PASTE BULKHEAD FAILURES

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ABSTRACT: Bulkhead failures represent one of the greatest risks of any minefill operation. This paper details five bulkhead failures that have occurred at two different Australian paste filling operations over the past three years. The bulkhead design techniques are outlined, as are specific details of the failures, analysis of the failures and discussion of the causes and finally the resulting changes in the design and filling strategies adopted.

1. INTRODUCTION

Mine fill operations introduce a number of significant risks into the overall mining operation. Arguably the greatest of these risks is bulkhead failure. In this paper "bulkhead" refers to an impermeable (water retaining) structure; systems may be established to drain water from behind such bulkheads. "Barricade" refers to a permeable free draining structure. However, it should be noted that within Australia the terms "bulkhead" and "barricade" are used interchangeably to describe both draining and non-draining structures that contain paste fill within stopes.

Whilst the consequences of hydraulic fill bulkhead failures are well recognised in industry, the risks of paste fill bulkhead failures are not so well recognised. However, paste fill bulkhead failures are a significant risk and over the past three years a number of failures have occurred in Australia.

Unfortunately due to the sensitivity of bulkhead failures, limited information has historically been presented to the wider mining industry. Therefore, one of the key objectives of this paper is to present the details of five bulkhead failures, the likely causes for their failures, consequences and subsequent systems put in to reduce the risk.

The failures presented in this paper have occurred at two paste filling operations referred to as "Mine A" and "Mine B".

2. MINE A FILLING OPERATION

2.1. Introduction

Mine A, uses a pillarless retreat long hole open stoping mining method. The stopes are 30-60 m high and typically 20 m wide and 20 m along strike. The operation uses paste backfill as a passive support element and the paste is exposed both vertically and horizontally as part of the mining sequence.

The paste fill is produced from mine tailings taken in slurry from the processing plant. The tailings are dewatered, and combined with ordinary Portland cement (OPC). The paste is then reticulated to depths up to 1,000 m into the open stope voids.

2.2. Bulkhead Design

Mine A uses full sprayed fibrecrete bulkheads as shown in Figure 1. Figure 2 displays the geometry of a typical 5.0 m wide by 5.0 m high bulkhead. The fibrecrete is sprayed on a pre-fabricated steel frame. The frame does not form part of the barricade and simply provides a backing for spraying of the fibrecrete. No rockbolts or shear pins are installed through the bulkhead/rock interface. No holes of any kind are installed in the bulkheads. The bulkheads are remined using standard drill and blast techniques.

Fig. 1. Fibrecrete bulkhead. Bobcat drill rig shown coring paste from behind the bulkhead.

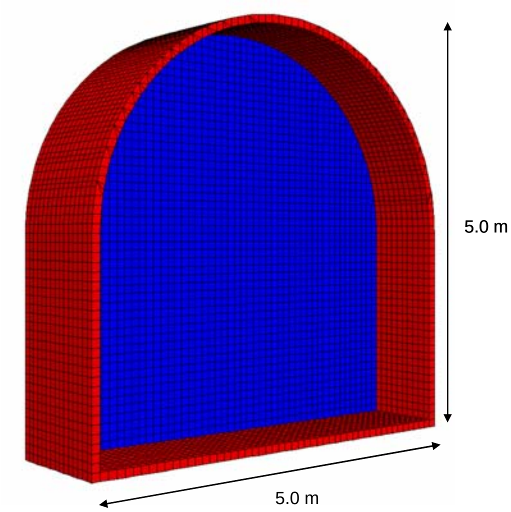
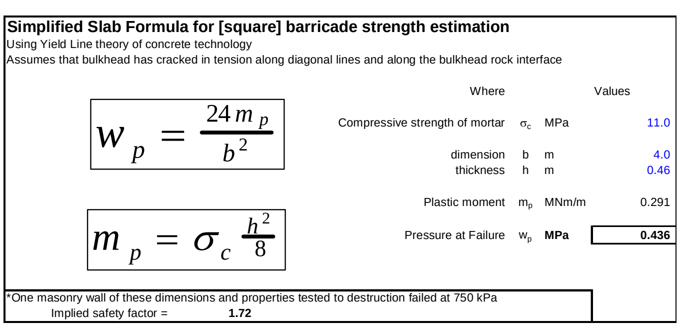


Fig. 2. Geometry of typical Mine A bulkhead.

The current methodology used to design the fibrecrete bulkheads is a form of yield line theory. Figure 3 illustrates the ultimate strength calculator used.



Simplified Slab Formula for [square] barricade strength estimation
Using Yield Line theory of concrete technology
Assumes that bulkhead has cracked in tension along diagonal lines and along the bulkhead rock interface

$$w_p = \frac{24 m_p}{b^2}$$

$$m_p = \sigma_c \frac{h^2}{8}$$

Where			Values
Compressive strength of mortar	σ_c	MPa	11.0
dimension	b	m	4.0
thickness	h	m	0.46
Plastic moment	m_p	MNm/m	0.291
Pressure at Failure	w_p	**MPa**	**0.436**

*One masonry wall of these dimensions and properties tested to destruction failed at 750 kPa
Implied safety factor = **1.72**

Fig. 3. Yield line bulkhead design calculator.

This formula was originally proposed by Beer (1986) to estimate the ultimate strength of a masonry barricade. As described by Revell & Sainsbury (2007), numerical modeling provides an improved method to model bulkhead ultimate strengths and Mine A is in the process of implementing the numerical modeling technique. However, the empirical evidence does support the use of the yield line calculator with many hundreds of bulkheads constructed and only specific factors have resulted in the three failures presented in this paper occurring.

The bulkhead design is based on the paste fill being poured into the stope at such a rate that the strength gain of the paste is at least equivalent to gravitational loads from the height rise of the paste. The bulkheads are designed to withstand 200 kPa. This is based on a maximum filling rate of 10 m per day (10 m * 2 t/m^3 * 9.81 m/s^2 ≈ 200 kPa). During this interval the paste begins to hydrate and the load translated to the wall is less than the hydrostatic pressure. As the mining has progressed deeper the footprint of the stopes has reduced. As a result, normal practice is now to pour a 7 m plug and allow this to cure for 24 hours before filling recommences. The 7 m plug ensures the bulkhead is fully covered.

The bulkhead fibrecrete thickness varies from 250 to 350 mm depending on the drive dimensions and the bulkheads are allowed to cure for 24 hours before filling commences.

3. MINE A FAILURE 1

3.1. Summary

The stope being mined was experiencing significant fall-off on one of the side walls. The increasing rate of fall-off prompted the decision to cease remote loading and commence paste filling. As the fill level in the stope reached the 10 metre limit in the first 24 hours, the bulkhead failed, resulting in approximately 500 m^3 of uncured fill flowing into the level (see Figure 4). No personnel were injured due to the failure. Investigations indicated that the failure resulted from the load imposed by 300 tonnes of rock falling off into the uncured paste fill.

Fig. 4. Photograph of bulkhead failure 1.

3.2. Causes and Contributing Factors

Based on a detailed investigation the following was identified:

- Original mining sequence and development designs resulted in falloff along one of the stope walls.
- Increasing rate of falloff prompted decision to start filling as quickly as possible.
- An unstable rill of material was left behind within the stope.
- Due to both the rill left behind in the stope and the stope footprint the 10 m height of fill was placed in less than 6 hours.
- The key item was that the bulkheads, filling strategies and procedures were based on static loading. The risk of dynamic loading had not been identified in the planning and operational stages of this particular stope or any stope at the mine.

The summary of causes above highlight one of the key issues when stope fall-off is occurring. Due to the fall-off, the objective is to fill the stope as quickly as possible to reduce the risk of further falloff causing production or safety issues for the mine. However, at the same time there is a need to limit the volume of uncured fill within a stope so that the consequences of a major falloff event are minimized.

3.3. Outcomes

The major step implemented was the introduction of fill exclusion zones behind the bulkheads. Mullock bunds and "No Entry" signs were placed a nominal distance back from the bulkhead. The aim is that the bunds would contain and reduce the energy of any failure events and it eliminates any personnel exposure directly at the bulkhead during the highest risk time, i.e. when the fill level is going past the bulkhead. No specific distance for placing the bunds back from the bulkhead was specified but rather the drive geometry is used where possible to place the bund around corners etc so that the energy of any fill failure is reduced before hitting the bund.

In addition the following additional steps were implemented.

- The failure occurred whilst a primary/secondary stoping sequence was in place. The mine had already planned to change to a pillarless retreat method to assist in controlling mining induced stresses.
- An arch (radius of curvature of 6.5 m) was added to the pre-fabricated steel frames. Figure 5 below illustrates the increase in ultimate load of the arched bulkhead relative to a flat bulkhead.
- Risk of falloff was added as a checklist item in the paste fill note.
- Fill manuals were updated to include detail of failure so that future personnel are trained on the potential for dynamic loading.

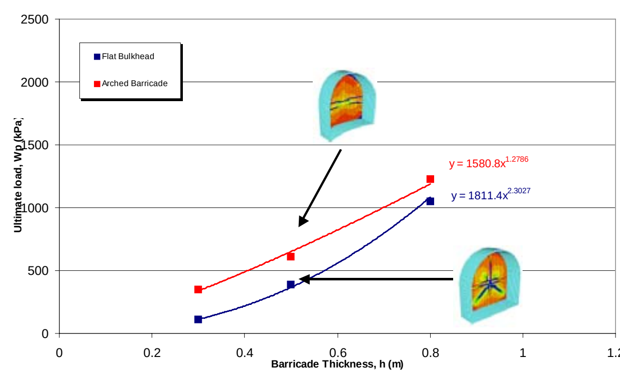


Fig. 5. Ultimate load for Mine A barricades after 1 day fibrecrete curing.

4. MINE A FAILURES 2 AND 3

4.1. Summary

Failures 2 and 3 were similar to Failure 1 in that the paste plug had been poured and was being allowed to cure. Fall-off from within the stope is then understood to have created dynamic loading on the bulkhead causing partial failure as shown in Figures 6 and 7.

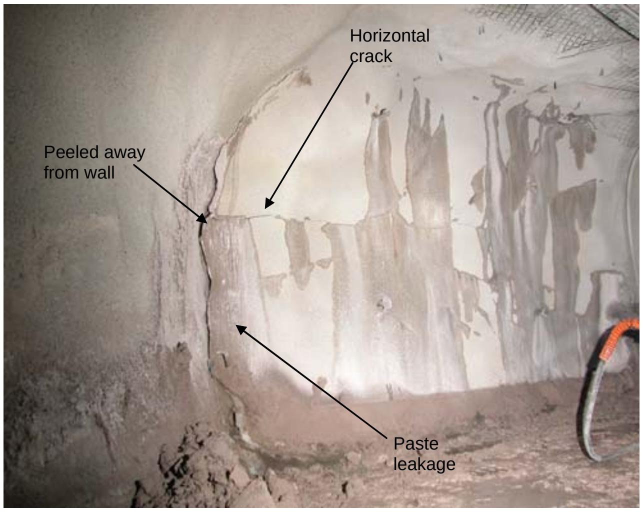


Fig. 6. Photograph of bulkhead Failure 2.

Fig. 7. Photograph of bulkhead Failure 3.

4.2. Causes and Contributing Factors

Based on a detailed investigation the following was identified:

- As with Failure 1 fall-off is believed to have created dynamic loading on the bulkhead.
- Both bulkheads were significantly wider (8 m) than standard bulkheads.
- Both bulkheads were positioned on the footwall drive/x-cut intersection.
- Both failures occurred along the bulkhead-wall rock interface.
- It should be highlighted that the bunding and "No Entry Signs" had been appropriately placed on the level and prevented any personnel from being exposed to the hazard and limited the area affected by the paste spill.

4.3. Outcomes

Additional controls implemented on the bulkhead design following Failures 2 and 3 were as follows:

- If initial investigations indicate the bulkhead must be built near an intersection, the location must be checked by the paste fill supervisor who will assess whether the bulkhead can be placed greater than 1 m from the intersection giving due consideration to exposing personnel to other hazards.
- When a bulkhead has to be built within 1 m of an intersection it should have rock bolts inserted into the rock wall to provide additional shear resistance.

5. MINE B FILLING OPERATION

5.1. Introduction

Mine B, uses an uphole bench stoping method to extract the narrow vein orebody. The ore is typically 0.5 m thick and dips at around 60°. The operation uses paste backfill as a passive support element and the paste is exposed vertically and horizontally simultaneously. Figure 8 shows a stope ready to be filled. The top of the paste plug covering the bulkhead can be seen.

Fig. 8. Mine B stope ready to be filled.

The paste fill is produced from reclaimed mine tailings from a tailings storage facility (TSF) and this is blended with 30% coarse sands that were extracted and stockpiled from a nearby open pit. The tailings and sand are combined with OPC and hypersaline water (TDS 166,000 mg/L). The paste is reticulated to depths up to 500 m into the open stope voids. The reticulation system is characterised by having a high horizontal to vertical ratio with stopes being filled with a horizontal to vertical ratio of 3.5. As a result, the paste fill has a relatively high slump of around 230 mm.

In the upper levels Mine B has only 2 mining fronts. As a result, the mining and paste fill cycle times are critical. The paste between the bulkhead and the brow of the stope is mined after 2 days and the vertical and horizontal paste fill is designed to be exposed after only 4 days.

5.2. Bulkhead Design

Figure 9 shows the details of a specific stope fill pour. It can be seen that each stope is composed of 3 panels. Paste is introduced at the top level only and cascades down the top two panels to fill the lower panel. No visual inspection is available of the filling of the lower panels, since the bulkheads are constructed prior to commencement of filling. Figure 9 also shows the detailed inspections required during the filling process. Some of these inspections were implemented following the bulkhead failures.

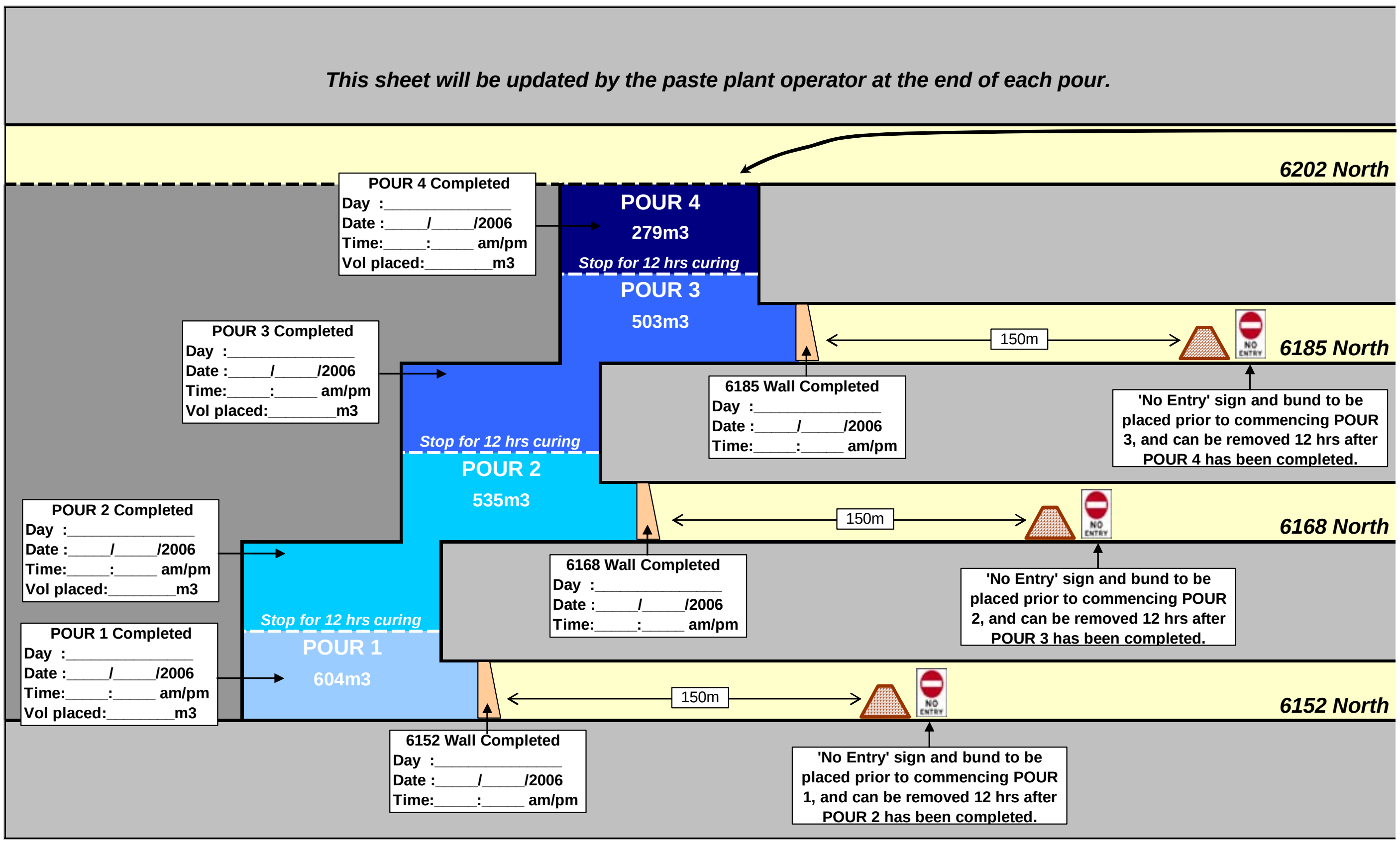


Fig. 9. Mine B stope filling sequence.

Initially Mine B used full sprayed Aquacrete bulkheads as shown in Figure 10. This was to be replaced with fibrecrete after approximately 6 months once fibrecrete was to be used in the development cycle. Aquacrete is a gypsum product that is provided in dry form in bulk bags. It is then combined with water at the spray nozzle and is applied in a similar way to fibrecrete. Figure 11 displays the geometry of the Mine B shanty back drive profile. The Aquacrete is sprayed on a pre-fabricated arched steel frame. The frame does not form part of the barricade and simply provides a backing for spraying of the Aquacrete. Initially no holes were installed in the bulkheads although this was modified over time as discussed later in this paper. The Aquacrete was allowed to cure for 48 hours prior to commencement of filling.

Fig. 10. Aquacrete bulkhead.

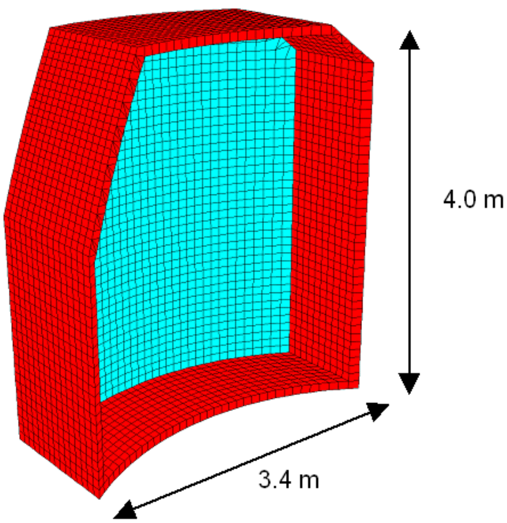


Fig. 11. Geometry of typical Mine B bulkhead.

Initially the bulkheads were remined using standard drill and blast techniques. Again this was modified over time as discussed later in this paper.

The design methodology of Mine B barricades utilised the FLAC3D Shotcrete Bulkhead Model as described by Revell and Sainsbury (2007).

The bulkhead design is based on the filling method shown in Figure 9. Paste is poured to cover the bulkhead and allowed to cure for 12 hours before filling recommences. Using this filling strategy, numerical modeling and assessing a suitable Factor of Safety resulted in a design bulkhead load of 246 kPa.

6. MINE B FAILURE 1

6.1. Background

The first stage of filling (Pour 1) was being undertaken. After approximately 2.5 hours the bulkhead at the base of the stope failed catastrophically as shown in Figure 12. At the time of the failure the height of the paste fill plug was estimated to be 6.5 to 7.0 m high.

Fig. 12. Bulkhead Failure 1 incident scene.

Figure 12 shows that the failure propagated from the base of the bulkhead. Inspections of the bulkhead indicated the bulkhead thickness was 150 mm at the base, while the average thickness was 200 mm. The design thickness was 300 mm. Other key observations made during the investigation include the following:

- No evidence existed of fall-off within the stope.
- The bulkhead appeared laminated, with cold-jointing within the Aquacrete.
- The base of the wall appeared damp, indicating water may have pooled against the base of the bulkhead (this situation is shown for another bulkhead in Figure 10).

- There was significant ground water (0.25 l/s) inflow into the stope, potentially causing an additional load against the bulkhead.
- The failure appeared to be catastrophic indicated by the splash marks on the walls and ventilation bag.
- From the bulkhead back to 50 m along the drive, there were tide marks up to a height of 2 m and residual paste to a depth of 1m.
- Beyond the 50 m mark the level of residual paste in the drive was the same as the tide marks.
- Paste had leaked though the base of previous bulkheads.
- The paste flowed 200 m down the drive and the water a further 70 m.
- Pallets that were located in front of the bulkhead prior to failure were carried 270 m down the drive.

6.2. Analysis of Failure

Because the fill had not undergone any significant hydration prior to the failure, the load on the bulkhead is simply the hydraulic pressure from the height of the paste. A 7 m height results in a pressure of 132 kPa at the base of the bulkhead.

The initial bulkhead design had been based on an Aquacrete unconfined compressive strength (UCS) of 10 MPa (other properties such as tensile strength and Young's Modulus are also used in the model). However, coring of the sprayed Aquacrete panels completed as part of the quality control testing indicated there was significant scatter of the UCS results between 5 and 11 MPa. Furthermore, a significant number of uncemented "powdery" zones were observed. As a result, the back analysis was completed on a 5 MPa Aquacrete bulkhead and 5 MPa composite Aquacrete bulkhead with 20% by volume with no cohesion and tensile strength. Addition of the weaker zones causes an overall strength reduction from 5.0 MPa to approximately 3.8 MPa.

The geometry used to simulate the bulkhead failure is illustrated in Figure 13. Figure 13b illustrates the distributed loading profile applied to simulate barricade loading at the time of failure.

Figure 14 illustrates the ultimate failure load and failure mechanism of a 5 MPa Aquacrete bulkhead. Failure of the bulkhead can be observed to propagate from the base of the bulkhead when the maximum load (at the base) reaches 130 kPa. For the 5 MPa composite Aquacrete bulkhead the same failure mechanism is observed when the maximum load (at the base) reaches 120 kPa.

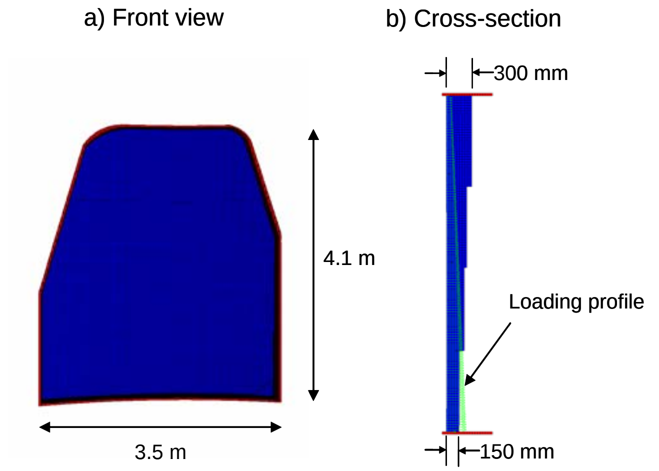


Fig. 13. Geometry of bulkhead.

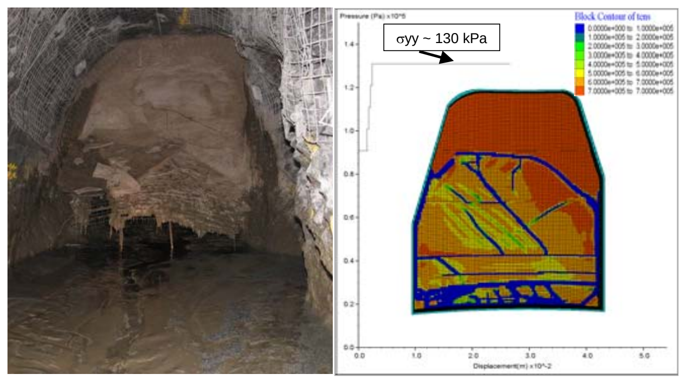


Fig. 14. Ultimate load and failure mechanism of 5 MPa Aquacrete bulkhead.

For this bulkhead geometry and loading configuration, failure of the bulkhead is governed by the 150 mm thickness at the base of the barricade, as the ultimate strength of the barricade is not sensitive to the weaker zones and cold joints within the Aquacrete material.

6.3. Causes of Failure

The key causes of failure were determined as follows:

- Bulkhead was not sprayed to design thickness in areas inspected. The bulkhead appeared to be at its thinnest at the base of the bulkhead.
- Water ingress into the stope which may have increased bulkhead load and also potentially weakened the bulkhead.
- Cold-jointing of Aquacrete may have reduced overall strength of bulkhead.

6.4. Outcomes

Actions implemented following the failure included:

- More detailed documentation on bulkhead construction and specifically methods to ensure bulkhead thickness is according to design.
- Systems put in place to remove water from bulkhead location.
- Increased testing of Aquacrete.
- Eliminate water entering the stopes during filling.
- Investigate methods to reinforce base of bulkheads.
- Mullock bunds and “No Entry” signs were moved back to at least 150 m from bulkhead. Initially the bund and “No Entry” sign were located only 30 m from the bulkhead. The bunds were also specifically designed to contain any paste from a bulkhead failure.

One of the key lessons from this failure was the energy involved in the failure. There was generally a perception in industry that due to the nature of paste fill, if a bulkhead failed it would be a low energy event. The failure at Mine B indicated this was not the case and resulted in a new awareness of the risks of paste fill bulkheads failures.

7. MINE B FAILURE 2

7.1. Background

Two weeks after Failure 1, as described above, another bulkhead failed. However, the causes for this failure were different from those of the first failure.

The first stage of paste filling the stope (Pour 1) was completed at 1752 hrs on Friday, 2 June 2006. This stage involved placing a 6 m high ‘paste plug’ against the bottom bulkhead and then allowing the plug to cure overnight. The volume required for this pour was calculated to be 466 m^3. This volume was poured and then cured for a minimum of 12 hours overnight.

Stage 2 (Pour 2) of the stope commenced the following morning at 0745 hrs. The purpose of Stage 2 was to pour paste on top of the cured plug and then up against the bulkhead on the next level above (see Figure 9). At 1545 hrs, Stage 2 was approximately 15 minutes away from being completed when the bulkhead on the lower level catastrophically failed.

Figure 15 illustrates the bulkhead after failure. As observed, the Stage 1 (Pour 1) paste plug had not reached the required height of 6 m, leaving the top of the bulkhead exposed to the full hydraulic head created by Pour 2.

Fig. 15. Failure 2 incident scene.

Other key observations made during the investigation include the following:

- A volume of paste was retained on the upper levels. Whilst some volume had been allowed it is likely this was insufficient.
- Paste flowed 250 m down the ore drive from the bulkhead.
- Paste appeared to be of good quality and had commenced hydration (paste in ore drive could be walked on).
- No evidence existed of fall-off within the stope.
- Paste plug had cured well.
- Drive dimensions at the barricade location were 4.2 m wide and 4.4 m high. Due to the greater bulkhead dimensions the Aquacrete design thickness was 400 mm.
- The bulkhead note indicated the actual thickness sprayed was only 300 mm.
- Sections of the bulkhead recovered were 300 mm thick.
- Personnel positioned 150 m down the drive observed the paste flowing at a speed similar to a wave at the beach, and at a depth high enough to cover the wheels on their vehicle.

7.2. *Analysis of Failure*

Based on the pour volume data and paste hydration data a numerical model was developed to estimate the bulkhead loading at the time of failure. It was estimated that a uniform load of 140 kPa was applied for the bottom 3.4 m (height of plug or Pour 1) and 415 kPa to the top 1 m of the bulkhead.

The FLAC3D Shotcrete Bulkhead Model was used to calculate the estimated load required to cause complete failure of the bulkhead. As for Failure 1 described above, the modeling was completed for both the 5 MPa Aquacrete and 5 MPA composite Aquacrete Bulkhead. The load for the bottom 3.4 m of the bulkhead was kept constant at 140 kPa and the load on the upper 1 m was increased incrementally until failure occurred. This bulkhead geometry and loading profile is shown in Figure 16.

The FLAC3D Shotcrete Bulkhead Model predicted the load at the top of the bulkhead required to cause failure was 570 and 470 kPa for the 5 MPa homogeneous and composite Aquacrete models respectively. (Figure 17 shows the 5 MPa composite Aquacrete bulkhead failure).

For this bulkhead geometry and loading configuration, failure of the bulkhead is sensitive to the bulkhead material properties. Simulation of weaker zones within the Aquacrete material causes a 100 kPa reduction on bulkhead strength.

Inspection of the failed bulkhead indicates that shear failure along the bulkhead-wall rock interface may have contributed to the failure. As illustrated in Figure 17, yielding along the bulkhead-wall rock interface is predicted, but this yielding is caused by crushing failure of the Aquacrete material as the edges of the bulkhead are forced into the wall rock — not by shearing, or sliding, along the bulkhead-wall rock interface.

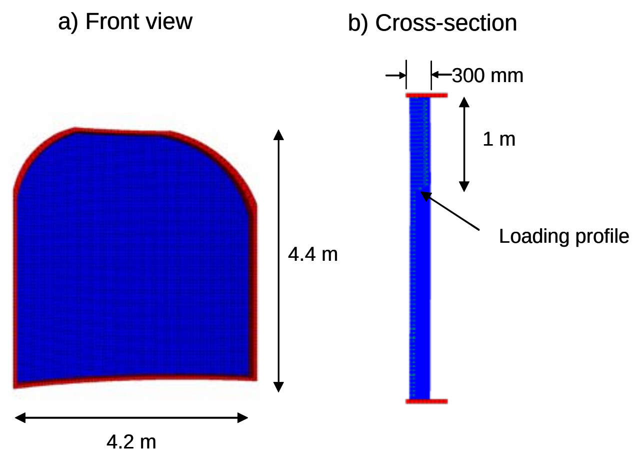


Fig. 16. Geometry of bulkhead.

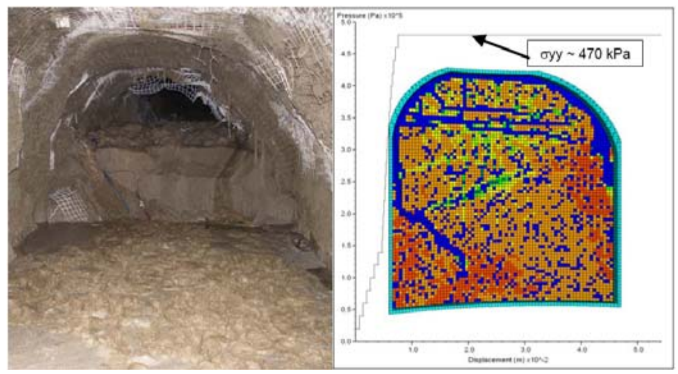


Fig. 17. Ultimate load and failure mechanism of 5 MPa composite Aquacrete bulkhead.

7.3. *Causes of Failure*

The key causes of failure were determined as follows:

- The paste plug (Pour 1) did not reach a sufficient height to fully cover the bulkhead. As a result, the bulkhead was exposed to higher than design loading.
- The cause for the insufficient height was additional paste being held up on the upper levels compared to that predicted.

7.4. *Outcomes*

Actions implemented following the failure included:

- Paste level monitoring systems were installed in the bulkheads. This consisted of conductivity probes that provide a signal back to behind the bund placed 150 m from the bulkhead.
- Polyethylene level pipes were installed in the bulkhead. These are inspected 12 hours after each bulkhead plug is poured. Filling only

recommences once it is confirmed that paste is above the bulkhead.

- Sign-off checklists were introduced for each pour. Figure 9 is the summary checklist that is placed in the control room, whilst more detailed checklists are also completed.

In addition to the above actions the introduction of fibrecrete was expedited. This resolved two issues. Firstly it minimized the lack of confidence in the quality control of the Aquacrete product. Due to the introduction of fibrecrete no detailed assessment of the variability in Aquacrete properties was completed. Secondly it minimized the risk of cold joints. Since the Aquacrete was supplied in bulk bags only a certain number of bags could be stored at the bulkhead location due to the limited drive dimensions. This subsequently contributed to the potential for cold-jointing with the bulkhead being sprayed over at least 2 shifts. Also handling the bulk bags was a labor intensive process which may have contributed to inadequate bulkhead thicknesses being sprayed.

Figure 18 shows a bulkhead under construction before spraying of the fibrecrete. This photo was taken after the failures. The introduction of the drain/inspection pipes can be seen along with the conductivity sensors in three locations up the height of the walls. Also shown are blast pipes. These are filled with explosive to remove the wall to allow extraction of the next stope. When this photo was taken conventional drill and blast techniques were being used to mine the 4 m of paste back to the brow. However, more recently additional blast pipes are installed perpendicular to the bulkhead which has removed the need to mobilise a drill rig to the bulkhead site.

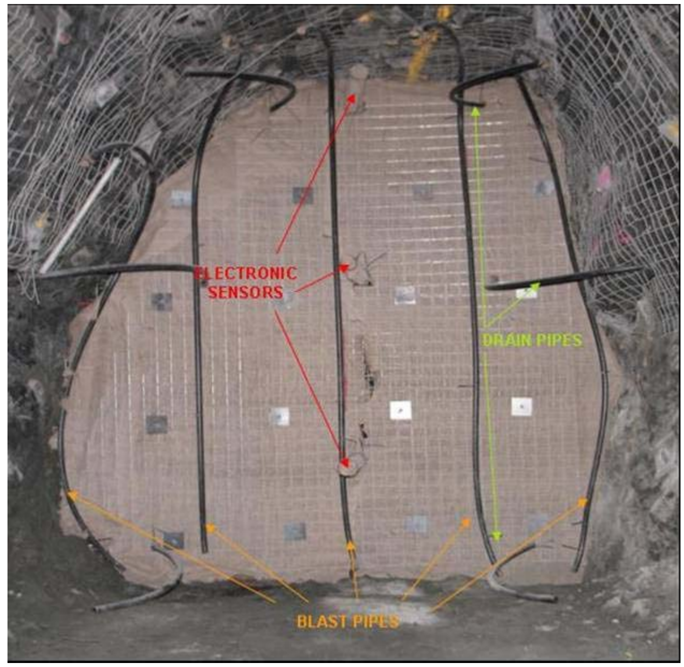


Fig. 18. Bulkhead under construction.

8. CONCLUSIONS

The failure of paste fill bulkheads presents a significant risk to operations employing paste fill. It has been found that paste fill bulkheads can fail with significant energy and the paste fill may be mobilised over large distances. As a result, it is critical that rigorous engineering design principles are employed in bulkhead designs and that comprehensive installation and monitoring procedures are implemented.

ACKNOWLEDGMENTS

The authors would like to acknowledge the two mines from which information was used in this paper. The majority of information presented is based on the mine personnel investigations and findings. Due to the sensitive nature of the information the mines and personnel cannot be named. The authors do not wish to take credit for this information but rather it is hoped that the information presented contributes to the improved safety of all minefill operations.

REFERENCES

REVELL, M.B., SAINSBURY, D., 2007. Advancing Minefill Bulkhead Design Using Numerical Modeling. Minefill 2007.