applied stress, after which the collapse settlement tends towards a constant value. The constant value for claystone is four to five times that for sandstone. The rapid increase in collapse settlement with increasing applied stress, at low applied stresses, is attributable to the limited unsaturated compression of the material at low applied stresses.

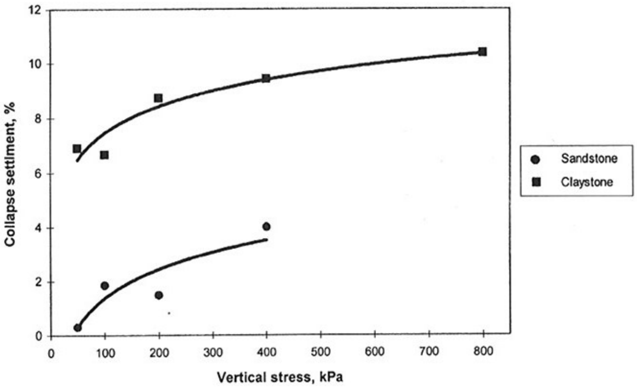

Fig. 2 Relationship between collapse settlement and applied stress for sandstone and claystone

Direct shear tests were carried out on the sandstone and claystone to obtain strength properties under both as-placed and saturated conditions. The primary aim was to investigate the effect of water on the strength properties of the backfill materials. The tests were conducted on 100 mm × 100 mm sandstone and claystone specimens, initially compacted at their as-sampled moisture content to their field densities at a thickness of about 30 mm. The maximum particle size of the material used was restricted to 9.5 mm by scalping. The peak shear strengths of the materials were obtained for applied vertical stresses of 50, 100, 200 and 400 kN/m^2 at the moisture content as sampled and under saturated conditions.

Fig. 3 summarizes the results of the direct shear tests for both the sandstone and the claystone. The two materials have similar values of cohesion, *c*, and friction angle, ϕ, at their moisture contents as sampled. The slightly lower strength of the claystone may well be due to its lower density. Both materials show a reduction in their strength properties when inundated, but the reduction is much greater for the claystone. Interestingly, a reduction in the value of ϕ is responsible for most of the strength reduction of the claystone, whereas a reduction in *c* is responsible for most of the strength reduction of the sandstone. Whereas the strength envelopes for the sandstone were linear, the strength envelopes for the claystone are better described by curves.

On the basis of the laboratory investigation of the sandstone and claystone backfill materials at Jeebropilly colliery some conclusions can be drawn regarding the settlement and

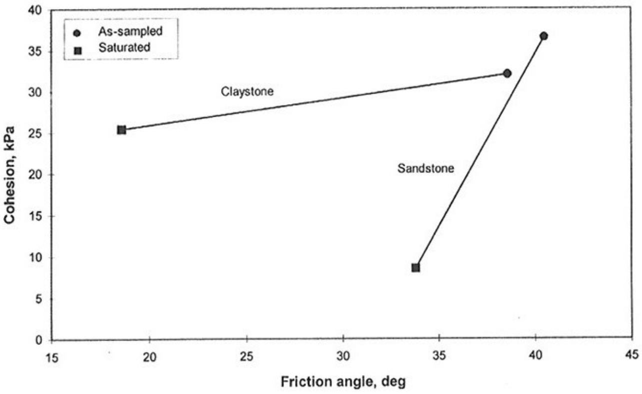

Fig. 3 Results of direct shear tests on as-sampled and saturated sandstone and claystone

strength of backfill materials. These conclusions apply to truck-and-shovel backfilling operations and are not necessarily applicable to other backfill placement methods.

First, the laboratory tests demonstrate the significance of the self-weight settlement of backfills during placement at their natural moisture content. This settlement has been shown to be rapid and is believed to occur primarily during placement, continuing for only a short time thereafter. The laboratory tests showed no significant long-term creep settlement under self-weight loading. Rearrangement and crushing of the particles appear to be the phenomena contributing most to this mode of settlement. The use of well-graded material might reduce the contact stresses by increasing the number of points of contact and so reduce the settlement. However, despite the large impact on settlement of the rearrangement and crushing of particles, their effect on reducing the macro-porosity is limited.

Moisture is believed to play the most significant role in the settlement of backfill materials and is probably the most important factor influencing volume change within the backfill, both during and after backfilling. Coal-mine overburden materials typically include claystone, mudstone, siltstone and sandstone, which all have potentially high clay-mineral contents. These materials when blasted, subjected to handling and transportation and, finally, dumped in the backfill may possess limited cohesion and cementation. They may swell and slake appreciably on exposure to water, possibly reverting to disaggregated soils, although weakly cemented lumps may also form. The results of the laboratory collapse tests clearly show the affinity of the Jeebropilly backfill materials for water, which results in the rapid destruction of their structure. The reduction in strength of the material on saturation that was shown in the laboratory direct shear tests is clearly a major cause of collapse settlement. Both the cohesion and friction angle of the materials decrease on saturation. This reduction in strength results in the reduction of macro-porosity and hence induces settlement. Collapse settlement results in saturation owing to the large reduction in permeability that accompanies collapse. Collapse settlement is followed by long-term creep settlement at a rate that decreases with time. This long-term settlement is, however, not pure consolidation settlement but a combination of consolidation and collapse of previously unaffected parts of the fill, which may take a very long time to saturate.

In-situ bearing capacity tests

A series of plate bearing tests[13] was conducted on recently placed backfills and on one-month, 12-month and five-year old backfill. This was aimed at investigating the change in the bearing capacity of the backfill with the time elapsed after the completion of backfilling.

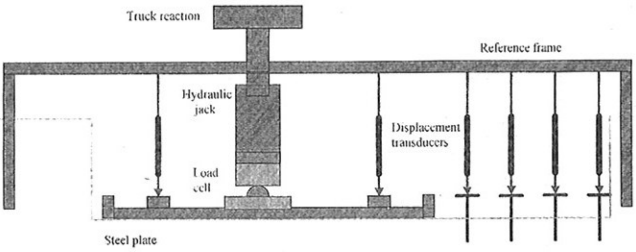

Fig. 4 Schematic of plate bearing test arrangement

At each test location a shallow excavation was made in the surface of the backfill to remove any topsoil and to smooth the surface sufficiently for testing. A steel plate 750 mm in diameter was bedded down on the bottom of the excavation and loaded in increments of 20 kN/m^2 by means of a jack acting against a 120-t mining truck. The load was applied at the centre of the plate and distributed by three radial ribs. The applied load was measured using a 20-t load cell mounted on the centre of the plate (Fig. 4). Loading was continued until the maximum travel of the jack was reached in consequence of the truck rising on its springs. This occurred at vertical stresses on the backfill of about 200 kN/m^2. Deflections were recorded by three displacement transducers spaced at 120° at the edge of the plate and mounted on a reference frame. They were read simultaneously at 5-s intervals and the readings were averaged at each interval. Three more displacement transducers were used to measure the deformation of the backfill surface at up to 1.5 m from the plate. Tests were repeated at least once at each site, with a minimum distance of 10 m between test locations.

The *in-situ* density of the backfill material adjacent to the area tested was determined by the sand-replacement method.[14] Samples were also collected for the determination of moisture content. The condition of the backfill at each

Table 1 Backfill conditions at test locations

Location	Age	Moisture content, %	Density, t/m^3	Average moisture, %	Average density, t/m^3
1	Fresh	12.8	1.23	14.2	1.3
2	Fresh	15.5	1.35	14.2	1.3
3	1 month	13.4	1.27	13.8	1.3
4	1 month	14.2	1.24	13.8	1.3
5	1 month	–	–	13.8	1.3
6	1 year	16.2	1.26	15.9	15
7	1 year	15.7	1.65	15.9	15
8	1 year	–	–	15.9	15
9	5 years	8.7	1.63	8.3	1.7
10	5 years	7.9	1.60	8.3	1.7

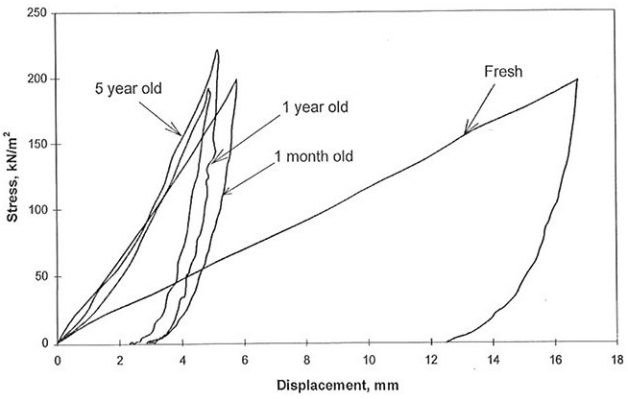

Fig. 5 Typical plate-bearing test results

Table 2 Results of plate bearing tests on backfill materials

Site	Age	Applied stress, kN/m^2	Initial settlement, mm	Plastic settlement, mm	Initial E, MPa	Average unloading, MPa
1	Fresh	218	10.52	4.42	11.1	26.5
2	Fresh	198	16.78	4.27	6.3	24.9
3	1 month	199	4.74	2.47	22.6	43.3
4	1 month	199	5.78	2.84	18.5	37.6
5	1 month	218	4.83	2.72	24.2	43.0
6	1 year	194	4.49	2.74	23.1	38.0
7	1 year	172	3.01	1.98	30.7	46.6
8	1 year	187	4.93	2.61	20.4	38.6
9	5 years	218	5.70	1.28	20.6	91.6
10	5 years	221	5.15	2.3	23.0	51.5

location is summarized in Table 1. Typical stress–displacement curves for each of the differently aged backfill materials are presented in Fig. 5.

The slopes of the plate bearing test curves were used to estimate the Young's modulus, E, of the backfill. The displacement of a rigid footing on an elastic half-space is given by

$$S_i = qB\frac{(1-\nu^2)}{E}I_s \qquad (1)$$

where S_i is immediate settlement, q is applied stress, B is diameter of the plate, ν is Poisson's ratio of the backfill and I_s is an influence factor, which equals 0.785 for a circular footing. The equation can be used to calculate the value of E for the initial and average unloading parts of the plate bearing test curves. A value of 0.3 was assumed for the ν of the backfill material. The values obtained for the initial and average unloading moduli are given in Table 2.

Despite slight increases in the moduli of the backfill with increasing age, the results indicated no clear relationship between the age and the bearing capacity of the backfill. Large increases were observed, however, in the strength and stiffness of the backfill as loading progressed. This was more pronounced in the younger backfills and demonstrates the significant effect on the backfill properties of compaction and preloading. The results indicate that even a little compaction by mining vehicles gives the backfill sufficient stiffness to sustain further load. The degree of compaction is, therefore, likely to be more significant than the age of the backfill in determining its bearing capacity.

Table 2 shows that there is little difference between the test results for one-month, one-year and five-year old backfills. Nevertheless, tests on freshly dumped material indicated moduli much lower than those of the aged materials. This is probably because the fresh material had had little traffic pass over it and was compacted mainly by its self-weight. The test results suggest that the bearing capacity of the backfilled area is generally quite adequate for normal construction activities. Bearing stresses of up to 200 kN/m^2 were achieved in the tests without significant displacement at the surface of the backfill. Although continuing self-weight induced settlement of the backfill is unlikely to be significant,[15] collapse settlement at depth due to saturation or recovery of the groundwater table may be significant and should be considered.

Conclusion

The estimation of the settlement and the bearing capacity of backfilled open-cut coal mines is of great importance for further development of the rehabilitated land. Because of the site-specific nature of the backfill materials and settlement patterns and the large number of significant factors none of the available soil mechanics theories has been able to quantify successfully the different components of settlement in open-cut mine backfills. In the study reported here a programme of laboratory tests was carried out that simulated the mechanisms of backfill settlement. The two major causes of surface settlement in backfill are the self-weight of the spoil material and inundation by rising groundwater and surface runoff. These were investigated by laboratory compression and direct shear tests. Self-weight settlement of backfills during placement at their natural moisture content was shown to be rapid and is believed to occur primarily during placement, continuing for only a short time thereafter. The laboratory tests showed no significant long-term creep settlement resulting from self-weight effects. Moisture is believed to play the most significant role in the settlement of backfill materials by reducing their strength. Collapse settlements caused a large proportion of the tested settlement by rapid destruction of the structure of the backfill material.

The investigation showed that the bearing capacity of the backfill is a function mainly of compaction, not of the age of the backfill. The modulus or stiffness of the backfill is significantly increased by previous loading, in some cases up to threefold. Backfill material experiences some compaction through the passage of mining vehicles, which is likely to be sufficient to provide a bearing capacity that will support normal construction activities. The limited testing performed suggests that completed backfills are capable of supporting loads of up to 200 kN/m^2 while sustaining displacements acceptable for a wide range of residential and industrial developments. The backfill may, however, be susceptible to collapse settlements due to saturation in the long term.

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