

STRESS INCREASE ANOMALY IN CEMENTED PASTE BACKFILL: RISK IDENTIFICATION FROM MONITORING

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This paper presents a preliminary analysis of the stress increase anomaly observed in Cemented Paste Backfill (CPB) within mine stopes. This anomaly occurs during rest periods when no additional CPB is placed into the stope, leading to an unexpected rise in stress that is not accounted for in traditional backfill design. Such stress increases can impose additional loads on the stope barricade wall, posing potential risks. Recent field monitoring data has repeatedly demonstrated this phenomenon, which is hypothesized to be linked to thermal expansion caused by temperature increases during CPB hydration. Laboratory experiments have confirmed that temperature-induced volumetric expansion within semi-confined spaces, such as stopes, can lead to elevated internal stresses in CPB. In this study, fifty-six (56) instances of stress increase anomalies were collected and analyzed. A new parameter, the Stress Anomaly Ratio (SAR), is introduced, defined as the ratio between the maximum stress increase anomaly and the maximum stress recorded after filling. The analysis revealed that SAR values can reach up to 3.25, with an average of 1.2. Probability density functions and histograms of the data are presented, showing a significant probability (71.4%) that SAR exceeds 1. This indicates that the stress increase anomaly is a critical factor that must be considered in backfill design to ensure structural integrity. The findings of this study provide valuable insights for geotechnical and mining engineers, enabling safer and more effective design of CPB-based mine stope backfilling. By accounting for the stress increase anomaly, engineers can mitigate the risk of barricade wall failure and enhance the overall safety of underground mining operations. Further research into the risks associated with CPB stress increases is essential to ensure the long-term stability and safety of mining environments.

Keywords: cemented paste backfill, stress increase anomaly; temperature change; stope; underground mine; risk.

1. Introduction

Cemented Paste Backfilling is a widely adopted method for filling mined-out voids (stopes) in underground mines. It serves two primary purposes: providing regional stability to the underground mining environment and maximizing ore recovery. Over the past three decades, Cemented Paste Backfilling has become a popular and sustainable solution in mining operations due to its effectiveness (Zhao et al., 2020). Cemented Paste Backfill (CPB), the material used in this process, is a mixture of cement, tailings (mine waste), and water. This mixture is prepared at a surface mixing plant and then transported underground to the stopes through a network of reticulation pipes, either by gravity or pumping systems. Once placed in the stope, the CPB is designed to gain sufficient strength within a few days, forming a self-supporting structure. This allows for the safe mining of adjacent stopes while maintaining overall stability.

Before backfilling, a safe and cost-effective barricade wall (bulkhead) must be designed and constructed to retain the CPB within the stope. This wall temporarily seals the entrance of the drift, typically located near the base of the stope, preventing the CPB from flowing out before it hardens. Barricade wall failures can lead to catastrophic events, including fatalities and significant rehabilitation costs, making it a critical structure in the CPB system. Its design must balance safety, construction time, and cost efficiency (Wu et al., 2020). Traditionally, the retention capacity of the barricade wall is determined based on the geostatic stress exerted by the CPB during the consolidation phase. However, recent field monitoring using buried sensors has revealed stress increase anomalies in certain areas of the stopes, where the measured stress exceeds the expected geostatic stress. These anomalies are not accounted for in current design practices. The complexity of CPB behavior, stope geometry, the multitude of influencing variables, and the limited availability of data make it challenging to provide a deterministic explanation for this phenomenon. As a result, the stress increase anomaly has been identified as a new and significant risk in Cemented Paste Backfilling, necessitating further investigation to ensure the safety and reliability of mining operations.

This paper presents a preliminary analysis of the stress increase anomaly observed in both field monitoring and laboratory experiments. The study includes a statistical analysis of collected data, focusing on identifying the probable causes, events, affected areas, and potential consequences of this phenomenon. Field monitoring data suggest that the stress increase anomaly may be linked to temperature rises in the CPB during hydration, a phase where the CPB experiences a temporary increase in temperature (Tao et al., 2022). Laboratory experiments further support temperature change as the most likely explanation for the anomaly. However, some numerical models propose that the anomaly could also be influenced by creep from the

surrounding rock formations. The findings of this study provide valuable insights for engineers and researchers, enhancing their understanding of this potential risk. By incorporating these findings into the design process, engineers can develop safer and more cost-effective Cemented Paste Backfilling systems, ultimately improving the stability and sustainability of underground mining operations.

2. Cemented Paste Backfilling Mechanisms

Once the ore is extracted from the stope, the access drift is sealed with a barricade wall. The stope is then filled with Cemented Paste Backfill (CPB), which is pumped from the surface through a network of reticulation pipes (Veenstra et al., 2024). The CPB exerts geostatic stress on the stope walls, including the barricade. Geostatic stress is calculated as the product of the CPB's unit weight and the depth of the fill (Zheng and Li, 2020). As the CPB consolidates, its effective stress increases, enhancing the friction between the CPB and the stope walls—a phenomenon known as arching (illustrated by upward arrows in Figure 1a). Simultaneously, the CPB undergoes a cement hydration process, which generates an exothermic reaction. This reaction releases heat, causing the CPB to expand thermally (Lu and Selvadurai, 2024). During thermal expansion, the direction of arching reverses, leading to an increase in stress at the base of the stope (illustrated by downward arrows in Figure 1b). This also results in higher horizontal stress exerted on the barricade wall. Figure 1c illustrates an idealized measurement of stress at the base of the stope, from the initial filling phase through to the thermal expansion phase. During filling, the total stress increases proportionally with the amount of fill until filling is complete (represented by the thick line in Figure 1c). Ideally, once filling ceases, the CPB stress (or pressure) should diminish and stabilize, following the dotted line a-c in Figure 1c. However, recent field monitoring data from buried pressure sensors have revealed anomalies. Instead of stabilizing, the measured stress continues to increase unexpectedly. This stress increase, which follows line a-b in Figure 1c, can exceed the maximum stress recorded during filling ($\sigma_{max, fill}$) and peaks at σ_a . This phenomenon is attributed to temperature increases, as indicated by thermistors installed alongside the pressure sensors (Thompson et al., 2012). Laboratory experiments have confirmed this behavior by replicating the boundary conditions of typical CPB in scaled-down, temperature-controlled models (Ting & Hasan, 2023; Ting et al., 2020). Alternative explanations, such as creep, have also been explored through numerical simulations (Qi and Fourie, 2019).

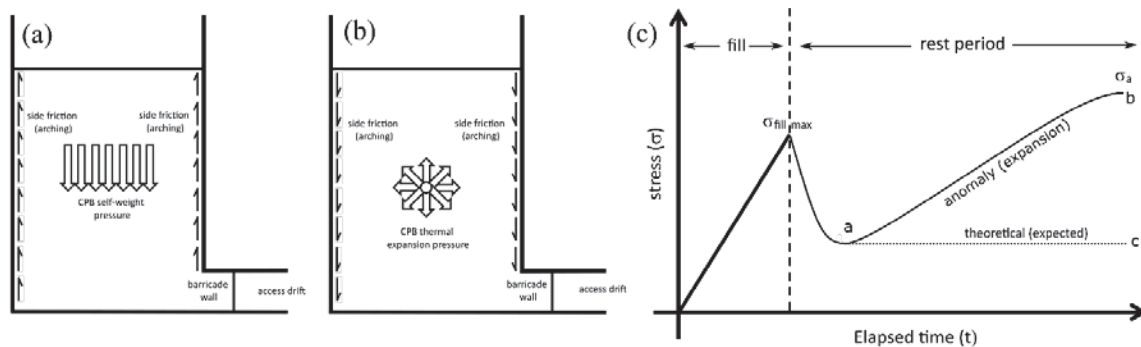


Fig. 1. Schematic diagram of cemented paste backfilling mechanism in stope: (a) The filling of CPB in stope, (b) The thermal expansion of CPB in stope, and (c) Idealized stress response during filling and thermal expansion.

Cemented paste backfilling can be carried out in a single stage or multiple stages, with rest periods in between. In the multiple-filling method, the first filling typically serves as a "plug fill." During the rest period following this initial fill, the CPB is expected to set, stabilize, and effectively plug the lower portion of the stope. This process reduces the stress exerted on the barricade wall during subsequent fillings. The backfilling process concludes once the adjacent stope is blasted, marking the end of the stoping cycle.

3. Analyses

Stress increase anomaly data have been collected from recent field monitoring of cemented paste backfilling in mine stopes, as well as from laboratory experiments. Key sources include Copper's Kidd Mine (Thompson et al., 2009), Cayeli Mine (Thompson et al., 2012), Raleigh Mine (Hasan et al., 2013; James et al., 2015), Red Lake Mine (Oke et al., 2021a, b), and laboratory models (Ting and Hasan, 2023). In field monitoring, data were obtained from buried total earth pressure sensors installed within the stopes prior to filling. These sensors were monitored continuously from the start of filling until the end of the stoping cycle. Laboratory data, on the other hand, were collected using vertical stress sensors during a temperature testing program, simulating conditions from filling to thermal expansion.

The stress propagation observed in laboratory models (Ting & Hasan, 2023) at elevated temperatures ($\geq 20^\circ\text{C}$ and above) exhibited behavior consistent with field monitoring data, albeit at a lower magnitude. For example, the horizontal pressure trends in the Raleigh Mine, Kalgoorlie, Australia, closely mirrored the

laboratory results. Figures 2a and 2b illustrate pressure sensor measurements from single and double filling events in two different stopes, respectively. During the first filling, the measured stress corresponds to the geostatic stress exerted by the CPB, indicating that the CPB is still in a liquid (unconsolidated) state. Arching is established by the end of the filling phase. In subsequent fillings (Fig. 2b), additional stress is recorded, but it no longer aligns with the geostatic stress. Consolidation is evident after the first fill, as the stress decreases over time until thermal expansion causes a stress increase, even without additional CPB being added during the rest period. Figure 2b also demonstrates that the stress increase due to thermal expansion continues even after the second filling. Both figures highlight that the stress increase during the rest period exceeds the maximum total stress recorded during the filling phase. This unexpected behavior underscores the importance of considering thermal expansion effects in CPB design and monitoring.

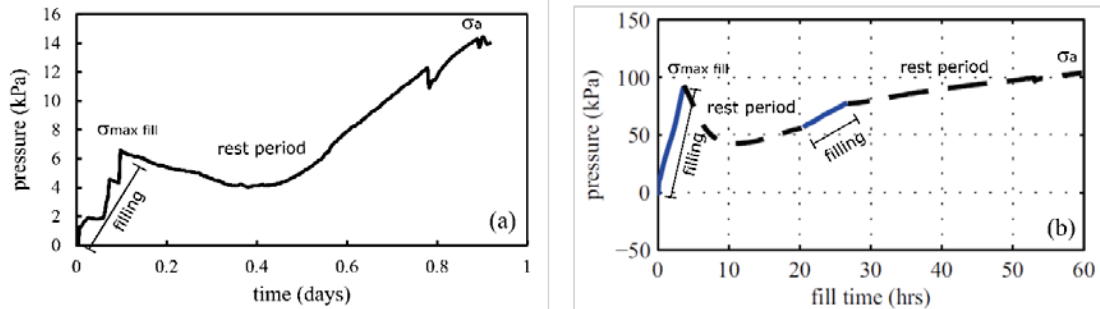


Fig. 2. Field monitoring of cemented paste backfill: (a) Horizontal pressure stope 2 (after Hasan et al. 2013), (b) Horizontal pressure stope 1 location 2 (after James et al. 2015)

From each field monitoring report, measurements indicating stress anomalies during rest periods were identified. Two key parameters were extracted: the maximum stress during filling ($\sigma_{max\ fill}$) and the peak stress during the stress increase anomaly (σ_a). Using these values, the Stress Anomaly Ratio (SAR) is calculated as follows:

$$SAR = \frac{\sigma_a}{\sigma_{max\ fill}} \quad (1)$$

A total of 56 pairs of $\sigma_{max\ fill}$ and σ_a were successfully collected, and the Stress Anomaly Ratio (SAR) was calculated for each pair. Among these, two data points were obtained from laboratory models. Figure 3 presents the Probability Density Function (PDF) and a histogram of the 56 SAR values. The SAR values range from 0.19 to 3.25, with a mean value of 1.2. The standard deviation (σ_{sd}) is 0.63, and the p-value is 0.84. Notably, 71.4% of the data points have an SAR exceeding 1, with a mean SAR of 1.4 for these cases. The data distribution is not normal but is skewed to the right, primarily due to the presence of extreme values on the higher end. Most of the data are clustered around the mean. Unfortunately, there is a gap in the histogram between SAR values of 1.75 and 2.5, where no data points were recorded. At this stage, the authors are actively seeking and collecting additional data from other reliable sources to further validate and refine these findings.

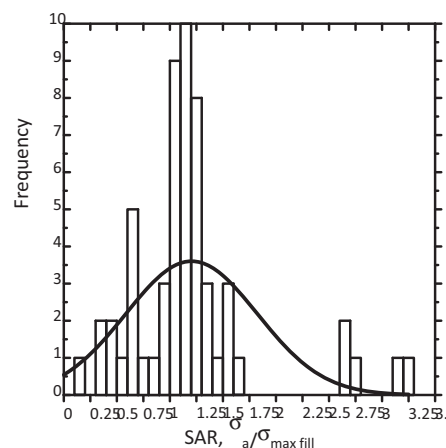


Fig. 3. Probability Density Function and histogram of stress increase anomaly ratio, SAR

An SAR value exceeding 1 is a significant concern, as it indicates that the additional stress exerted on the barricade wall surpasses the design stress (geostatic stress). Figure 3 highlights that the probability of a stress increase anomaly with an SAR greater than 1 is substantial (71.4%). This underscores the importance of accounting for such anomalies in the design of cemented paste backfill systems to ensure the safety and stability of barricade walls.

The findings can be applied to perform probabilistic analysis alongside geotechnical simulations (e.g., Finite Element Method or FEM) to enhance the design of the barricade wall. The outcomes of this analysis can also provide a basis for reassessing the deterministic safety factor. Since the wall must endure additional stresses resulting from stress anomalies, the safety factor should be adjusted by introducing a partial load factor (f_{SA}). This factor must be directly proportional to Stress Anomaly Ratio (SAR) values exceeding 1, ensuring the wall's stability under elevated stress conditions.

5. Conclusions

The stress increase anomaly in cemented paste backfilling is a well-documented phenomenon, primarily attributed to the thermal expansion of CPB during hydration. This study analyzed 56 data points collected from reliable field monitoring reports, including two from laboratory models. The data reveal that the stress increase during rest periods can either be less than or exceed the maximum stress generated during the prior filling phase. To quantify this behavior, a new parameter, the Stress Anomaly Ratio (SAR), is introduced. SAR is defined as the ratio between the maximum stress increase anomaly and the maximum stress of the CPB prior to the rest period. The probability density function and histogram of SAR values are presented, showing that the probability of SAR exceeding 1 is significant (71.4%). The mean SAR value is 1.2, with a standard deviation (σ_{sd}) of 0.63 and a p-value of 0.84. These findings highlight the importance of considering stress increase anomalies in the design of cemented paste backfilling systems. This preliminary analysis provides valuable insights for geotechnical and mining engineers, enabling them to design safer backfilling practices, minimize the risk of barricade wall failure, and ensure the overall safety of underground mining operations.

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