International Journal of Rock Mechanics & Mining Sciences 70 (2014) 1–15

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Experimental and numerical investigation of high-yield grout ore pass plugs to resist impact loads

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A R T I C L E I N F O

Article history:
Received 30 July 2013
Received in revised form
20 March 2014
Accepted 21 March 2014
Available online 8 May 2014

Keywords:
Impact load
Ore pass plug
High-yield grout
Drop hammer
Rock impact simulation

A B S T R A C T

In the last fifteen years, Tekseal high yield foaming grout ore pass plugs that could later be easily removed, have been poured above chute maintenance areas providing protection from high energy rock impact and isolating workers from the hazard. Construction and removal methods will be briefly explained. Since it is not economically feasible to investigate the problem of ore pass plug impact response using full-scale experimental studies, this paper presents a combined four-stage approach that includes (1) laboratory testing to investigate the mechanical behaviour of the high-yield foaming grout; (2) high-precision impact testing of reduced-scale models of ore pass plugs; (3) high-fidelity physics-based numerical model calibration using experimental data; and (4) full-scale modelling of mine ore pass plugs using calibrated material models. To calibrate numerical models, three one-metre diameter steel pipes filled with Tekseal high yield foaming grout were tested with falling steel projectiles of different shapes. Impact tests provided data on the depth of penetration and size of the craters formed by the projectiles. Numerical models were calibrated by optimising the material parameters and modelling techniques to provide the best match with the experimental results. Full-scale numerical models of ore pass plugs were developed for typical ore pass dimensions and subjected to impact events by falling rock projectiles. The proposed approach has allowed investigating energy absorbing characteristics of ore pass plugs to further predict and increase understanding of their capacity to withstand high-speed impacts by large falling projectiles.

1. Introduction

Deep level mines use a system of ore passes to convey the ore to a collection point underground for hoisting to the surface. Operations with a large lateral extent may have several ore pass systems. Because of large ore throughputs, wear is significant, particularly in the vicinity of chutes and brows where there is impact and high ore velocity. These critical parts of the ore handling system often need repairs as part of planned maintenance, exposing workers to potentially significant risk. Downtime for any component is downtime for the whole system [1] with the potential for significant production opportunity losses caused by production interruption.

Ore passes (normally unlined) are treated as unsupported underground excavations with the potential of falling objects such as large ore boulders, collective ore build-up and large thin slabs from "onion peeling" of the ore pass walls. To better understand the operating environment, Hadjigeorgiou et al. [2] usefully describe ore pass operational failure mechanisms and damage in Canadian mines. If workers are to maintain these areas, then they must be isolated from falling objects and vital infrastructure also requires protection. In 1998 the first shaft plugs were constructed from Tekseal in an Australian underground mine. In the last five years almost twenty shaft plugs have been constructed in different mine operations in Australia including mine operation of Xstrata Copper.

In 1993 Westmin Resources [3] at Myra Falls Mine (Canada) constructed a Tekfoam bulkhead in the base of an ore bin after receiving design advice as a result of research conducted at Noranda Technology Centre. It was recognised that the aerated cement product had the ability to absorb impact without the bulkhead being destroyed. Bearing foundation equations were used to calculate the penetration from impact as the impact energy absorbed by the foam cement was easily calculated. Live pressure tests on bulkheads showed that if the roadway span to thickness ratio was greater than 0.5 then the bulkhead would fail as a plug.

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http://dx.doi.org/10.1016/j.ijrmms.2014.03.010
1365-1609/

Today numerical analysis is used to calculate the effect of impact on structures. This paper presents experimental and numerical studies to investigate the response of Tekseal high yield foaming grout to impact loading for ore pass plug design as a result of multiple inquiries from Australian mining operations. Originally Tekseal was developed as a simple, innovative and cost effective permanent plug seal system for the underground coal industry where it was specifically designed for deep, high convergence mines [4]. It has repeatedly demonstrated its ability to accept significant levels of entry closure. Thousands of Tekseal mine ventilation goaf seals have been constructed in the United States.

2. Properties of Tekseal

Tekseal is a pumpable, cementitious grout that forms a cohesive, homogeneous, semi-ductile mass that exhibits shear and compressive strengths. During the mixing and pumping process through Monopumps, Tekseal additives allow air to be entrained forming a homogenous foamed mixture at delivery. Anchorage is provided primarily by the Tekseal bearing and/or adhering to irregularities in the rock surface of the ore pass after all loose material is removed. Its ability to absorb significant strain allows the material to not fail catastrophically, but to deform gradually under load.

These ductile properties (deformation under load) indicate that the seal could accept as much as 20% convergence and possibly maintain shear, tensile, and compressive strengths above its unconfined values [4]. Because of the energy absorbing characteristics of Tekseal, many ore pass plugs have been constructed to withstand a rock fall from above while maintaining a safe working environment beneath the plug in order for maintenance to be carried out on critical infrastructure. The other advantage of using a light-weight foaming grout is that the plug can be more easily removed after it is no longer required. Other properties of Tekseal are: (a) can be pumped up to 200 m; (b) rapid cure times; tests have shown that 200 psi (1.38 MPa) Tekseal in situ compressive strength will be above 1 MPa after 3 days [1]; and (c) because of aeration, the grout has a dynamic absorption capacity well beyond its unconfined compressive strength capacity of 1–2.76 MPa.

3. Ore pass plug design

To assist in plug location an estimate or measure of the ore pass void shape and dimensions is required and often an accurate assessment can be made with a Cavity Monitoring System (CMS) giving a laser 3D digital image [5]. Whenever possible, residual material from the walls of the ore pass should be removed by washing. Ore is tipped on top of the liner plates until a 1–2 m gap is left to the location where the central base elevation of the plug is required. Fine sand is poured from a finger raise ideally forming a flat to convex shaped sand cap over the ore. Wedge or concave shaped bases are not recommended as impact causes additional load and stress redistribution that could result in tensile failure of part of the grout base when these shapes are present. If the finger raise prevents central placement of the sand then the sand can be placed from a dump point higher up. Care must be taken that sand poured from an inclined ore pass does not form a wedge shape in the base of the Tekseal plug. Plugs are designed with a diameter to depth ratio of 1:1 at the plug centre with a convex base forming a shear contact on the ore pass walls of ≈ 1 m larger than the ore pass diameter. Fine sand is recommended so that it will not be penetrated by the Tekseal. If water is leaking into the ore pass, care must be taken to incorporate a drainage system to prevent water building up on top of the plug. Ore and sand beneath the plug is removed and the plug base is hosed to remove loose material. Plugs can be worked beneath 24 h after the last part of pouring grout. The mine operator will need to implement a regular visual inspection procedure. Fig. 1 shows a schematic cross-section of a plug with a convex shaped pile of fine sand.

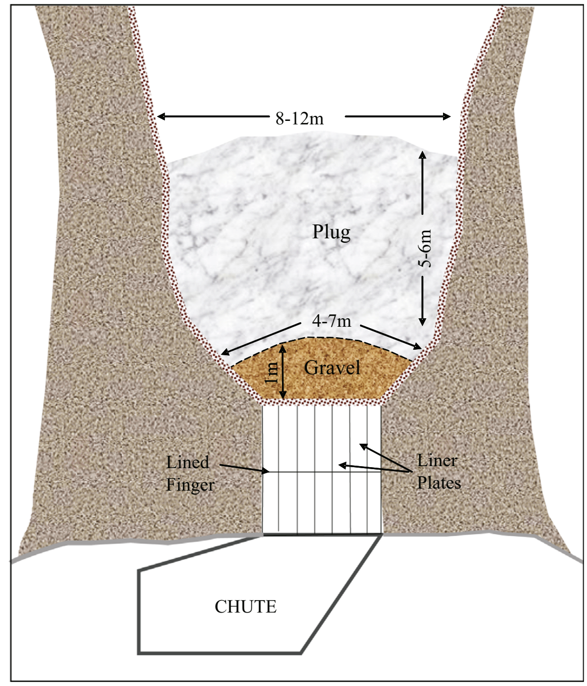

Fig. 1. Schematic arrangement of plug, supporting sand and chute [1].

4. Ore pass plug removal

The methods that have been used to remove ore pass plugs include sequential shot firing and high pressure water jet cutting. Holes for explosives can be either bored in the cast Tekseal plug or pentices have also been made up from plastic tubing and cast into the plug providing charging holes. Ring firing experience is relevant when it comes to designing a blast-hole pattern to fire out shaft/ore pass plugs. Boring the plugs is required immediately after Tekseal curing time is complete so that the holes can be ventilated either naturally or with compressed air using a multi outlet manifold with 25 mm poly pipe type setup. A heavy rope can be cast into the centre of the ore pass plug and a water-cutting device attached below the base of the plug. The high-pressure water cutter is winched upwards pulling the water cutter through the plug.

5. Experimental investigation

5.1. Characterisation of high-yield grout

In order to accurately represent the behaviour of the foam concrete, a series of laboratory tests for material characterisation were conducted. The laboratory test programme included (1) Uniaxial compression test; (2) Indirect tensile test (Brazilian test); (3) Triaxial test; and (4) Isotropic compression test. These tests were carried out according to the International Society of Rock Mechanics suggested methods [6,7]. The water cement ratio adopted was 2:1. Three sample sizes were obtained with length (height) to diameter ratio of $L/D=2$: cylinders with diameter