Engineered controls to mitigate nitrate leaching from explosives in blast holes

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Abstract

The principal rock fragmentation methodology in both open pit and underground mining is blasting using commercial bulk explosives. Bulk explosives used in most modern mining operations contain between 70% and 94% of ammonium nitrate. When loaded into the blasthole and in contact with the groundwater, these explosives leach nitrogen species into the groundwater. Different factors such as water inflow and outflow, explosive composition and sleep times, affect the quantities of nitrogen species effectively leaching into the environment. While the most common bulk explosive Ammonium Nitrate Fuel Oil (ANFO) readily dissolves in water, explosive manufacturers have designed more water-resistant explosive emulsions for better performance in damp and wet conditions. However, issues around water contaminating explosives, affecting their performance, and explosives leaching nitrogen species in the groundwater, with adverse effects on local ecosystems, remain.

While in many jurisdictions agriculture is the main source of nitrogen species leaching into the groundwater and the environment, the contribution of mining, and blasting in particular, is increasingly becoming a point of focus for external stakeholders as well as a likely target for regulatory bodies. Current control measures range from improved, more water-resistant formulations of bulk explosives, through better blast designs, to best operational practices to avoid spillage and leakage while also minimising sleep times thereby vastly decreasing the time between loading and initiation. These controls, however, do not entirely eliminate leaching which is also exacerbated by the sleep time and large groundwater flows. To completely eliminate the presence of nitrogen species in the groundwater caused by blasting, an impermeable barrier needs to be installed between the explosive and the borehole. Traditionally, liners have provided this impermeable barrier eliminating any leakage of explosives in cracks and voids and avoiding the explosive-water contact as the conduit for nitrogen species leaching. Liners have the added benefits of improved explosive performance, increased sleep times and elimination of blast fumes. Even though lining blastholes is an engineered control to the environmental problem, it is not a common practice in most mining operations due to the inefficient installation process, the operational burden, the added costs and the risks

introduced to the charging process. This paper discusses some of the barriers in routinely adopting this groundwater control technique, suggests possible solutions and explores a relevant case study.

Introduction

The discussion around explosives in wet environments has traditionally focused on explosive performance, with suppliers continuously developing explosive formulations and delivery methods to increase the explosive's water resistance. However, since the 1980s the role of explosive associated nitrogen species in groundwater and waterway contamination has gradually gained attention.

In the last decade, several mining projects have been subject to increased scrutiny on the nitrogen content of their effluent mine water. In some jurisdictions with particularly sensitive waterways and a high societal expectation on water quality and eco-system protection, mine operators need to consider the potential of upcoming regulation on leaching of explosive related nitrogen species, including nitrate, nitrite and ammonia. Probably the most advanced jurisdiction is British Columbia (BC) in Canada, where the Ministry of Environment and Climate Change Strategy has developed a Technical Guidance on the Preparation of Nitrogen Management for Mines using Ammonium Nitrate Fuel Oil Products for Blasting (Environmental Protection Agency, 2018). The Guidance Note can be used on a voluntary, preventative basis or as part of the submission for an Environmental Management Act (EMA) permit.

One of the most effective controls against leaching of nitrogen species from explosives post-delivery down the blasthole, a contact point inherent to the blasting operation, is the use of liners. While traditional polyethylene (PE) liners often introduce more issues than they provide solutions, engineered multi-composite polymer liners can deliver a solution while being cost effective and operationally practicable. In addition to mitigating nitrogen compound release, other benefits, often interlinked, can be achieved.

The role of explosives in nitrogen leaching

Nitrogen species leaching into the groundwater and surrounding ecosystem is often associated with agriculture and livestock. However, lately more attention has been directed to the leaching of nitrogen species from blasting in mining operations.

Commercial explosives all contain nitrogen compounds because of the high energy release in their decomposition and formation of N_2 as well as the formation of large volumes of gas enabling the rock fragmenting process. However, it is precisely these nitrogen compounds that are a key contributor to nitrogen species leaching into mine water, including nitrates, nitrites and ammonia.

While environmental studies and modelling often predict the contaminating impact of metallic components contained in the rock mass, nitrogen species leaching into the water is often overlooked in preliminary studies. Morin and Hutt (Morin and Hutt, 2009) suggest that due to the low concentration of nitrogen species in rock, pre-mining tests often produce low aqueous concentrations of nitrogen species and are not accounted for in predictions. Only after mining production starts and blasting commences, the true extent of nitrogen species leaching becomes evident and as such, case studies on existing operations become an important source of information.

One of the earlier and often cited sources is a study of nitrogen and phosphorus nutrients entering the aquatic environment around British Columbian coal mines (Ferguson and Leask, 1988) providing a prediction methodology to calculate nutrient release. The study states that between 0.2% to 5.1% of the nitrogen in the explosive will be lost to the water, depending on the type of explosive. However, other studies suggest that between 12% and 28% of mass nitrogen used in explosives (Morin and Hutt, 2009) and between 4.7% to 32.2% of mass nitrogen used in explosives (Sedenko, 2018) respectively was leached by the groundwater.

While the wide range of values, from 0.2% to 32.2%, could raise questions around the value of using case studies as a predictor, a wide variety of factors come into play including explosive type, hydrogeology, sleep times, operational discipline and whether the leaching occurs pre- or post-detonation.

Sources of explosive related nitrogen species

All commercial explosives whether ANFO, watergels or emulsions are ammonium nitrate (AN) based with additions of fuel oil, waxes, salts and other additives. The release of nitrogen species into the groundwater stems from the dissolution of the AN in water, releasing ammonia and nitrate, or from its chemical reaction products.

Explosive manufacturers design and commercialise explosives with different degrees of water resistance such as ANFO which dissolves 25% in 6 minutes, and emulsions which dissolve 1.2% after 6 days (Revey, 1996). However, all explosives have contact points along their life cycle, some of which are unintended such as during storage, transport and on-bench handling, while others are inherent to the blasting activity. At any point where there is contact with water, there is a potential for nitrogen species leaching to occur at their respective rates.

Spillage in storage and transport

AN is often delivered to larger mine sites in bulker bags and is then stored in sheds or silos. Explosive emulsions are either transported as desensitised matrixes and later sensitised or manufactured on the mine site from AN solution. Both the AN and the explosive emulsions are then loaded in delivery units or mobile processing units (MPUs) using pumps, gravity feed or loaders. In both products and processes there are multiple transfers that can result in spillage and subsequent contact with water.

Spillage in delivery

On larger mine sites, bulk trucks or MPUs deliver the explosives to the blastholes, using augers for ANFO and Heavy ANFO and pumps and hoses for emulsions and high emulsion content Heavy ANFO. Spillage can result from simply delivering explosives aside the hole, from drippage while moving from hole to hole or from flushing hoses and auger prior to returning to the workshop or between changing product types.

Spillage in the hole

The ideal blast hole is cylindrical and in competent rock, but many blast holes are in weathered and fractured ground, intersect large cavities or even drill into past underground workings. While drilled vs. designed hole depth is often verified prior to loading, fractures and cavities are hard to detect until the explosives start running away in the cracks and voids (if at all detected). Continuously measuring the explosive charge height while loading can signal runaway explosives but often many kgs of explosives disappear in these voids prior to detection. If discontinuities in the explosive column occur, explosives might fail to detonate.

Damp holes

In deciding whether to load ANFO (dry product) or water-resistant emulsion (wet product), holes are often ‘dipped’ and marked prior to loading. If no water is detected the hole is loaded with dry product. However, even if no water is present, the hole walls can still be damp and the highly hygroscopic AN prill will absorb moisture from the environment potentially leading to nitrogen species leaching. This effect increases with sleep time, the time between loading and blasting, which often takes days but sometimes takes weeks.

Wet toes

Often water accumulates in the bottom or toe of the blasthole, and emulsions are preferred because of their higher water resistance. However, small quantities of stagnant water in the bottom of the hole are often neglected where the preferred choice of explosive is ANFO, either because of the lower cost of ANFO or for ‘simplicity’ when most holes are considered dry. A simple calculation suggests that in a 311 mm diameter drill hole with 1m of water in the toe over 5 kgs of the contained nitrogen will have leached into the water within 6 minutes [62.29 kgs/m x 94% AN x 35% contained N x 25% leaching].

Dynamic water

In underground and open pit mining below the groundwater table, when a blasthole intersects an area with high hydraulic conductivity and significant water inflow, the water can simply wash the explosives out of the holes regardless of the solubility. These explosives carried with the water will not detonate and will eventually dissolve in the water, in-situ or downstream.

Misfires

Misfires occur when the explosive charge, or part thereof, does not detonate. This can be caused by e.g. discontinuities in the explosive column, poor timing sequence design, failure of the initiation system, desensitisation by pressure transmission between holes, etc. Due to stringent misfire prevention practices in most jurisdictions and better and safer initiation technology, misfires occur less frequently nowadays and probably have a limited contribution to nitrate leaching.

Non-ideal detonation

Explosives are designed and manufactured to be stoichiometrically balanced and to produce an ideal detonation whereby the explosive ingredients decompose to steam, carbon dioxide, nitrogen gas and heat. However, when the explosives have a positive oxygen balance, a non-ideal detonation occurs leading to poor explosive performance. The reaction products contain NO_2 and NO_3 gases which produce orange blast fumes. As part of the rock fragmenting mechanism, these gases also expand in cracks and microcracks of the blasted rock and are then transported to processing facilities or waste dumps with the potential of being leached into processing water, tailings or effluent water.

Methodologies to mitigate nitrogen leaching from explosive sources

Because the explosive-water contact occurs throughout the entire lifecycle of the explosive, not a single solution to mitigate nitrogen species leaching exists. However, even a combination of current practices and methodologies leaves several of the contact sources without an effective control.

Operational discipline

Because most explosives are stored separately from initiation systems, are transported in desensitized form and are not readily initiated through ignition or a spark, spillage is probably not regarded as critical from a safety point of view as for example hydrocarbons or fuels. However, careful management and deployment of bulk explosives through controlled transfer of materials, use of overflow recipients and safety valves, spill kits, spillage procedures and rigorous on bench practices does reduce wastage thereby minimizing nitrogen species leaching as well as costs.

Use of water-resistant explosives

Due to the high solubility of ANFO in water, any damp or wet blasthole should use an emulsion or a water-resistant blend of emulsion and ANFO, whereby the emulsion coats the ANFO. Although most explosive suppliers have emulsions with excellent water-resistant capabilities, some issues remain while other challenges are introduced.

Firstly, emulsions usually come at a higher cost per tonne and have a higher density (0.9-1.4 g/cm^3) than ANFO (0.8 g/cm^3), increasing the overall explosive cost per blasted tonne. Additionally, due to the higher density and higher volumetric energy content, emulsion often provides too much explosive energy for the required blast result causing overblasting of softer rock, excessive vibration, highwall damage etc. Desired blasting outcomes would require a lower density ANFO but water presence dictates a higher density, higher energy emulsion not ideally suited to the rock.

While emulsions have a drastically reduced solubility in water, nitrogen leaching from emulsions still occurs (Revey, 1996). Increased sleep times increase the total amount of nitrogen species entering the groundwater but eventually also degrade explosive performance resulting in reduced fragmenting power and in non-ideal detonation. This generates NO_2 and NO_3 blast fumes and is another contributor of nitrogen species to the rock and groundwater.

Finally, while the additives and the intimate contact between fuel phase and oxygen phase in the explosive emulsion provide significant protection against dissolution in stagnant water, dynamic waterflows can wash away emulsions into voids and cracks or even out of the blasthole in underground vertical upholes. The washed-out emulsion remains without detonation, disperses in the environment and could leach into the environment at almost the same rate as ANFO in some circumstances (Sedenko, 2018).

Use of blasthole liners

While several nitrogen species leaching points are due to error, negligence or at least not by design, the explosive-blasthole contact point is inherent to the blasting process. Blasthole liners are a comprehensive engineered control to protect explosives from water in this intentional point of contact. Liners, or sleeves, are usually made from synthetic materials and provide an impermeable barrier between the explosives and the environment. In addition, they take a cylindrical shape the size of the blasthole diameter when deployed and contain the explosives in a consistent explosive column.

Blasthole liners have been around for decades, but their uptake has been limited despite the multiple benefits. While inexpensive, these traditional polyethylene liners have several issues, limiting their use as a solution against nitrogen leaching.

Firstly, the polyethylene material is usually too weak to be a reliable solution in often abrasive and broken ground. Liners will rip and tear, water will ingress and explosives will leak out defeating the main purpose of the liner. Making these liners more resistant and thus more suitable to the environment, comes at the cost of increased weight with significant trade-offs in ease of use and manual handling.

Secondly, deployment of liners adds another step and another visit to the blasthole in an already labour-intensive blasting process. Deployment is often slow and difficult with liners twisting, folding and blocking holes further delaying the process. These difficulties are exacerbated in underground environments with long, vertical upholes and difficult and confined working conditions. Another consideration, particularly when using traditional liners in combination with ANFO, is the risk of build-up of static electricity on the synthetic liner and the, albeit low, risk of initiation due to the creation of sparks.

Finally, the tendency to prescribe emulsions over engineered barrier controls has limited the adoption of liners with more significant premiums attainable in the sale of emulsions. Even if other factors, such as rock mass competence or highwall conditions, favour the use of lower density ANFO, mining operations are often directed to higher density, water-resistant emulsions by the suppliers.

Blasthole liners do provide a comprehensive solution to mitigate the leaching of nitrogen species from explosives into the groundwater particularly at the post downhole delivery contact points where explosive-environment contact is inherent to the blasting process. However, material properties, operational inefficiencies and commercial interests have resulted in a very limited uptake. Blasthole liners do not provide solutions outside the blastholes, in other key points such as transfer between recipients or on-bench spillage.

Solutions to common lining challenges

Liners are often considered a cheap, commodity-like accessory to the blasting process manufactured by bulk plastic manufacturers. Dedicated R&D and engineering, however, has addressed most of the challenges commonly encountered with traditional lining. By eliminating the flaws and inefficiencies of traditional liners, blasthole lining again becomes a compelling solution to nitrogen species leaching while addressing other blasting concerns at the same time.

Material competency

Traditional polyethylene liners are extruded in bulk volumes emphasising lower costs opposed to greater performance. Reconsidering material requirements and using the latest polymer manufacturing technologies has enabled the development of multi-composite, high-tensile strength, conductive liners with impermeable, heat-sealing and ripstop properties at a fraction of the weight. Industrial production can achieve costs that make them a feasible solution while providing a highly resistant water barrier.

Ease of use in deployment

Currently automated liner deployment is a remote prospect but ease of use and process flow of blasthole charging can be addressed through targeted modifications in the liner design. Gusseting[1] during manufacturing for instance, provides a liner with a lay-flat width smaller than the hole diameter. Once deployed down the hole and charged with explosives the liner expands to take on the hole diameter. The

[1] Gusseting of blasthole liners is protected by MTI-PAT-028(exp)

gusseting allows for easy downhole deployment eliminating twisting, folding and choking of the blastholes, avoiding delays and process losses.

Blasthole liners with heat-sealing properties can be easily provided with an impermeable seal at the bottom of the hole when using semi-automated feeder mechanisms. These machines, mountable on the back of a utility vehicle or mobile processing unit, allow for fast and consistent deployment.

While lining deployment is an additional process, it can be done post-drilling but independent of the charging process, either in advance or immediately prior to charging. If done prior to charging and the same explosive and charging methodology is used, the lining process will add time to the overall blasting process. However, if the liner enables the use of an alternative explosive better suited to overall conditions rather than a highly water-resistant pumpable emulsion, significant time savings can be achieved. A time-and-motion study in a large New South Wales (Australia) coal mine showed that by pre-lining and switching to an augered Heavy ANFO, charging time of a blast pattern could be reduced by more than half.

Table 1 Time-and-motion study on large Australian coal mine comparing use of 30/70 pumpable emulsion and augered HANFO in 229 mm non-lined and lined blastholes

	Charging with pumpable emulsion	Lining and loading with HANFO	Pre-lining and later loading with HANFO
Time to line	0 sec	2 min 24 sec	2 min 24 sec
Time to load	4 min 37 sec	1 min 44 sec	1 min 44 sec
Total charging time	4 min 37 sec	4 min 8 sec	2 min 24 sec

Static buildup

The build up of static electricity while loading lined holes with ANFO can be addressed by integrating a carbon yarn in the woven polymer. This patented carbon yarn will eliminate the safety risk and ensure compliance with local regulation on antistatic materials and the use of ANFO. However, integration of the antistatic yarn is only possible in woven materials and not in bulk, multi-purpose extruded polyethylene.

Engineered liners; a solution to nitrogen species leaching and more

The use of engineered liners deals with the legacy problems of traditional liners while providing the most effective, wide-spectrum solution to nitrogen species leaching in the explosive-blasthole contact point .

Avoid blasthole leakage

Deploying a highly resistant liner in blastholes eliminates all contact with water in the toe of holes, damp walls or potentially rainwater or surface water inflow post loading, in turn eliminating any leaching of nitrogen species into the environment. Even in holes intersecting very active hydrogeological layers, both in open pit and underground operations, the explosives are protected within the impermeable barrier. This avoids the explosives being washed out of the hole into the environment or being disintegrated, washed away and dissolved eventually.

In highly fractured ground, rock mass with cavities or areas with pre-existing underground workings, ripstop and high-tensile strength liners contain the explosives within the drilled diameter of the blasthole and can span large intersection of cavities. The liner contains the explosive in a single, continuous column avoiding any spillage into the fractures and voids. At the same time, it eliminates discontinuities in the explosive's column ensuring full column initiation and avoiding post blast partial misfires and explosive residues. Even if the blastholes are initially dry, spillages and residues from voids and fractures can eventually end in processing circuits or waste dumps and continue to leach nitrogen species in processing or run-off water. This occurrence is eliminated by lining the blastholes.

Ensure ideal detonation

One of the root causes of non-ideal detonation is contamination of compliant, well-designed explosives with water, drill cuttings and fallback. When a blasthole is lined, ingress of foreign material into the explosives, be it dynamic water or drill cuttings from the surface, is eliminated providing the proper conditions for ideal detonation. Positive oxygen-balanced, non-ideal detonation produces NO_2 and NO_3 gases and injects these into the rock mass. Ensuring ideal detonation through lining produces inert nitrogen instead ultimately eliminating another source of leachable nitrogen species.

Further benefits

While there is a strong and sensible argument to line blastholes with engineered liners from a nitrogen species leaching perspective additional benefits, although some mutually interdependent, exist.

Explosive performance

Leaching of nitrogen into the environment also means leaching energy rich nitrogen bonds into the environment. These nitrogen bonds are the key explosive energy and gas providers for rock fragmentation and their leaching has a detrimental effect on the explosive's rock breaking performance. Eliminating nitrogen species leaching allows the explosive to perform to its full potential and consume the explosive energy the mine has ultimately purchased. Given the liner material doesn't degrade in the timescale of blasting, sleep times can be greatly extended allowing to blast when production, not explosive integrity, dictates

The same nitrogen deficiency, caused by nitrogen species leaching, leads to a positive oxygen balance and generation of blast fumes which has potentially significant health, safety, and regulatory impacts.

Ensuring ideal detonation by maintaining the designed oxygen balance will ensure no NO_2 and NO_3 gases are released.

Other contaminants

In addition to ammonium nitrate, commercial bulk explosives contain fuel oils, hydrocarbons, salts, emulsifiers, waxes etc. By providing an impermeable barrier, liners also protect the environment from contamination with these other explosive additives.

Explosive selection

Blasthole lining provides an additional degree of freedom in explosive selection by eliminating the water resistance constraint in many instances. This allows mining operations to match the explosive type with the rock mass to achieve the desired blast outcome. At the same time, premium emulsions can be substituted by less expensive but fit-for-purpose ANFO. This substitution most probably offsets the liner cost and, on many occasions, provides a net cost saving.

Improved recovery

Finally, in areas with very high waterflows, particularly in underground vertical upholes, lining can simply enable blasthole loading to the full drill hole depth where previously impossible. Apart from eliminating wastage and spillage this allows better stope and ore recovery by blasting to design.

Case study; UG gold mine

An underground gold mine in the Bibiani gold belt in West Africa experiences severe issues when loading vertical production upholes in their ore producing stopes due to large amounts of water flushing out of the holes. Some of these holes would intersect underground waterflows. The situation deteriorates significantly during the wet season from April to June.

The mine uses a watergel explosive with high water-resistance. The product is recognised in the industry as a ‘sticky’ product that would hold up well in vertical upholes. However, even this high performing explosive would require up to 3 attempts per hole for the explosive to stick, prior to the installation of retention plugs. The holes of up to 25m in length could lose up to 100 kgs of explosives when completely flushed out after loading. While not the key focus of the mining operation at that moment, the large quantities of flushed explosives would eventually find its way to the groundwater.

The mine decided to trial engineered lining in a stope blasting ring at a production level at 1575m depth with several holes intersecting waterflows. The wettest hole as well as the two adjacent holes were selected for lining. A highly resistant liner was deployed using the charging equipment and secured in the hole with inflatable plugs. The three holes were then charged with watergel. During the charging operation no explosives leaked from the holes and the holes were loaded in a single pass. Better rock breakage and stope height was most likely achieved due to a fully loaded column and a continuous charge.

The application of the engineered liner in this operation with extreme flows of dynamic water shows that explosives can be contained and protected from the environment even in harsh conditions. If the explosives can be contained, then nitrogen species leaching from the blasthole can be mitigated. It is worth highlighting that similar results could be achieved using packaged explosives, a product the liner effectively emulates. However, packaged explosives come at a significant cost premium compared to bulk explosives.

While conditions in this case study are not commonplace, they illustrate lining performance in a worst-case scenario. Additionally, multiple examples exist of mines struggling to contain explosives in underground blastholes due to waterflow. In some regions, such as West Africa, this is seasonal due to the wet and dry cycle. In other countries with wet climates and high watertables this is mostly subject to the geology and permeability with similar examples found in Ireland, New Zealand and the Nordic countries.

Conclusion

Blasthole lining has been around for decades but due to the various operational and material issues with liners and the lining process, the use of water-resistant explosives has been the preferred solution for mining operations operating in humid or wet environments. This solution has been strongly promoted by the explosive suppliers fetching premium prices for these water-resistant explosives in the absence of a compelling alternative until recently. However, with nitrogen leaching from explosives becoming an increasing focal point of the impact of mining on the environment and waterways, it is becoming evident that water-resistant explosives can reduce but cannot eliminate nitrogen species leaching.

Applying material and process engineering expertise to the multi-purpose, commoditised polyethylene liners can overcome the traditional lining flaws. Multi-layered and composite polymers address material performance. Interwoven carbon yarns eliminate the buildup of static on the liner in the explosive delivery process. Gusseting and semi-automated feeder mechanisms introduce new efficiencies in the lining deployment process.

The installation of an impermeable barrier of engineered material, eliminates many of the contact sources between the explosive and the groundwater, providing the best possible solution to mitigate nitrogen leaching post-delivery of the explosives down the hole. The migration of nitrogen species into the environment also implies the loss of high-energy content nitrogen bridges from the explosives with reduced explosive performance and blasting outcomes as a necessary consequence. New material and process technologies make lining again a compelling control in the mitigation of nitrogen leaching species at the same time allowing procured explosives to perform at their full potential for the intended rock fragmentation.

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