Study of Shotcrete Support Performance in a Gate Road Drivage under High Stress Conditions

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Abstract

The gate roads and lateral galleries driven in high depth longwall mines are subjected to high induced stresses due to extraction of adjacent panels. Such induced stresses cause damage and spalling of side walls and widening of the gate roads leading to failure of the competent roof by sagging. Conventionally, such gate roads are supported by means of steel arches. Use of such support system is not operationally effective and its repair work also is unsafe and time consuming. This paper reports the results of a study to assess the performance of fiber reinforced shotcrete support for control of spalling in a longwall gate road using field experimentation and numerical simulation. The study has been helpful in better understanding of the mechanism of side spalling in gate roads and assessing the efficacy and performance of shotcrete support with other practically possible support combinations in controlling thereof. Design guidelines based on cost–performance optimization of the support have also been suggested integrating the results of numerical modeling and field observations.

Introduction

Shotcrete is the generic name for cement, sand and fine aggregate concretes which are applied pneumatically and compacted dynamically under high velocity. The mixture along with some other additives steel fiber and silica fume is carried through pipe by means of compressed air and 'shot' over the perimeter in thin layers through nozzle for supporting underground openings. Although the use of shotcrete for the support of underground excavations was pioneered by the civil engineering industry but in recent years, the mining industry has become its major user for support of underground structures. It has been applied with success for stabilization of shaft pillar (MGMI, 2002), longwall gateroads (Singh and Basu, 2001) and support of permanent galleries (Verman *et al.*, 1995) in coal mines as well. An important area of shotcrete application in underground mining is in the support of permanent openings such as ramps, haulage, shaft stations and crusher chambers. Nowadays, shotcrete is preferred for rehabilitation of conventional rock bolt and wire mesh support which is otherwise very disruptive and expensive. The incorporation of steel fibre reinforcement into the shotcrete is an important factor in its broadening application areas as it minimizes the labour intensive mesh installation process.

This paper describes the findings of a study carried out by the authors to investigate the efficacy of shotcrete support in longwall gate roads subjected to high abutment stress. Strata behaviour monitoring was done in pre-marked shotcreted and non-shotcreted zones of the gate road under investigation and observations were taken as the face came closer to the observation site. Three and two dimensional numerical modeling has been done to simulate the efficacy of shotcrete support under the prevailing stress condition.

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Mechanism of shotcrete working as support

When the adequately mixed shotcrete is sprayed at the wall to be supported at a high velocity of 20-100 m per second, a layer of cement and sand particles penetrates pores, cracks, joints in the rock mass and forms a basic foundation for the upper layers to be sprayed. As the shotcreting continues, the fines are squeezed into pores, cracks and joints in the rock mass. The shotcrete starts sticking on the initial layer of fines and subsequently, a layer gets formed. A shotcrete support stabilizes the rock mass by maintaining the existing stability, acting as a media transferring load from otherwise failure prone weak zone to comparatively stable zone, and providing additional confinement to the wall against shear/tensile failure. Reinforcement of plain shotcrete by steel fibre provides ductility to an otherwise brittle material in addition to bridging of failure zones. It allows the support to accommodate the unevenly distributed non elastic deformation of side wall of the rock structure without undergoing failure. Even when the shotcrete sustain failure under extreme loading condition, these fibres work as a bridging medium thus putting a check on free extension of the crack so developed. Silica fume allows the shotcrete to achieve much higher compressive and flexural strength as compared to the plain shotcrete. It also enables application of thicker shotcrete layer in a single pass and reduction of rebound.

Site Plan and Mining Sequence

The field trial of this study was made in a longwall mine gate road at 500m depth where the gate road drivage was experiencing considerable side spalling due to high abutment stress at the retreating longwall face. The site plan of the experimental gate road is shown in Fig. 1. Shotcreting was done in zone A and B in the top gate road of longwall panel D11 when the D10 longwall

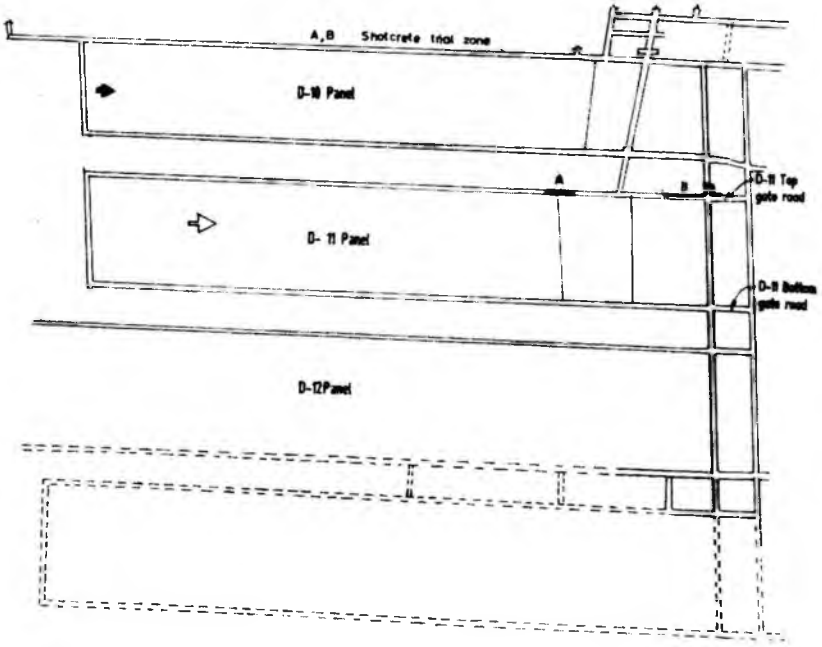

Fig.1: Site Plan of Field Experimentation

panel was completely extracted. It was noticed that on the rise side of D11 top gate road, there is a goaf of already extracted D-10 panel. Therefore, the barrier pillar is already subjected to induced stress from D-10 panel. Shotcreting was done on the rise side of the gate road on two sites marked as 'A' and 'B' (Fig. 1). Shotcreting was done by plane shotcrete, steel fiber (57Kg/m^3 of shotcrete) reinforced shotcrete (SFRS) and SFRS with rock bolts. Roof of the gate road was not shotcreted because it stands stable in the gate road.

Numerical Simulation

Numerical simulations were conducted to study the mechanical behaviour of the shotcrete support, rock bolt and props in D11 top gate road when subjected to different stages of induced stresses due to mining of D11 panel. The induced stress in the gate road due to mining of D11 panel is a 3D problem and can not be approximated by 2D analysis. Therefore, 3D elastic stress analysis of D10 and D11 mining was performed using a 3D Finite Element software package. The elastic stresses in the vicinity of the top gate road of D11 longwall panel were extracted in a plane perpendicular to the axis of the gate road. In doing so, it was ensured that the abutment stress did not change after subsequent advance of the face.

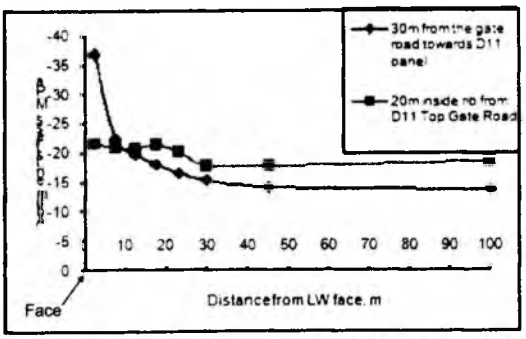

Fig. 2: Abutment stress obtained from 3D model for different stages of extraction in longwall panels D10 and D11

The induced abutment elastic stress thus obtained was suitably reduced to account for the possible reduction due to caving. Fig. 2 shows the abutment stress extracted from 3D model for different stages of longwall extraction.

The induced stress thus obtained from a finite element model for different positions of the face in D11 panel were incorporated in the 2D FLAC model (Fig. 3). The D11 panel was mined in stages such that the shotcrete location in the gate road is located at a distance of 45m, 30m, 23m, 17.5m, 12.5m, 7.5m and 2.5m from the face. The corresponding stress profiles were recorded in vertical plane normal to the axis of the gate road in files named as D11_45, D11_30, D11_23, D11_17.5, D11_12.5, D11_7.5 and D11_2.5 respectively. It was done to represent the changing stress condition as the face approached the shotcreted zone. This strategy of modeling allowed us to conduct an extensive numerical simulation study for changed stress environments. Representative properties of rock and structural supports were obtained based on laboratory tests performed at ISM rock mechanics laboratory and reported elsewhere (Singh and Basu, 2001; ISM, 2004).

The shotcrete support was simulated as an elasto-plastic beam element with its representative modulus and strength values as obtained from the laboratory tests. The plastic moment and moment of inertia for different thickness of shotcrete elements were obtained using following standard equations:

Moment of inertia of shotcrete element,

$$I = \frac{bh^3}{12} \quad \text{.....} (1)$$

where, b is the width and h is the thickness of shotcrete

Plastic moment $\bar{M}_p = \sigma_y \dfrac{bh^2}{4}$ ..... (2)

where, σ_y is the yield strength, b is the width

and *h* is the thickness of shotcrete. For plane strain condition, width b is taken as unity.

The properties for 30mm and 300mm thick shotcrete supports were computed using basic properties of shotcrete: Young's Modulus=25GPa, Poisson's ratio, n=0.22, Yield flexural strength=4.5MPa. To take account of plain strain condition, the modulus value of shotcrete was divided by $(1-v^2)$.

- For 30mm shotcrete, moment of inertia = 2.25e-6 m^4 and plastic moment = 1000Nm.
- For 300mm shotcrete, moment of inertia = 2.25e-3 m^4 and plastic moment = 100,000Nm.

The rock bolt was simulated by means of cable elements with following properties:-

Elastic modulus E= 205GPa,

Axial stiffness, k bond = 1.5e10 N/m/m

Shear stiffness, s bond = 8e5 N/m/m

Yield strength= 5.5e5 N.

Area = 5e-4 m^2

This corresponds to a bolt diameter of 25mm and fully grouted in a borehole diameter of 38mm.

A criterion for side spalling without support was established and the extent of spalling for different distances of the face was obtained from the numerical modeling on this basis (Fig. 4). The horizontal (X) displacements of the side wall supported with 30mm thick shotcrete (Fig. 5) were compared with that of unsupported sidewall. It was found that the 30 mm shotcrete could reduce the total horizontal displacement from 65cm to 35cm when the face was at a distance of 2.5m from the shotcreted area. Further study showed that horizontal displacement of the side wall could not be reduced further by use of 300mm thick shotcrete or 30mm thick shotcrete with 1.5m long rock bolt.

The bending moment plots of 30mm (Fig. 6) and 300mm thick shotcrete (Fig. 7) show that the thicker shotcrete attained the moment nearer to its yield value much earlier due to its high bending stiffness. The 30mm shotcrete layer started yielding when it was at a distance of 23m from face and it failed when the face approached 2.5m from the shotcreted zone.

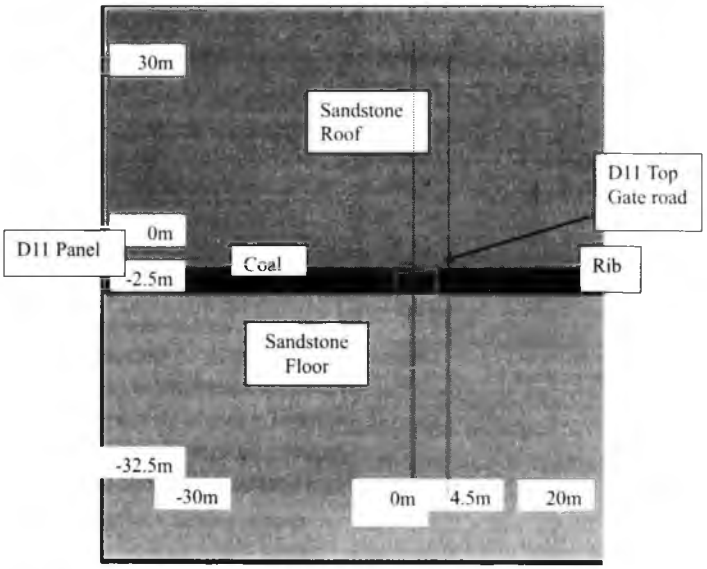

Fig.3: Two dimensional model showing D11 Top gate road, the rib pillar and D11 Panel

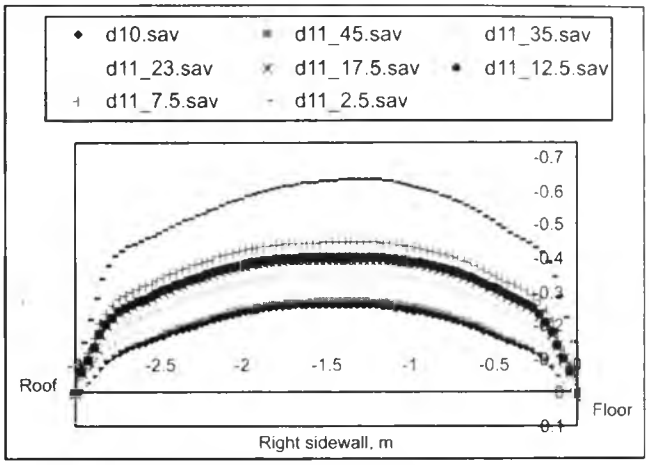

Fig. 4: Horizontal displacement profile of right sidewall from roof to floor of the gate road without any support. The d10.sav indicates after mining of D10. d11_45.sav ... d11_2.5.sav indicates 45 ... 2.5 m distance of the LW face from the shotcete.

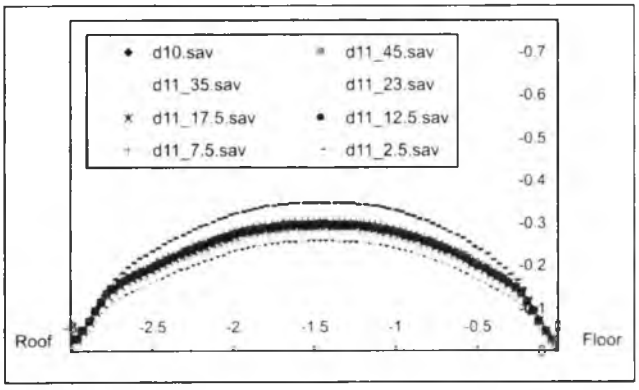

Fig.5: X displacement profile in right sidewall supported with 30mm thick shotcrete (Index same as in Fig. 4).

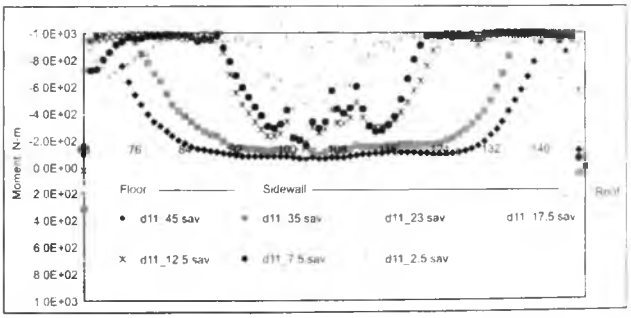

Fig. 6: Bending moment in right sidewall shotcrete in gate road having 30mm thick shotcrete (Index as in Fig. 4).

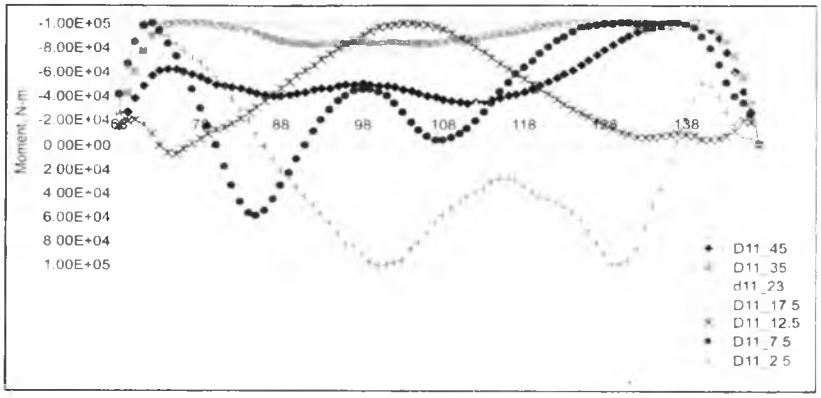

Fig. 7: Bending moment in 300 mm thick shotcrete in right sidewall of gate road (Index as in Fig. 4).

No significant influence of rock bolt on bending moment of shotcrete was observed. The localized shear failure only was observed near the bolt. Though, the bolt has no significant influence on bending moment and displacement as obtained by numerical modeling but from field observation, it seems that even 1.5m rock bolt binds the yielded layers together. Fig. 8 shows the simulated load on a 40t yielding prop with 30mm thick shotcrete and 1.5m rock bolt for different face distances. The plot shows that the load on prop gradually increases with face advance and achieves the maximum value of 12 t when the face reaches to 2.5m distance.

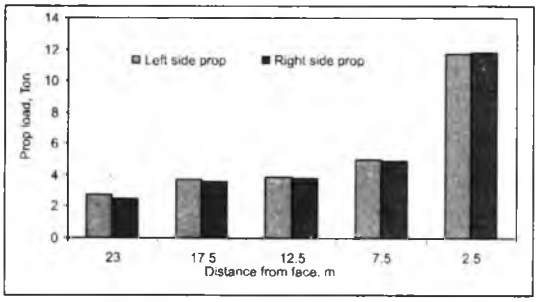

Fig. 8: Load on prop vs distance from face

Field observation

Field observations were taken to study the load-deformation behaviour of gate road strata in the experimental panel without shotcrete support and with shotcrete support when subjected to induced stresses due to longwall mining. Mapping for fractures and strain monitoring in the shotcrete layer was also done to quantify the efficacy of shotcreting in the prevailing stress environment. Strata behaviour monitoring was done by installing a suitable number of (a) vibrating wire (VW) strain gauges in vertical and horizontal plane (b) VW type load cells over friction props (c) measurement of side spalling in non-shotcreted and shotcreted area and (d) visual observation and recording of initiation and progressive widening of fractures in shotcrete layer with face advance.

The first crack in shotcrete appeared when the distance of face from the shotcreted zone was 15m at both the shotcrete sites (A & B, Fig. 1) having plain and SFRS respectively. The crack widened from 5mm to 18mm as the face reached 1m to the shotcrete. At this stage, the top section of shotcrete failed. However, the middle and lower sections remained intact with the side wall of the gate road even when the LW face passed over the area. In the SFRS section, bridging of the steel fibers was observed across the cracks (Fig. 9). Mapping of the field observed fractures showed that almost all the fractures in the shotcrete wall were vertical, i.e. from top to bottom. Subsequently, a few vertical fractures were joined by development of inclined fractures. The un-shotcreted sidewall of the gate road continued to spall as the face advances towards the observation site. The observed spaling as a function of distance from face is shown in Fig. 10. In the bolted portion of the shotcrete, fractures

did appear. Fully grouted rock bolt of 1.5m length installed in middle of the shotcreted wall was not able to control the development of fractures. However, in this case, spalling from the top portion of the shotcrete was not observed even when the face crossed the area.

Fig. 9: Crack development in the SFRS layer showing bridging of steel fibers across the crack

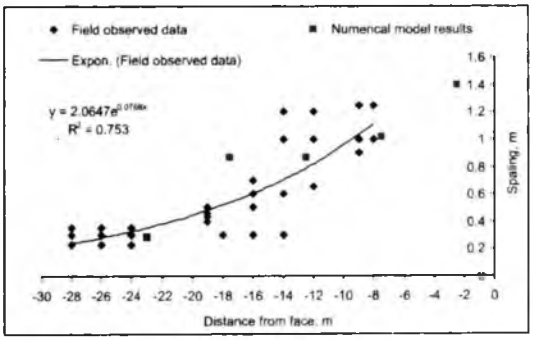

Fig. 10: Observed spalling in right sidewall in D11 top gate road.

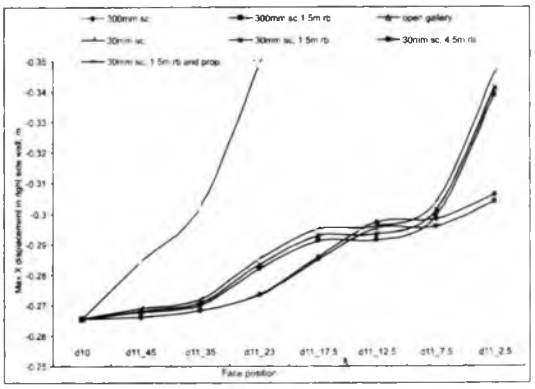

Fig.11. Model obtained performance of different kinds of supports and their combination (Index at x-axis as in Fig. 4).

The strain built up in the shotcrete along the vertical direction was compressive in nature. This might be one of the reasons that cracks did not appear along the horizontal direction in the shotcrete. There was insignificant development in the horizontal strain in the shotcrete. However, the vertical fractures occurred even in absence of recorded horizontal strain built up. It may be noted, here, that the shotcrete was applied in a sidewall which had already yielded due to the abutment stress after mining of the adjacent D10 LW panel. The fractures in coal were not regular in nature and were forming irregular size of coal blocks. The fractures/cracks in the shotcrete appeared due to displacement of these blocks as a result of induced loading due to mining in D11 panel. Thus, the vertical fractures appeared due to differential movement of two blocks on which the shotcrete was applied and the strain gauge might be sitting on the middle of the block which did not show any strain. The load on friction prop with a setting load of 2.5t increased to 12t when the face reached close to it.

The comparative performance study of different kinds of supports and their combinations (Fig. 11) showed that additional support of the rock bolt of 1.5m length and 40 t prop with 30mm shotcrete has got little influence over 30mm shotcrete support alone. The X-displacement achieved with 300mm shotcrete with or without bolt is the lowest. However, the shotcrete of such higher thickness start yielding, i.e. high bending moment develops due to displacement in the wall, which causes yielding in the shotcrete layer even when the face is far behind the shotcreted location. This is mainly due to higher composite stiffness of a thicker shotcrete layer, which makes it unable to sustain the bending stress imposed by the sidewall movement in the gate road.

Conclusion

The fiber reinforced shotcrete (FRS) – bolt is a viable and cost effective support system

for the gate roads and other underground openings subjected to high induced stresses. Its potential has already been proved in support of the loosening grounds in coal mines. An effective shotcrete application should have an optimal thickness compatible with its strength and sidewall stress such that it yields and remains stable till the face comes nearer to it. The numerical simulation study showed that 30mm thick shotcrete when applied on a relatively de-stressed coal surface in a gate road can sustain induced stress up to 6-7MPa. This is equivalent to 23-17m distance of the longwall face from the shotcrete zone in a gate road at a depth of 500m. When the induced stress increases to 10MPa, the shotcrete layer, though fractured, remained in place holding the side wall and prevented spalling. At induced stress level of 17MPa, it got dislodged from the upper half portion of the sidewall. The results of numerical simulation were found to be in line with the field observation and accordingly, it was possible to formulate a design criterion for supporting gate roads under similar stress conditions. The shotcrete layer should be applied on the wall which has already undergone some extent of de-stressing due to induced stresses.

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