Dynamic testing of Tekseal high yield grout to provide ore pass plug design for impact

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Abstract

Significant wear in ore passes particularly in the bow and chute areas is proportional to the tonnage throughput with increased wear associated with running ore passes empty. During planned shutdowns it is necessary to isolate maintenance crews from falling objects. In the last 15 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 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 three-stage approach that includes 1) high-precision impact testing of reduced-scale models of ore pass plugs; 2) high-fidelity physics-based numerical model calibration using experimental data; and 3) 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 shape using the High-Capacity Impact Testing Facility at the University of Wollongong. Impact tests provided data on the depth of penetration and size of the craters formed by the projectiles. Numerical models were calibrated by optimizing the material parameters and modelling techniques to provide 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. This research will enable better understanding of ore pass plug performance during high energy events and provide further engineering definition to mitigate risk to ore pass maintenance personnel.

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 (Carr and Krause, 2005) with the potential for significant production opportunity losses caused by production interruption.

Ore passes (normally unlined) are treated as unsupported ground with the potential of falling objects such as large ore production boulders, collective ore build-up and large thin slabs from distressing and “onion peeling” of the ore pass walls. To better understand the operating environment, Hadjigeorgiou et al. (2005) 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 with ≈ 20 shaft plugs constructed in the last five years at mine operations including Xstrata Copper.

In 1993 Westmin Resources (Reipas, 1996) 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.

Today numerical analysis is used to calculate the effect of impact on structures. Minova undertook research to investigate the response of Tekseal high yield foaming grout to impact loading for ore pass plug design as a result of inquiries from mining operations.

Originally (Minova, 2008) 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. 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 which 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 the seal could accept as much as 20% (Minova, 2008) convergence (18% under laboratory tests) and possibly maintain shear, tensile, and compressive strengths above its unconfined values.

Because of the energy absorbing characteristics of Tekseal, many ore pass plugs have been constructed to withstand a rock fall 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 listed as follows:

- Can be pumped up to 200 metres.
- Rapid cure times. Tests have shown that 200 psi (1.38 MPa) Tekseal in situ (Carr and Krause, 2005) compressive strength will be above 1 MPa after 3 days.
- Because of aeration the grout has a dynamic absorption capacity well beyond its unconfined compressive strength capacity of 1-2.76 MPa (Density range for these strengths 0.35-0.60)
- Acid mine resistant (MSHA test after 6 months immersion in water with pH 3)

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 (Optech, 2008) system giving a laser 3D digital image. 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 metre gap is left to the location where the central base elevation of the plug is required. Fine sand is poured from a finger pass 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 pass prevents central placement of the sand then the sand can be placed from an entry 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 metre 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 hours after the last part of pouring grout. The mine operator will need to implement a regular visual inspection procedure. Figure 1 shows the washed base of a plug and Figure 2 a cross-section of a plug with a convex shaped pile of fine sand.

Figure 1 Base of plug showing drill holes (Carr and Krause, 2005)

Figure 2 Schematic arrangement of plug, supporting sand and chute (Carr and Krause, 2005)

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. Figure 3 below shows the manifold for cooling and drying blast holes.

Figure 3 Base of plug showing drill holes

Figure 4 Water cutting device

Try and bore the plugs ASAP 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 25mm 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. Refer to Figure 4. The high pressure water cutter is winched upwards pulling the water cutter through the plug.

5 Experimental investigation

5.1 Description of the shaft plug physical models

Shaft plug physical reduced-scale models were manufactured by filling large steel cylindrical shells with the Tekseal High Yield Grout. Three specimens were prepared by Minova Australia and delivered to the University of Wollongong High-Bay Structural Laboratory for testing. The shaft plug physical models had the dimensions as shown in Figure 5. Shaft plug models were prepared for impact testing by the technical officers by attaching 4 strain gauges to each specimen and connecting all measuring devices to the high-acquisition system for recording the dynamic responses from load cells and strain gauges.

Figure 5 Shaft plug physical models: (a) dimensions; (b) handling steel cylinders filled with Tekseal in the Structural Laboratory

5.2 Description of the impact testing shapes

Three types of impact heads that can be fitted to the drop hammer facility and the 300-mm extension to facilitate connection of the impact heads to the large capacity load cell were manufactured for this study. The impact heads were attached to the falling anvil of the drop hammer machine. The impact testing shapes used in this study are shown in Figure 6. The impact testing shapes were fabricated from mild steel and had an adaptor for attaching them to an extension or directly to the drop hammer machine load cell.

Figure 6 Impact testing shapes: (a) 250 mm square platen; (b) 300 mm hemi-spherical platen; (c) 300 x 50 mm rectangular platen

Figure 7 shows how the hemispherical impact head and the rectangular impact heads were attached to the anvil of the drop hammer machine at the High-Bay Laboratory, University of Wollongong.

Figure 7 Attachment of impact shapes to the drop hammer anvil: (a) hemispherical platen with extension; (b) rectangular platen with adaptor

5.3 Description of the Impact Testing Facility

The UOW structures laboratory contains the largest drop hammer facility for structural impact testing in Australia. The facility has the ability to generate impact loads by a free-falling mass of 600 kg from the height of up to 6 metres. Monitoring equipment includes high-capacity load cells for measuring impact loads up to 2000 kN, high speed laser displacement sensors, accelerometers, strain gauges and high-speed camera. Figure 8 presents a general view of the drop hammer facility at UOW.

Figure 8 (a) Drop Hammer Facility at the University of Wollongong; (b) example of high-speed video recording of the interaction between the falling hemispherical platen and the shaft plug model

6 Description of the numerical models

Finite element modelling was conducted using LS-DYNA (LS-DYNA, 2008) Version 971 computer program. LS-DYNA is a general purpose transient dynamic finite element program for analysis of large dynamic deformations of structures. LS-DYNA is used to solve multi-physics problems including solid mechanics, heat transfer, and fluid dynamics either as separate phenomena or as coupled physics, e.g., thermal stress or fluid structure interaction. LS-DYNA is an industry accepted dynamic first-principle based code for analysis of structures under extreme loads generated by blast and impact events with the ability to compute large deformations due to flexure, shear, and material failures.

6.1 Finite element modelling

Finite element models used in this study are shown in Figure 9. The shaft plug physical models are simulated as one quarter of a circular cylinder due to two symmetry planes. These models are constructed with an outer cylinder with a diameter 1000 mm and a thickness 10 mm representing the steel shell, and two inner concentric cylinders, representing the Tekseal infill. The central cylindrical zone uses a more refined mesh to better simulate the interaction with the falling steel shape. Solid elements with a single integration point were used to model the steel box walls and floor and the grouting foam infill. Overall model dimensions and the sizes of finite elements were determined from a mesh convergence study. The mesh convergence study included a number of runs of the model with variable model dimensions and increasing levels of mesh refinement. In the final model, the steel cylinders and grout were modelled with 25-mm by 50-mm solid elements, and the areas being directly affected by the impact were modelled with 25-mm and 10-mm square solid elements. Interaction between the grout material and steel cylinders is simulated using a tied surface-to-surface contact surfaces. Models of the shaft plug consist of about 25,000 nodes and 30,000 solid elements.

Figure 9(a) shows the finite element model of the shaft plug subjected to impact loading from a hemispherical platen. The platen is modelled as a rigid body, with the density adjusted to provide for the total mass of an anvil and the impact head, which is estimated as 680 kg. The platen is given the prescribed initial velocity of 7.67 m/sec. The impact head interacts with the target through a contact interface, which results in the impact load acting on the Tekseal infill.

Figure 9 Finite element models of the shaft plug subjected to impact by (a) hemispherical platen; (b) flat square platen; (c) rectangular platen

Figure 9(b) shows the finite element model of the shaft plug subjected to impact loading from a flat square platen. The platen is modelled as a rigid body with a total mass of 647 kg. The platen is also given the prescribed initial velocity of 7.67 m/sec. Figure 9(c) shows the model of the shaft plug subjected to impact loading from a rectangular platen. The platen is modelled as a rigid body with a total mass of 640 kg. The contact between the impactor and the Tekseal material is defined by a CONTACT_AUTOMATIC_SURFACE_TO_SURFACE algorithm in LS-DYNA. It is the recommended contact type for most impact applications as it employs a two-way contact treatment, i.e. the subroutines in addition to checking the slaves nodes for penetration, also check the master nodes for penetration through the slave segments.

6.2 Material models

Foaming grout Tekseal was modelled using Material Type 173 based on Mohr-Coulomb criterion in LS-DYNA. The material has a Mohr Coulomb yield surface, given by $\tau_{\max} = C + \sigma_n \tan(\phi)$, where $\tau_{\max} =$

maximum shear stress on any plane, σ_n = normal stress on that plane, C = cohesion, ϕ = friction angle. The tensile strength is given by $\sigma_{\max} = C / \tan(\phi)$. After the material reaches its tensile strength, further tensile straining leads to volumetric voiding.

Appropriate material modelling parameters for the Tekseal foaming grout were determined through triaxial testing of cylindrical specimens provided by Minova. A summary of the key parameters used in the numerical simulations of the shaft plug impact experiments is given in Table 1.

Table 1 Material properties for 200 psi Tekseal grout

Material	Young's Modulus (MPa)	Poisson's Ratio	Friction Angle (deg)	Cohesion (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)
200 psi Tekseal	167	0.18	23.35	0.406	1.4	0.3

Steel cylindrical shells were modelled using Material Type 3 representing elasto-plastic behaviour of the steel material. The steel was assumed to be Grade 300 with a yield stress of 300 MPa. The projectile was modelled using Material Type 20 representing absolutely rigid steel material.

6.3 Boundary conditions

Global boundary conditions were included to represent the shaft plug specimens installed on the strong floor inside the drop hammer facility. Gravity loads for all structural elements (self weight of steel shells and Tekseal) were included in all analyses using the command *BODY_FORCE that applies gravity loads to all parts of the model.

7 Results of numerical analysis

Based on the FE models and the loading and material properties described in Section 6, non-linear impact analyses were carried out for the shaft plug specimens. All models were analysed so as to replicate the loading and boundary conditions as close as possible to the experimental conditions for the subsequent model calibration studies. It should be noted that the three models discussed further used the material properties of Tekseal grout shown in Table 1 which is based on triaxial testing of the small cylindrical specimens provided by Minova. Data on the actual material properties of Tekseal grout used for casting the large cylindrical specimens was not available at the time of writing this paper.

7.1 Penetration by hemispherical platen

Comparison of the experimentally derived crater parameters with the predicted results shows that the depth of penetration by the hemispherical projectile is over-predicted by the numerical simulation. In Figure 10a, the residual depth of the crater from the numerical simulation is about 92 mm, which is significantly larger than the experimentally measured final depth of the crater of 73 mm. The crater diameter in the numerical simulation is also over-predicted with a diameter of 280 mm compared to the experimentally measured crater diameter of 260 mm as demonstrated in Figure 10b. Calibration of the material parameters of Tekseal for the model with the hemispherical projectile will be undertaken in Section 9 in order to minimise the discrepancies in the predicted crater dimensions.

Figure 10 Crater dimensions in Tekseal caused by hemispherical platen impact: (a) numerically predicted; (b) observed in experiment

Figure 11 (a) Time history of penetration by hemispherical platen (3m impact); (b) predicted maximum dynamic vertical stresses in Tekseal material

7.2 Penetration by square platen

Comparison of the experimentally derived crater parameters with the predicted results shows that the depth of penetration by the square projectile is significantly under-predicted by the numerical simulation. In Figure 12a, the residual depth of the crater from the numerical simulation is about 32 mm, which is significantly lower than the experimentally measured final depth of the crater of 44 mm. The crater dimensions are demonstrated in Figure 12b with displacement –time history shown in Figure 13a.

Figure 12 Crater dimensions in Tekseal caused by square platen impact: (a) numerically predicted; (b) observed in experiment

Figure 13 (a) Time history of penetration by square platen (3m impact); (b) predicted maximum dynamic vertical stresses in Tekseal material

7.3 Penetration by rectangular platen

The comparison of the experimentally derived crater parameters with the predicted results shows that the depth of penetration by the square projectile is significantly under-predicted by the numerical simulation. In Figure 14a, the residual depth of the crater from the numerical simulation is about 100 mm, which is significantly lower than the experimentally measured final depth of the crater of 205 mm. The crater dimensions are demonstrated in Figure 14b.

Figure 14 Crater dimensions in Tekseal caused by rectangular platen impact: (a) numerically predicted; (b) observed in experiment

Figure 15 (a) Time history of penetration by rectangular platen (3m impact); (b) predicted maximum dynamic vertical stresses in Tekseal material

7.4 Shaft plug numerical model calibration

Using the computer program LS-OPT, a sensitivity study was performed on the models of shaft plug. The depth of penetration into the Tekseal grout by the steel projectile was defined as the model response metric. The chosen design variables are listed in Table 2. Assumed variation of the nominal values from the earlier discussed triaxial tests defined their upper and lower bounds. Using the Latin Hypercube Sampling algorithm, 43 sampling points were selected. LS-DYNA simulations were performed using the finite element models of the shaft plug described in Section 6. The linear response surface was built, and the ANOVA based sensitivity study was performed.

Table 2 Design variables used for sensitivity study

Design variable	Description	Initial value	Lower Value	Upper Value
coh	Cohesion (MPa)	0.4	0.4	1.2
phi	Angle of friction (rad)	0.3	0.2	0.4
g	Shear modulus (MPa)	70	50	150
nu	Poisson's ratio	0.18	0.15	0.4
ro	Density (g/cm ³)	0.45	0.4	0.6

ANOVA plots (Figure 16) show normalised coefficients of the linear response surface for the hemispherical and square impact heads. The most significant variable in both cases turned out to be “coh”, which is a coherence parameter in the Mohr-Coulomb yield surface, followed by the angle of friction parameter (“phi”). The other variables (the shear modulus (“g”), poison’s ratio (“nu”), and the density (“ro”)) have less significant effect on the depth of penetration but in the case of the square platen these parameters seem to be more important than for the hemispherical platen as evidenced from Figure 16 (a) and (b).

Figure 16 Sensitivity plots for design variables: (a) hemispherical platen; (b) square platen

Figure 17 shows the penetration curve for the model of the shaft plug using the hemispherical projectile and the calibrated values of the material properties. It can be noticed that the calibrated penetration curve results in the final penetration and crater depth is nearly the same as the depth of penetration determined from the impact tests.

Figure 17 Calibrated penetration curve for: (a) hemispherical platen; (b) square platen

8 Modelling response of typical Tekseal plug

Following experimental studies and the model calibration phase of this investigation, finite element models of a full size shaft plug were developed. As shown in Figure 18, the shaft plug has a depth-to-diameter ratio of 1:1 with a diameter of 5.0 m selected as a representative of typical shaft/pass diameters. Two impact scenarios are considered in this investigation: 1) falling round-shaped rock projectile with a mass of 1.5 ton; and 2) falling slab-shaped rock projectile with a mass of 10 ton. In both scenarios the projectiles are given the impact velocities to represent impact from falling from heights 70 m and 200 m as the lower and upper bounds of possible pass heights. The ore pass is assumed to be vertical in all shaft plug models.

Figure 18 demonstrates that the shaft plug model includes the surrounding rock that interacts with the plug at the rock interface. For the simulation to closely represent the actual impact problem, it is necessary to capture the interaction between the projectile and the plug. It has been recommended that while using solid elements, mapped meshing with hexahedral elements is preferred for non-linear impact simulations. The mesh on the shaft plug has to be refined adequately enough to have a fine mesh in regions of interest i.e. areas where there are large deformations. For the circular plug with central impact, the area surrounding the impacting projectile is of primary importance. A fine mesh at the central core of the plug is accompanied by a coarser mesh in the periphery. An optimal mesh size was determined by the calibration studies described earlier in this report. The size of finite elements in the central zone of the plug was the same as in the calibrated models. The elastic modulus of the rock projectiles is very high when compared to the Tekseal plug material, therefore it is safe to model the projectiles as a rigid body.

Figure 18 Finite element models of the shaft plug subjected to: (a) falling round-shaped rock of 1500 kg; (b) falling rock slab of 10,000 kg

LS-DYNA presents a number of contact types and a number of parameters that control various aspects of the contact treatment. The contact between the impacting projectile and the plug is defined by a *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE algorithm. It is the recommended contact type for most impact applications as it employs a two-way contact treatment, i.e. the subroutines in addition to checking the slaves nodes for penetration, also check the master nodes for penetration through the slave segments.

Numerical models of the shaft plug included the failure of the target grout material due to impact damage which is modelled by two techniques; (1) an erosion technique where elements that have strained beyond a user-specified limit are deleted, and (2) node-splitting technique based on 'Tied Node Contact'.

Large plastic deformations, particularly crushing of elements, can drive the run time of a computational problem up by orders of magnitude even though the element that is driving the time step is contributing little to the problem (i.e. the element has failed). Another advantage of the erosion strain is that it provides a mechanism to delete these elements thereby improving the efficiency of the problem. Since many of the

constitutive models do not include failure or erosion, LS-Dyna has a separate ADD EROSION option that can be used to include failure. The ADD_EROSION option has a variety of criteria including Maximum Principal Stress, by which the element is considered failed when $\sigma_1 \geq \sigma_{\max}$, where σ_1 , $\sigma_{\max}$ are the maximum principal stress and the failure maximum principal stress, respectively.

In the node-splitting approach, sets of nodes are created on the contacting surfaces at the plug-rock interface. These nodes are tied together and a failure criteria is specified which defines when the adjacent elements along rock interface are separated by splitting the tied nodes. A failure criteria based on the maximum shear stress criterion have been used for the predictions of a shear failure of the plug at the rock interface. Shear strength of 0.5 MPa was used in the shear stress failure criterion for Tekseal grout based on the triaxial test data.

The main purpose of this numerical investigation is to determine the operating limits of 1:1 ratio Tekseal plugs and whether the Tekseal plugs are capable of absorbing the impact energy without sustaining catastrophic damage due to one of the following failure mechanisms:

1. Shear failure of the plug at the rock interface;
2. Tensile failure at the base of the plug resulting in scabbing failure, and
3. Breaching failure of the plug by the projectile.

8.1 Response of the plug to round-shaped rock impact

The shaft plug model is investigated for impact by the round-shaped rock with a mass of 1.5 ton falling from distances 70 m and 200 m. This is considered as a lower bound of the possible loading scenarios that the typical plug can experience. The rock is modelled as a rigid sphere with a diameter of 0.8 m and assigned an initial velocity of 37 m/s and 63 m/s representing the fall distances 70 m and 200 m, respectively.

Figure 19 Penetration of the 1.5 ton round-shaped rock in the shaft plug: (a) 70 m height of impact; (b) 200 m height of impact

A sectional view of the LS-DYNA models for a shaft plug subjected to the round-shaped rock impact is shown in Figure 19. Figure 19(a) shows the final penetration in the plug by a 1.5 ton rock falling from a height 70 m. The maximum penetration is found to be about 500 mm. The relative displacements of the rock and the plug are presented in Figure 20(a) which shows that the rock reached its final penetration within 25 msec after the impact. Also, it can be seen that the plug's vertical movement was negligible that suggests that the shear failure and breaching failure mechanisms are not relevant for this impact loading scenario. Analysis of the relative velocities of the plug and the rock in Figure 20(a) shows that the initial velocity of the rock reduces to zero in about 25 msec after the impact and stays at this level after that. This is an indication of the fact that the full kinetic energy of the rock projectile is absorbed by the Tekseal

material and not returned back to the projectile. The loss of energy corresponds to large plastic deformations of the Tekseal material in the direct contact with the round-shaped projectile.

Figure 19(b) shows that the shaft plug is able to sustain an impact loading from the round-shaped 1.5 ton projectile falling from a height of 200 m. In this case, the LS-DYNA model predicts the maximum penetration in the plug of about 1.0 m. The relative displacements of the rock and the plug for a 200-m impact in Figure 19(b) also suggest that the plug is not likely to experience boundary shear failure damage since the plug's vertical movement is negligible. The relative velocities of the rock and the plug in Figure 20(b) confirm that the rock's initial kinetic energy is fully absorbed by the Tekseal material after about 35 msec and the rock is fully terminated by the plug.

Figure 20 Penetration of the 1.5 ton round-shaped rock in the shaft plug: (a) 70 m height of impact; (b) 200 m height of impact

8.2 Response of the plug to slab-shaped rock impact

The shaft plug model is additionally investigated for impact by the slab-shaped rock with a mass of 10 ton falling from distances 70 m and 200 m. This is considered as an upper bound of the possible loading scenarios that the typical plug can experience. The rock is modelled as a rigid slab with the cross-sectional dimensions 0.5m by 2.0 m and height of 4.0 m. The slab projectile is assigned an initial velocity of 37 m/s and 63 m/s representing the fall distances 70 m and 200 m, respectively.

A sectional view of the LS-DYNA models for a shaft plug subjected to the slab-shaped rock impact is shown in Figure 21. Figure 22(a) shows that the energy of the falling slab from a height of 70 m exceeds the capacity of the plug and results in a shear failure of the plug at the rock interface. From analysis of the relative displacements and velocities for the rock and the plug, Figure 21(a) and Figure 22(a), the penetration of the slab-shaped rock is about 1.75 m. This penetration corresponds to the moment when the rock interface is fractured and the plug and the rock begin joint vertical sliding with a velocity of about 5 m/s after approximately 80 msec as indicated by the merged curves A and B in **Error! Reference source not found.**(a). These results indicate that the Tekseal plug will not be able to absorb the full energy of the 10t slab-shaped rock projectile falling from a height of 70 m and is likely to collapse due to a shear failure of the plug-rock interface.

Shear Failure
between Plug and Rock

Shear Failure
between Plug and Rock

Figure 21 Failure of the plug due to impact by the slab-shaped 10 ton rock: (a) 70 m height of impact; (b) 200 m height of impact

Figure 22(b) also shows that the plug is likely to be severely damaged by the falling slab-shaped 10 t rock from a height of 200 m. Maximum penetration in the plug is found to be more than 5 m. The joint vertical sliding movement of the plug and the rock starts after about 100 msec with the rock slab moving faster than the plug. This indicates the potential for the breaching failure mode by the projectile in addition to the shear failure of the plug at the rock interface.

Figure 22 Penetration of the 1.5 ton slab-shaped rock in the shaft plug: (a) 70 m height of impact; (b) 200 m height of impact

8.3 Base failure mode of the plug

The high-speed impact by a falling rock projectile sends a compression wave propagating through the plug. At the bottom surface the compression wave is reflected as a tension wave. If the tension is sufficient to form a fracture surface and a scab, the material between the plane of fracture and the free surface acquires the momentum trapped in it and may be induced to separate with appropriate velocity from the body of the plug. As stated in (Evans, 1972), critical fracture stresses are deduced to be some 3 to 8 times the static tensile strength of material, the lower the static strength, the higher the factor. In the absence of experimentally confirmed data on critical fracture stresses for Tekseal, it may be assumed that critical tensile stresses required for inducing the scabbing failure at the bottom surface of the plug are of the order 2 to 3 times the static tensile strength.

To evaluate the likelihood of the base failure mode of the plug, three impact loading scenarios involving round-shaped rock projectiles are considered. It has been established earlier that large slab-shaped rock projectiles are likely to result in shear failure and breaching failure modes of the plug, and therefore, it is not necessary to study the potential for base failure for the large slab-shaped rock projectiles.

Figures 23a to 23c show the contours of maximum tensile stresses across the height of the plug on a diametrical cross-section of the plug. Of particular interest are the stresses near the bottom surface of the plug. Figure 23a shows that the maximum tensile stresses near the bottom surface of the plug do not exceed 0.1-0.2 MPa for the 400 kg round-shaped projectile falling from a height of 70 m. For both 200 psi and 400 psi Tekseal, the static tensile strength will be higher than these maximum tensile stresses. It can be concluded that it is unlikely that the scabbing failure will be induced by a tension wave for both 200 psi and 400 psi Tekseal plugs by a 400 kg round rock.

The magnitude of the tensile stresses will increase when the plug is subjected to impact by the 1.5 ton round-shaped projectile. Figure 23b demonstrates that the tensile stresses will reach 0.3-0.4 MPa near the bottom of the plug. Critical tensile stresses required for inducing the scabbing failure for both 200 psi and 400 psi Tekseal plugs will be higher than the maximum tensile stresses. It would not be expected for a section of plug to fall off the plug base.

In Figure 23c, when the plug is impacted by the 1.5 ton round-shaped projectile from a height of 200 m, the tensile stresses near the bottom will increase to 0.5-0.6 MPa and spread over a distance of about 1.0m in diameter in the centre zone at the bottom. It is likely that this level of tensile stresses will be sufficient for inducing the scabbing in the 200 psi Tekseal plugs with a section of the plug being ejected off the bottom surface. The tensile strength of 400 psi Tekseal plugs would be sufficient to prevent a scabbing failure in the plug base.

Figure 23 Maximum tensile stresses at the bottom surface of the plug for: (a) 400 kg round-shaped projectile, 70 m height of impact; (b) 1.5 ton round-shaped projectile, 70 m height of impact; (c) 1.5 ton round-shaped projectile, 200 m height of impact

6 Conclusions

Significant wear in ore passes particularly in the bow and chute areas is proportional to the tonnage throughput with increased wear associated with running ore passes empty. During planned shutdowns it is necessary to isolate maintenance crews from falling objects. In the last 10 years Tekseal high yield foaming grout ore pass plugs have been poured above chute maintenance areas providing protection from high energy impact and isolating workers from the hazard. 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 three-stage approach that includes:

- 1) high-precision impact testing of reduced-scale models of ore pass plugs;
- 2) high-fidelity physics-based numerical model calibration using experimental data; and
- 3) 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 shape using the High-Capacity Impact Testing Facility at the University of Wollongong. Impact tests provided data on the depth of penetration and size of the craters formed by the projectiles. Numerical models were calibrated by optimizing the material parameters and modelling techniques to provide 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.

It is found from a series of impact experiments with different impact shapes that the high void content of the aerated cement foam makes Tekseal an ideal material to absorb impact by falling projectiles. The experimental results were crucial for this study to calibrate the numerical models of shaft plugs. Numerical modelling using Finite Element Analysis was accomplished for the low velocity impact testing of scaled models of shaft plugs. A solid element model was used in LS-Dyna to study the impact problem. Two approaches were used to model the interface between the rock and the Tekseal material and the interaction between a rigid projectile and Tekseal; node-splitting technique and erosion method with a maximum principal stress and plastic strain criteria. It has been adopted as a standard approach to the post-failure responses of elements due to its simplicity and cost effectiveness. It can be concluded that the global impact responses of Tekseal material can be simulated using the finite element method with proper failure criteria, a node-splitting technique and an erosion method. These numerical models can be used to provide useful data and guidelines for product design without requiring expensive and time consuming experimental testing.

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. In particular, the focus of this investigation has been to determine the operating limits of 1:1 ratio Tekseal plugs and the likelihood of the following three potential failure mechanisms for the 200 psi and 400 psi Tekseal plugs:

- 1) Shear failure of the plug at the rock interface;
- 2) Tensile failure at the base of the plug resulting in scabbing failure, and
- 3) Breaching failure of the plug by the projectile.

It is found that if the Tekseal plug is over-loaded by a very heavy falling projectile (e.g. rock slab with a mass of about 10 ton), the plug is likely to fail catastrophically due to a shear failure of the plug at the rock interface. Round-shaped projectiles up to 1.5 ton falling from above to distances up to 70 metres are not expected to initiate any of the three failure mechanisms. For the falling distances up to 200 metres, heavy round-shaped projectiles are not likely to induce the shear failure and breaching failure modes, but a section of plug may fall off the bottom of the plug into the chute due to the formation of a fracture surface and a scab near the bottom surface.

Comparative analysis of the performance of 200 psi and 400 psi Tekseal plugs tends to suggest that 400 psi Tekseal material would be better suited for the shaft plugs when large impact forces are expected due to

either large projectiles or very long ore pass heights. This would ensure the high resistance of the plug to the three failure modes discussed in this report (shear failure, base failure, and breach failure).

This research will enable better understanding of ore pass plug performance during high energy events and provide further engineering definition to mitigate risk to ore pass maintenance personnel.

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