the No. 1 horizon and the combined No. 2 and No. 3 horizons need to be designed to a high safety factor. However, mining of the No. 2 and No. 3 horizons had been in progress for over 10 years whilst no consideration had been given to mining the No. 1 seam horizon. As a result some areas within the No. 2 and No. 3 horizons, had been mined to a safety factor considered marginal for multi-seam extraction. Therefore, in order to permit mining of the No. 1 horizon, it was decided that all marginal areas in the No. 2 and No. 3 horizons must be ashfilled prior to being under-mined.

Mining of the No. 1 horizon below ashfilled workings has now been in progress for over 4 years, during which time no adverse interaction between the lower and upper horizon workings has been noted. Ashfilling appears to have stabilized the upper No. 2 and No. 3 horizon workings and to have limited strata displacement resulting from interaction of pillar stress profiles between upper and lower mining horizons. Consequently, an additional 5 million tonnes of coal reserves have been generated.

During the last 15 years there have been numerous other occasions when small scale use has been made of ashfill to stabilize workings. Mine offices, houses, railway lines and the like have been built above ashfilled workings. Workings in an advanced state of collapse have been stabilized. In almost all instances, ashfill has been effective in ensuring stability of bord and pillar workings.

Thus, local experiences have highlighted that ashfill can have an extremely favourable influence on pillar stability. Therefore, research into quantifying this influence in order to achieve the maximum benefits from incorporating ashfill into potential thick seam mining methods is justified, especially in view of the economic viability of ashfilling under conditions which presently exist in the four potential thick seam mining coalfields.
8.4 The Physical, Mineralogical and Chemical Properties of Ashfill

8.4.1 The need for research into local ashfill

If full advantage is to be taken of the potential stabilizing, or support, properties of ashfill, an understanding of the strength and deformation properties of the material is essential. In particular, careful consideration must be given to the properties of ashfills derived from PFA since this material is most abundant and offers the greatest potential support benefits because of its self-cementing properties. However, little of the previous published research relating to ash, specifically to PFA, and/or stowing can be utilized since:

1) The utilization of ash as a bulk stowing material is unique. Previous research has been concerned primarily with establishing the pozzolanic activity and stabilizing effects of PFA when added to cement and soil-based materials. In addition, test specimens and final products are generally at maximum dry density and optimum moisture content, conditions which are impossible, practically, to achieve underground.

11) PFA is a manufactured material. Consequently, the physical, mineralogical and chemical properties of the material are markedly different to those of other stowing materials. For example, particles are not angular like most mill-derived stowing materials but are predominantly spherical and hollow, over 50 per cent of the material by weight constitutes what is usually regarded as slimes and often discarded, and the material is self-cementing. Thus, ashfill quality is determined by a number of different factors to those which
determine uncemented and, in most instances, cemented fill quality.

iii) Large variations are known to occur in the properties of PFA overseas, both between power stations and within individual power stations. Thus, the properties which have been established for overseas PFA's may be significantly different to those of locally produced PFA's.

iv) Much of the research into the behaviour and effectiveness of stowing has been concerned with the function of fill in stopes of large vertical extent and limited lateral extent. Under these circumstances the influence of parameters such as percolation rate, consolidation and passive earth pressures is quite different to that in stowed bord and pillar workings of limited height but large lateral extent.

It is apparent that very few of the findings of previous research into ash can be applied directly to ashfill. In particular, no previous research has been conducted into the effects of ashfill on pillar behaviour. However, previous research has highlighted that before this research is conducted it is necessary to establish the properties of locally produced ashes and the manner in which these affect ashfill quality. A prerequisite for conducting this research is an appreciation of local ash production systems.

3.4.2 Ash production and ashfill placement systems

The ash content of most coals supplied to South African power stations is 25 to 30 per cent by weight. About 20 per cent of this ash is collected from the bottom of the furnaces in the form of clinker whilst the remaining ash is carried out of the furnaces with the flue gases.
Before passing into the atmosphere the flue gases pass through a system of precipitators which extract most of the suspended ash. This ash is known as PFA or flyash. Two types of precipitators are employed in South Africa, namely, mechanical precipitators and electrostatic precipitators. The chemical and physical properties of the PFA collected by each of these systems differs greatly, with PFA collected from electrostatic precipitators having a significantly higher pozzolanic activity, or strength, when mixed with water. Since all new power stations and many of the older power stations in the country are now equipped with electrostatic precipitators, research into ash behaviour has concentrated on PFA from this source.

Usually, flue gases pass through three or four banks of precipitators, referred to as fields, before being released into the atmosphere. Over 75 per cent of the PFA is collected by the first field, Field 1, whilst only 1 to 3 per cent of the PFA is collected by the last field in the system. Grootvlei Power Station is currently the only power station disposing of electrostatically precipitated PFA in underground workings in the form of ashfill. Consequently, most of the laboratory research into the properties of PFA has been conducted on PFA from this source. Similarly, nearly all field investigations have been conducted at Springfield Colliery, the disposal site for the ashfill.

A schematic plan of the ash collection and disposal system at Grootvlei Power Station is shown in Fig. 29. Four fields of electrostatic precipitators are employed at the power station. The percentage of each ash type produced, including clinker, and its average grain size, $D_{50}^*$, immediately prior to being pumped underground is

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$D_{50}^*$ is the particle size whereby 50 per cent (by weight) of the material consists of particles having a smaller nominal diameter.
also shown in Fig. 29. The grading curve of each ash type is shown in Fig. 30 along with that of a typical mill tailings material. It can be seen that PFA is a considerably finer material than mill tailings.

Each ash type is stored in separate hoppers on surface and pumped underground separately. Ash is mixed with water and pumped overland to be discharged down large diameter boreholes, from where it then gravitates through the mine workings in 250 mm diameter steel pipes to the ashfill site. Since no booster pumps are used underground, the ash content of the slurry has to be reduced to about 20 per cent solids by weight to extend the horizontal area of influence of an ashfilling borehole to a maximum distance of 5 km.

Sections of a colliery which are ashfilled have dimensions of about 200 x 200 m. Retaining walls are constructed around the perimeter of the area and the ash discharge point is selected to ensure a uniform ashflow throughout the area. Generally, the ash discharge point is located at the highest point in the area, with the lowest point in the area serving as the water discharge point.

Ashing of an area is normally restricted to a duration of one to two hours once or twice per day, during which time only one type of ash is deposited. This is to allow time for excess water to drain off, since at the very low slurry concentration of 20 per cent solids by weight, 8 m$^3$ of water is pumped into the workings for every 1 m$^3$ of ash placed. Ashfill is placed within an area at a rate of about 200 tonnes per hour (of ash), resulting in a ± 40 mm thick ashfill layer per ashing period.

Coarse ash tends to settle quickly out of the slurry and consequently a mould of coarse ash builds up around the
ash discharge point. However, fine ash remains in suspension much longer and tends to settle far from the discharge point. This results in segregation of the various ash fractions and thus, in a variable quality ash fill throughout an area.

8.4.3 Summary of ash properties which influence ashfill quality

Because of the current method of ash placement, ashfill comprises numerous thin layers of ash of differing types. Analysis of ashfill samples has highlighted that very large variations exist in the quality of ashfill constituting each of these layers. Such variations cannot be tolerated and ashfill quality must be carefully controlled if full advantage is to be taken of the potential support properties of ashfill. Therefore, considerable field and laboratory research has been conducted into those factors which govern in-situ ashfill quality. This research is detailed in Appendix VII. The more significant findings of the research include:

1) Pozzolanic activity of PFA, slurry concentration and time are the most important parameters controlling ashfill quality.

2) The pozzolanic activity of PFA is determined by the physical, mineralogical and chemical properties of the material.

3) The specific surface area and free lime content is a good measure of the pozzolanic activity of PFA produced from power stations equipped with electrostatic precipitators in the four thick seam coalfields. These parameters should not be less than 2 000 cm²/g and 2.5 per cent, respectively, if good quality ashfill is to be achieved.
iv) Ashfill quality improves markedly with increasing slurry concentration.

v) Ashfill gains strength slowly with time. Depending on the pozzolanic activity of the source material, the slurry concentration, and ashfill placement conditions, ashfill strength may only approach its ultimate value some 6 months after placement.

vi) The modulus of deformation of ashfill is a direct measure of ashfill quality.

vii) Ashfill quality can be improved significantly by grinding Field 1 PPA.

On the basis of these research findings, it can be concluded that with modifications to the current ash disposal reticulation system and with adequate supervision it is both practically and economically feasible to achieve a consistently high quality in-situ ashfill. However, a minimum period of at least 3 to 6 months is required before ashfill attains this degree of quality. Consequently, ashfilling must be incorporated into mining operations in such a manner that the strength properties of ashfill are not required to control strata displacement within the first six months of ashfill placement.

8.5 The Effect of Ashfill on Pillar Behaviour

8.5.1 Conceptual model of pillar failure

To understand the role ashfill can play in stabilising coal pillars, thereby enabling increased percentage extraction to be achieved from bord and pillar workings in thick coal seams, it is necessary to examine briefly the mode of failure of a coal pillar. Large scale
in-situ coal pillar tests by Wagner (1974), in which a displacement-controlled loading system was used, provided a detailed insight into the complex process of pillar failure. Fig. 31 shows the distribution of vertical stresses in the centre plane of a coal pillar at different stages of pillar compression. Also shown in this figure is the stress-compression diagram for the whole pillar. Two points emerge clearly from Fig. 31. Firstly, the load bearing capacity of the pillar corners and, to a lesser extent, pillar sides is small compared to that of the centre of the pillar. This highlights the importance of confinement on the strength of a pillar. Obviously, the corners and sides are the least confined portions of the pillar whereas the central portion is subjected to the greatest confinement. Secondly, the central portion of a coal pillar is capable of withstanding extremely high stresses even if the outer portions of the pillar have already failed.

It follows from these observations that even a small amount of confinement could result in a marked increase in overall pillar strength. Confinement to the sides of a coal pillar can be provided in a number of ways, for example, bolting of pillar sides and long wire ropes applied around the perimeter of the pillar. But by far the most effective means of confining a pillar is to fill the voids around the pillar. Fill material provides confinement to the pillar in two ways. Firstly, because of its weight, it exerts a certain pressure on the sides of the pillar. This pressure increases linearly with depth of fill but is generally very small because of the limited height of fill and the relatively low density of fill. For ashfill the effective fill pressure is typically of the order of 10 to 50 kPa. Far more important is the confinement which the fill material provides in reaction to lateral expansion of the pillar.
FIGURE 31 Distribution of vertical stress in a pillar undergoing compression (Wagner, 1974).
It is well known that if the load acting on a pillar is increased, the pillar will shorten in the direction of the applied load. At the same time the pillar expands laterally. This process is known as the Poisson effect. As long as the applied stresses are small compared to the strength of the pillar, the lateral deformations of the pillar are small. If the stresses acting on the pillar are increased and fracturing of the unconfined corners and sides of the pillar commences, the lateral deformation behaviour of the pillar changes markedly. This process is known as dilatation and manifests itself in the form of slabbing and spalling. A representative example of the lateral deformation behaviour of a coal pillar is given in Fig. 32. It can be seen that pillar dilatation commences at a stress level of about one half of the ultimate strength of the pillar and that the rate of dilatation reaches a maximum just prior to pillar failure. Also shown in Fig. 32 is the emission of micro-seisms which are indicative of internal fracturing in the pillar. The close relationship between lateral deformation and frequency of internal fracturing is remarkable.

From the discussion of the mode of pillar failure it follows that the main objective of fill is to provide confinement to the pillars and not to support the weight of the overburden. The effect of filling bords with ashfill is that the fill material will resist the lateral expansion of the pillar. Fig. 33 shows a typical section through an ashfilled bord and pillar panel. In this figure \( w \) and \( B \) denote the pillar and bord widths, respectively. The lateral expansion of the pillar that occurs after the introduction of fill is denoted by \( 'w \). For reasons of symmetry no horizontal movements can occur in the vertical planes I and II through the centre of the pillar and the centre of the bord, respectively. If \( E_F \) is the effective modulus of
FIGURE 32 Pillar behaviour during compression (Wagner, 1974).
Figure 33 Diagrammatic section through an ashfilled bord and pillar panel.
deformation of the fill material, then the fill reaction, \( O_F \), is given by the relationship -

\[
O_F = \varepsilon_{tF} \frac{E_F}{B} = \frac{\Delta W}{E} = k_F \Delta W, \quad \text{(MPa)}
\]  

(5)

where \( \varepsilon_{tF} \) is the lateral fill strain, and

\[
k_F = \frac{E_F}{B}, \quad \text{the fill stiffness (MN/m^3)}.
\]

Two important conclusions can be drawn from Eqn. (5). Firstly, the effectiveness of filling is directly proportional to the fill stiffness, \( k_F \). In turn, the fill stiffness is directly proportional to the quality of the fill material, as expressed by its effective modulus of deformation, and inversely proportional to the bord width. Secondly, the confinement provided to the pillar by the fill increases with lateral expansion of the pillar. Since most of the lateral expansion of a coal pillar is caused by slabbing and spalling of pillar sides, fill is most effective where and when it is needed most.

Further important conclusions can be deduced from Eqn. (5) if the lateral pillar displacement, \( \Delta W \), is expressed in terms of lateral pillar strain, \( \varepsilon_{tP} \), as -

\[
\sigma_F = \frac{E_F \cdot W \cdot \varepsilon_{tP}}{B} = k_F \cdot W \cdot \varepsilon_{tP}, \quad \text{(MPa)}
\]  

(6)

This equation highlights that the effectiveness of filling is also directly proportional to pillar width. Thus, the greatest benefits will be gained from ashfill at depth, where pillar sizes are large. Eqn. (6) may also be expressed as -
deformation of the fill material, then the fill
reaction, \( \sigma_F \), is given by the relationship -

\[
\sigma_F = \varepsilon_F \cdot E_F = \frac{\Delta w}{B} \cdot E_F = k_F \cdot \Delta w, \quad \text{(MPa)}
\]

where \( \varepsilon_F \) is the lateral fill strain, and

\[ k_F = \frac{E_F}{B}, \text{ the fill stiffness (MN/m}^3) \].

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\sigma_F = \frac{E_F \cdot \Delta w \cdot \varepsilon_F}{B} = k_F \cdot w \cdot \varepsilon_F \quad \text{(MPa)}
\]

This equation highlights that the effectiveness of filling is also directly proportional to pillar width. Thus, the greatest benefits will be gained from ashfill at depth, where pillar sizes are large. Eqn. (6) may also be expressed as -
where $k_c = \frac{v}{B}$ and is the strain magnification factor.

The strain magnification factor, $k_c$, relates pillar strain to fill strain for any given mining geometry by the relationship -

$$e_F = k_c \cdot e_p$$

Because of the confinement provided to the pillar by the roof and floor strata, the lateral expansion of a pillar, in particular that of failing pillars, is usually greatest at mid-height, unless a very weak band is present in the seam or at some other horizon. Therefore, for filling to be most effective, the height of fill must be more than half the pillar height. Filling should preferably extend up at least two-thirds of the total height of the pillar. Early placement of fill is also important since the fill reaction does not depend on the total lateral expansion of the pillar but only on that portion, \( w \), which occurs after filling of the bords.

Thus far, fill has been considered as an ideal, homogeneous material. However, as previously noted, current ashfilling technology results in an ashfill that is comprised of a large number of thin layers of fill of varying properties. Therefore, the assumption of a uniform modulus of deformation, $E_F$, of the fill requires some clarification. The effective modulus of deformation, $E_F$, of a horizontally layered fill material comprising of layers of different thickness, $t_i$, and deformation property, $E_i$, which is compressed by the lateral expansion of a coal pillar is given by the following equation -
\[ F_p = \frac{1}{T} \sum_{i=1}^{n} E_i t_i, \quad \text{(MPa)} \quad (9) \]

where \( T \) is the total thickness of fill (m).

The significance of Eqn. (9) is demonstrated if an ashfill comprising 80 per cent low quality ash and 20 per cent high quality ash is considered. Typical moduli of deformation of the two ash types are 20 MPa and 200 MPa, respectively. Applying Eqn. (9) it is found that the effective modulus of deformation of the layered ashfill is 56 MPa. In other words, the presence of 20 per cent good quality ash results in almost a threefold improvement in the effective properties of the poor quality ashfill. Similar considerations illustrate that if the pozzolanic activity of Field 1 PPA could be improved to that of Field 3 PFA, the effective modulus of deformation of ashfill would be more than doubled.

2.5.2 Model pillar tests

In order to assess quantitatively the effects of ashfill on pillar strength a number of model pillar tests were conducted. The results of initial tests were very scattered and little information could be deduced from them at the time. The scattered results were attributable to specimen collection and preparation processes and to the testing system. However, in the light of a better understanding of the properties of PFA these tests yielded valuable results and these are included with results obtained from more recent tests.

In the interim period a first estimate of the increase in pillar strength due to ashfill was obtained by utilizing Coulomb's criterion (Cook et al., 1973) whereby strength increase due to confining pressure may be described by the formula -
\[ \sigma_{zm} = C_0 + K \sigma_1, \quad (\text{MPa}) \]  

(10)

where \( \sigma_{zm} \) is the maximum axial stress (MPa), \( \sigma_1 \) is the confining pressure (MPa), \( C_0 \) is the uniaxial compressive strength (MPa), and \( K \) is a material property describing increase in strength with confining pressure, \( \sigma_1 \).

Whilst horizontal pillar strain is a function of the pillar width:height ratio, a representative value at failure is \( 2 \times 10^{-3} \). Thus, for an ashfill with an effective modulus of deformation of 200 MPa, the pillar confining pressure, \( \sigma_1 \), is:

\[ \sigma_1 = 200 \times 10^6 \times 2 \times 10^{-3} \]
\[ = 0.400 \text{ MPa} \]

The uniaxial compressive strength of a unit cube coal pillar was calculated to be 7.2 MPa, using the formula:

\[ \text{Strength} = 7.2 \sigma^{0.46} \quad (\text{MPa}) \]  

(11)

Salarmon and Munro (1967) established that this formula defines the strength of South African coal pillars.

Finally, taking a representative value of \( K \) equal to 5 for coal, Eqn. (10) was solved to yield:

- \( \sigma_{zm} = 7.2 \text{ MPa} \) for no ashfill
- \( \sigma_{zm} = 7.2 + 2.0 = 9.2 \text{ MPa} \) for ashfill

Thus, good quality ashfill was estimated to increase the strength of a coal pillar with a width:height ratio of 1 by about 28 per cent.
This estimate has been improved considerably in the light of more recent model pillar tests. In these latest tests, coal samples of 150 mm diameter and width:diameter ratios of 1 and 2 were centred in a steel pipe of 215 mm internal diameter and 6 mm wall thickness, Plate 3. The internal circumference of the pipe represents the vertical plane of symmetry through the centre of an ashfilled bord, depicted by the plane labelled 'I' in Fig. 33. The wall thickness of the pipe was designed so that this plane of symmetry would displace less than 0.03 per cent of the pipe diameter, or 0.07 mm during testing. The cavity between the model pillar and the steel pipe was filled with 25 mm thick layers of ashfill prepared from Grootvlei Field 3 PFA at a slurry concentration of 60 per cent solids by weight. One layer of ashfill was placed per day until the height of the ashfill was within 15 mm of the top of the model pillar. Ashfill samples were also collected for testing with model pillars. The radial dimensions of a coal pillar and ashfill correspond to a percentage areal extraction of 59 per cent.

After curing for the required period of time the model coal pillars were loaded under uniaxial compression at a displacement rate of 6 mm/hr. The load acting on the coal pillar was recorded using a strain gauged load cell whilst strain gauged cantilever arms measured vertical compression of the coal pillar. This latter measurement was required since a constant rate of loading could not be achieved when the peak strength of the pillar was approached, due to a limited amount of softness in the loading system. The lateral displacement of the coal pillar at mid-height was measured at 90 degree intervals around the circumference of the pillar using a system of pins and cantilever arms, Plate 4. Finally, pressure build-up in the ashfill at mid-height was recorded at four equal intervals around the circumference of the steel pipe using a network of strain gauged pressure
PLATE 3 Model coal pillars confined by ashfill.
1. Platen.
2. Vertical displacement cantilever arms (strain gauged).
3. Load cell (strain gauged).
4. Platen.
5. Confining barrel.
7. Lateral ashfill pressure pads (strain gauged).
8. Spherical coat.

PLATE 4 Instrumentation for testing model coal pillars confined by ashfill.
pads, Plate 4. All measurements were recorded continuously by a six pen chart recorder. An overall view of the testing system is shown in Plate 5.

To date, most pillars have only been tested at 200 days after placement of ash. The results of these tests are shown in Fig. 34, along with the results obtained from the previous testing program. The typical behaviour of pillars, both with and without ashfill, during testing is shown in Fig. 35. The average uniaxial compressive strength, $C_0$, and modulus of deformation, $E_d$, of ashfill samples was found to be 0.535 MPa and 100.3 MPa respectively. These values are considerably lower than the 200 day values presented in Fig. VII.5 but, nevertheless, agree well with the correlation established between $E_d$ and $C_0$, defined by Eqn. (VII.2). The low values are almost certainly due to the lower temperature to which the ashfill was subjected during the 200 days of curing.

The latest model pillar tests confirm that ashfill can increase pillar strength significantly, Fig. 34. On the basis of averaged test results, the strength of model coal pillars with a width:height ratio of 1 was increased by over 50 per cent and those with a width:height ratio of 2 by about 40 per cent due to the effects of confinement by ashfill. Furthermore, Fig. 35 illustrates that ashfill also has a significant influence on the post-failure behaviour of the coal pillars. Not only is the failure controlled but also, after sufficient post-failure compression, the load carrying capacity of a pillar stops decreasing and increases with further compression.

The results of previous model pillar tests, presented in Fig. 34, are believed to have been influenced strongly by specimen preparation. In particular, broken specimens were used to prepare the large width:height ratio
1. Loading frame.
2. Load cell.
3. Confining barrel.
4. Spherical seat.
5. Jack.
7. Screw displacer.
8. Chart recorder.
9. Strain gauge amplifiers.

PLATE 5 Overall view of model pillar testing system.
FIGURE 34 The influence of ashfill on model pillar strength.
Typical behaviour of model pillars during testing.
FIGURE 35 Typical behaviour of model pillars during testing.
pillars whilst the longer, and presumably stronger specimens, were used to prepare the smaller width:height ratio pillars. Thus, this preparation procedure effectively masked the influence of width:height ratio on pillar strength. Nevertheless, this consideration applies to both confined and unconfined pillars, and so it may be reasonable to conclude that the test results illustrate the influence of ashfill on pillar strength.

In these earlier tests, ashfill was prepared at a slurry concentration of 50 per cent solids by weight and pillars were tested within 48 hours of being confined by ashfill. As the lateral deformation of the confined model pillars increased water ran freely from the ashfill. It is logical to presume that water would also have been forced into any structural weaknesses within the coal pillars, thereby lubricating the surfaces of these weaknesses. This factor, in conjunction with the fact that the ashfill would have behaved as an almost cohesionless material, could easily have resulted in the strength of confined pillars being reduced rather than increased by the presence of ashfill. The scatter of test results, even for pillars with large width:height ratios supports this conclusion. In retrospect, the tests probably highlight the need to allow sufficient time for ashfill to cure before utilizing its potential support properties.

On the basis of the latest model pillar tests, the strengthening effect of ashfill on coal pillars is significantly greater than that previously estimated. In particular, an increase in pillar strength of almost double that estimated for a pillar with a width:height ratio of 1 has been achieved utilizing an ashfill of only half the stiffness (modulus of deformation) of that assumed in the estimate. But, before the results of the model pillar tests can be applied to the design of bord and pillar workings a number of areas require further
research. For example, the strength of model pillars (unconfined and confined) with a width:height ratio of 2, Fig. 34, must be more accurately defined by additional testing. However, one of the most important areas requiring additional research is the influence of pillar width:height ratio on model pillar test results.

Whilst the width:height ratio of model pillars was manipulated by changing the pillar length, this could also have been achieved by changing the pillar width. A subtle difference exists between these two aspects. When the width:height ratio of a pillar (or specimen) is increased by reducing the height:

1) pillar volume is reduced;

ii) pillar stiffness (defined as EA/h or Ew²/h for a square pillar), increases linearly in direct proportion to the decrease in the pillar height;

iii) loading conditions at the ends of the pillar (that is, lateral end constraints) remain unchanged;

iv) for an assumed constant lateral pillar strain at failure, lateral pillar displacement at failure is constant.

However, when the width:height ratio of a pillar is increased by increasing the width:

1) pillar volume is increased;

ii) pillar stiffness increases quadratically in direct proportion to the pillar width squared;

iii) loading conditions at the ends of the pillar (that is, lateral end constraints) are changed;
iv) for an assumed constant lateral pillar strain at failure, lateral pillar displacement at failure increases.

The influence of points (i) and (iii) on pillar strength can be taken into account by expressing the pillar strength formula, Eqn. (11), as -

\[
\text{Strength} = \frac{7.2 \cdot R^{0.59}}{\sqrt{V^{0.067}}} \quad (\text{MPa})
\]

(12)

where \( R \) is the pillar width:height ratio, and \( V \) is the pillar volume.

But, as far as can be ascertained, the influence of pillar width (or height) and pillar width:height ratio on lateral pillar strain at failure has yet to be defined quantitatively. This definition is required for interpreting model pillar test results, since, as reference to Eqn. (6) shows, ashfill effectiveness is directly proportional to lateral pillar strain. That is, had the width:height ratio of model pillars been manipulated by changing pillar width rather than pillar height, the effectiveness of ashfill may have been different.

This aspect is being researched currently. Preparations are also in progress to test model pillars of the same width as those previously tested, but with a width height ratio of 3. A limited number of tests (2) have also been conducted on model pillars with a width:height ratio of 2 which have been confined by ashfill that has cured for 400 days. These tests indicate that pillar strength is increased by almost 55 per cent (as compared to 40 per cent at 200 days). Testing of ashfill samples indicates that during the 200 days since the previous pillar tests the modulus of deformation of the ashfill
(which is directly proportional to ashfill stiffness) increased from an average of 100.3 MPa to 127.6 MPa, thus accounting for the increase in pillar strength. Again, the relationship between the uniaxial compressive strength, $C_0$, and modulus of deformation, $E_d$, satisfies Eqn. (VII.2), whilst both values are lower than those previously measured in the laboratory for 400 day old ashfill samples, Fig. VII.5.

8.5.3 Evaluating and optimising the benefits of ashfill in bord and pillar workings

On the basis of model pillar tests to date, it is not unreasonable to assume that good quality ashfill may increase pillar strength by up to 50 per cent, especially since the modulus of deformation of model pillar ashfill has been considerably less than that which has often been recorded for both laboratory and in-situ derived ashfill samples. Assuming such to be the case, a review of safety factors and percentage extraction highlights those areas in which the greatest potential exists for utilizing ashfill in bord and pillar workings in thick coal seams. Further assumptions on which this evaluation is conducted are:

i) the final effective safety factor of workings is not to be less than 1.6 (corresponding to less than a 0.3 per cent chance of collapse);

ii) the effective safety factor of workings is never to be less than 1.2, corresponding to about a 9 per cent chance of ultimate collapse (ashfilling to commence immediately after the formation of such workings);

iii) a maximum full face mining height of 6 m (based on strata control, operational and design considerations, especially at depth where large
(which is directly proportional to ashfill stiffness) increased from an average of 100.3 MPa to 127.6 MPa, thus accounting for the increase in pillar strength. Again, the relationship between the uniaxial compressive strength, $C_0$, and modulus of deformation, $E_d$, satisfies Eqn. (VII.2), whilst both values are lower than those previously measured in the laboratory for 400 day old ashfill samples, Fig. VII.5.

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2) the effective safety factor of workings is never to be less than 1.2, corresponding to about a 9 per cent chance of ultimate collapse (ashfilling to commence immediately after the formation of such workings);

3) a maximum full face mining height of 6 m (based on strata control, operational and design considerations, especially at depth where large
mining heights result in impractical pillar centre
distances);

iv) a bord width of 6 m.

Three types of thick seam bord and pillar mining methods,
each already having been described in Appendix III, need
to be evaluated, namely:

a) full face, (or equivalent methods such as bord and
pillar mining with top- or bottom-coaling) limited
to a minimum safety factor of 1,6 and a maximum
mining height of 6 m (by preceding assumptions (i)
and (iii) respectively);

b) with top- or bottom-coaling followed by stowing,
limited to a minimum safety factor of 1,2 and a
maximum mining height of 6 m (by preceding
assumptions (ii) and (iii) respectively);

c) with repeated cycles of stowing and top-coaling,
limited to a final effective safety factor of 1,6 ,
a minimum effective safety factor of 1,2 , at any
stage during mining operations, and a maximum
unfilled mining height of 6 m (by preceding
assumptions (i), (ii) and (iii) respectively).

Since a safety factor is simply the ratio between pillar
strength and pillar load, ashfilling will result in a 50
per cent increase in effective pillar safety factor.
That is, if pillars are confined by ashfill, a safety
factor of 1,07 will correspond to an effective safety
factor of 1,6. In the case of bord and pillar mining
with top- or bottom-coaling followed by stowing, case
(b), the full benefit of the pillar strengthening
effects of ashfilling cannot be utilized since the
safety factor of the workings cannot be less than 1,2.
Thus, after ashfilling, the effective final safety
factor is 1.8. However, with repeated cycles of stowing and top-coaling the opportunity exists to reduce this final safety factor to 1.6 by extracting another slice of coal on top of the ashfill. A method for determining the effective safety factor of partially ashfilled workings, that is, workings in which a second or subsequent unfilled slice has been extracted on top of the ashfill of the preceding slices, has yet to be devised. But, under all practical circumstances, if the safety factor of the workings disregarding the presence of ashfill is not less than 1.07 (corresponding to an effective totally ashfilled safety factor of 1.6) the effective safety factor of partially ashfilled workings will be at least 1.2.

In this regard, a design consideration needs to be noted regarding bord and pillar mining with repeated cycles of stowing and top-coaling. It was noted in section 8.5.1 that stowing should extend to at least two-thirds of the pillar height. Therefore, when employing this method, the height of the workings in the second slice may have to be restricted to only half that of those in the first slice. This is particularly important if only two slices are being mined, since considerable pillar dilatation could occur during the mining of the second slice if mining height is excessive. If more than two slices are being mined the safety factor of workings during the second slice operation, disregarding the presence of ashfill in the first slice workings, will probably exceed 1.6 and so pillar dilatation prior to ashfilling will be minimal. In all subsequent slices the ashfill will extend to at least two-thirds of the total extracted height.

Two approaches have been adopted in calculating the percentage extraction that could be achieved utilizing bord and pillar mining with repeated cycles of stowing and top-coaling, namely:
i) Select the pillar size that results in a safety factor of 1.6 in a 6 m thick seam if ashfilling were not utilized. Using this pillar size, compute the maximum height that could ultimately be extracted utilizing repeated cycles of stowing and top-coaling. On the basis of assumptions (i) and (iv) this approach yields an ultimate extracted height of approximately 11 m, irrespective of depth.

ii) Select a specific seam thickness and calculate the pillar size required such that when the full seam thickness is ashfilled the effective safety factor is 1.6. In this case seam thicknesses of 6 and 8 m were selected. The trends and significance of ashfill as highlighted by each of these two approaches are almost identical.

The maximum panel percentage extraction that can be obtained at various depths from 6, 8 and 11 m thick seams utilizing full face bord and pillar mining, and bord and pillar mining with top- and/or bottom-coaling followed by stowing, is shown in Fig. 36(a). It can be seen that the increase in percentage extraction achieved by utilizing the latter method increases with decreasing seam thickness and increasing depth. At a depth of 50 m the method results in an additional 3 to 6 per cent extraction whilst at a depth of 200 m an additional 5 to 9 per cent of reserves can be recovered. Because the 6 m restriction on mining height applies, this additional extraction is achieved as a result of the reduction in pillar width which occurs when the working safety factor is relaxed from 1.6 to 1.2. As such, the increase in percentage extraction achieved is less than if the safety factor were relaxed by increasing the mining height.
(a) Bord and pillar mining with top- or bottom-coaling followed by ashfilling.

(b) Bord and pillar mining with repeated cycles of ashfilling and top-coaling.

**FIGURE 36** Increase in percentage extraction achieved by incorporating ashfilling into bord and pillar mining.
Similarly, the increase in percentage extraction which results from utilizing bord and pillar mining with repeated cycles of stowing and top-coaling, rather than full face bord and pillar mining in 6, 8 and 11 m thick seams is shown in Fig. 36(b). Increases in percentage extraction are also tabulated in Table 28. For seams in excess of 6 m thick, the increase in percentage extraction achieved with the former method increases as depth decreases. An additional 20 to 30 per cent of reserves can be extracted at shallow depth (+50 m) from 8 to 11 m thick seams. At a depth of 150 m this increase reduces to the order of 12 to 17 per cent whilst at a depth of 300 m it is of the order of 8 to 11 per cent.

**TABLE 28** Additional percentage extraction that could be achieved by incorporating repeated cycles of ashfilling and top-coaling into bord and pillar mining in thick coal seams.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Seams Thickness (m)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
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<tbody>
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<td>6</td>
<td>10,6</td>
<td>11,8</td>
<td>11,9</td>
<td>11,1</td>
<td>10,7</td>
<td>9,4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20,6</td>
<td>17,6</td>
<td>15,5</td>
<td>13,2</td>
<td>10,7</td>
<td>9,2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>30,0</td>
<td>21,9</td>
<td>16,5</td>
<td>12,8</td>
<td>9,2</td>
<td>7,9</td>
<td></td>
</tr>
</tbody>
</table>

The significant decrease in additional percentage extraction achieved as depth increases to 150 m can be explained by considering the percentage extraction that would be achieved by full face bord and pillar mining in an 8 m and an 11 m thick seam if the 6 m mining height restriction did not apply. This percentage extraction
is also plotted in Fig. 36(b). Consider the case of mining in an 11 m thick seam. Curve A11 represents the percentage extraction that would be achieved utilizing bord and pillar mining without ashfilling to a height of 6 m. Curve B11 represents the percentage extraction that would be achieved if the 6 m restriction on mining height did not apply and bord and pillar mining without ashfilling extended to a height of 11 m. Curve C11 represents the percentage extraction that could be achieved utilizing bord and pillar mining with repeated cycles of ashfilling and top-coaling. It is apparent that at a depth of 50 m, the 6 m restriction on mining height results in the non-extraction of about 20 per cent of the coal reserve. This differential, defined by B11-A11, reduces rapidly with increasing depth to 150 m, where it is of the order of only 5 per cent. With further increases in depth the differential reduces at a much slower rate. Similar trends apply in the case of an 8 m thick seam (curves A8, B8, C8).

When repeated cycles of ashfilling and top-coaling are incorporated in bord and pillar mining, practical difficulties associated with mining to heights in excess of 6 m are removed. Pillar centre distances do not exceed those associated with mining to a height of 6 m, whilst practical mining and support problems are overcome because the effective working height is reduced by the presence of ashfill. Thus, those reserves represented by B11-A11 can be extracted. Consequently, the trend for the magnitude of B11-A11 to decrease rapidly with depth influences the trend of curve C11. That is, the percentage extraction achieved by bord and pillar mining with repeated cycles of ashfilling and top-coaling decreases rapidly with depth.

The preceding discussion highlights a significant conclusion concerning bord and pillar mining with repeated cycles of ashfilling and top-coaling. That is,
the increase in percentage extraction achieved with the method, defined in the general case, by C-A, has two components, namely:

i) that increase in percentage extraction defined by B-A, which is only due to ashfill functioning as a working platform, and

ii) that increase in percentage extraction defined by C-B, which is due to the strengthening effect of ashfill on pillars.

Irrespective of any restrictions imposed on mining height, the method will always achieve an increase in percentage extraction, defined by C-B. Reference to Fig. 36(b) shows that this increase is typically 10 to 12 per cent, irrespective of seam thickness (up to 11 m) and depth (down to 200 m).

It could be concluded, therefore, that if ashfill increases pillar strength by 50 per cent, and a 6 m restriction exists on mining height, bord and pillar mining with top- or bottom-coaling followed by ashfilling can result in the extraction of an additional 3 to 6 per cent of reserves at shallow depth (+50 m) from seams less than 11 m thick. At a depth of 200 m an additional 9 per cent of reserves will be recovered from a 6 m thick seam, reducing to 5 per cent in an 11 m thick seam. Alternatively, bord and pillar mining with repeated cycles of ashfilling and top-coaling may result in the extraction of an additional 8 per cent of reserves from a 6 m thick seam and 30 per cent of reserves from an 11 m thick seam at a depth of 50 m. At a depth of 200 m an additional +12 per cent of reserves can be extracted from seams 6 m to 11 m thick.
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But, these conclusions assume that ashfill increases pillar strength by 50 per cent irrespective of depth. This is not a valid assumption since the width:height ratio of pillars tends to become much greater with increasing depth and, as previously noted, ashfill effectiveness changes with width:height ratio. In particular, theoretical considerations, reflected in Eqn. (6), section 8.5.1, indicate that the greatest benefits of ashfill on pillar strength should be achieved at depth since, because pillar widths are larger, a specific pillar strain will induce a greater fill reaction or confinement pressure. This behaviour is not reflected in the preceding calculations of percentage extraction. Nevertheless, these calculations provide an initial estimate of the benefits to be gained from incorporating ashfilling into bord and pillar mining. At depths in excess of 150 m, where the greatest need exists to increase percentage extraction from bord and pillar workings in thick seams (e.g. in the South Rand Coalfield) these benefits are probably under-estimated.

Finally, it should be noted that in the light of theoretical considerations, Eqns. (5) and (6), the potential benefits of ashfill can be optimised by:

1) increasing the modulus of deformation, Eq, of the ashfill (which correlates with ashfill strength);

2) restricting bord width;

3) placing ashfill to a height of at least two-thirds of the pillar height as soon as possible after mining.
8.5.4 In-situ experience

During 1979 a full scale mining experiment, aimed at increasing volumetric extraction from thick coal seams, was completed in the combined No. 2 and No. 3 horizons at Springfield Colliery. The experimental mining was conducted at a depth of 175 m in a bord and pillar section which measured 150 x 200 m and which had been mined to a safety factor of 1.3. The average width of pillars and bords was 16 m and 6 m respectively. Pillars had a width:height ratio of 4.27. The coal horizon was 12 m thick and the area was isolated from adjacent panels by large barrier pillars and unmined ground.

The aim of the experiment was to successively top-coal and ashfill the area until no coal remained in the roof, thereby reducing the width:height ratio and thus the nominal safety factor of the coal pillars. After the completion of primary mining operations and prior to ashfilling, 24 extensometers were installed in the sides of the coal pillars to monitor pillar dilatation. Two boreholes drilled from surface into the coal horizon were also instrumented to monitor strata displacement. During ashfilling 18 flatjacks were installed in the ashfill, adjacent to the pillar extensometers, to monitor and correlate the build-up of ashfill pressure with pillar dilatation.

The safety factor of the experimented area was ultimately reduced to less than 0.6, corresponding to a 99.94 per cent chance of collapse in the absence of ashfill. Although the upper 3 m of the workings was not ashfilled minimal deterioration occurred within the area. The maximum lateral pillar displacement measured was only 2 mm, whilst the pressure build-up in the ashfill was, typically, 0.05 MPa. This corresponds to an effective ashfill modulus of deformation of 150 MPa.