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Development of roadway through backfilled stope for underhand mining: a case study

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Abstract

In underground mines, roadways are developed through rock mass for approaching to the ore body. In conventional metal mining methods, crown and sill pillars are left to support the upper and lower levels. These pillars contain valuable high-grade minerals which may be permanently lost if not extracted. In underhand mining, there is no need to leave crown and sill pillars since the stoping is done using a top-down sequence by paste backfilling of extracted stopes. The underhand mining method is performed at Sindesar Khurd Mine, India. In this method, roadways need to be developed through cemented paste fill (CPF) for the extraction of underlying stopes. The backfilling process is done in two stages. Initially, a plug pour (10% Cement) of 9 m height followed by bulk fill (4% Cement). In this study, the physio-mechanical properties of Plug fill and Bulk fill are determined in the laboratory. Further, numerical modeling was carried out using FLAC 3D software to simulate the development of a 4.8 m x 4.8 m roadway through the plug fill to analyze the stability of the roadway. The stope dimensions of 20 m width, 25 m length, 25 m height, and 800 m depth are numerically modeled. Mohr-Coulomb failure criterion is used for elastoplastic analysis. The results show that roadway is safe to use if CPF has an internal angle of friction of 30 deg and cohesion of 150 kPa and 50 kPa for plug fill and bulk fill, respectively. These properties provide the minimum yielding height of 0.25 m in the roof. Further, shotcrete linings with 100 mm thickness and M35 grade yield heights with negligible value. In essence, this study provides the minimum required cohesion and internal angle of friction for CPF if the roadway is to be developed in an underhand mining method.

Keywords

CPF (Cemented paste fill), Plug fill, Bulk fill, underhand mining

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1 Introduction

In deep metal mines, the mining method adopted is often an underhand top-down sequence, which is more economical and stable due to improved ore recovery and the support provided by paste filling the stope voids. Working at greater depth using an overhand (bottom-up) mining sequence results in a significant quantity of ore being tied up in crown and sill pillars. During stope extraction of overhand stopes, the failure of the hanging wall and crown is the most common problem. To mitigate such problems adopting underhand mining below cemented paste filling (CPF) mitigates many of these problems The paste fill mining is mainly adopted for recovering ore from the stopes left for support (Li et al., 2011; Sobhi & Li, 2017). Paste backfill is placed into voids of previously extracted primary stopes providing support for the extraction of secondary stopes. Preventing the collapse of walls and roofs, ensuring overall stability and subsidence control (Brady & Brown, 2006; Dirige et al., 2009). In addition, it provides ground support to pillars and walls, prevents caving and roof falls, and enhances pillar recovery, thereby improving productivity (Coates, 1981; Mitchell, 1989). The strength of the CPF is dependent on curing time, cement content, and the material properties of the fill material (Yang et al., 2017). There are instances during underhand stoping when development is required in the cured paste fill (Andrieux et al., 2003; Soni & Ripepi, 2019) to access the ore body and provide a location for downhole production drilling. It is therefore necessary to understand the stability of the roadway for the safety of men and machinery working under the paste fill (Belem & Benzaazoua, 2008; Sivakugan et al., 2015).

As per the literature, limited research has been done on the development of CPF. Most of the studies undertaken have been done in narrow veins and small-level interval stopes (cut and fill) using conventional support methods such as sill matt support. Because of these limitations, laboratory testing and numerical studies were undertaken to determine the strength parameters required to ensure the stability of development in cemented paste filled with and without a shotcrete lining. This paper presents the results of this work.

1.1 Underhand mining using CPF

Underhand mining is used to extract ore in deep, high-stress mines, allowing mines to manage stress and minimize development in weak, damaged rock masses. In underhand mining, there is no need to leave crown and sill pillars since the stoping is done using a top-down sequence and backfilling the overlying extracted stopes with CPF. This mining method is used at Sindesar Khurd Mine in northern Rajasthan, India. In this method, roadways are developed through cemented paste fill (CPF) to provide production drilling access for the extraction of the underlying stopes. The backfilling process is done in two stages. Initially, a 9m high plug pour with 10% Ordinary Portland Cement (OPC) is completed, followed by a bulk pour with 4% OPC being used to fill the remainder of the stope. Fig. 1 shows the mining sequence of developing the drill level inside the CPF plug of the overlying stope, followed by production drilling and blasting from this level, the extraction of the ore on the extraction level and finally the filling of the stope. Tell-tales are installed to measure the deformation of the paste mass in the roof of the drill level.

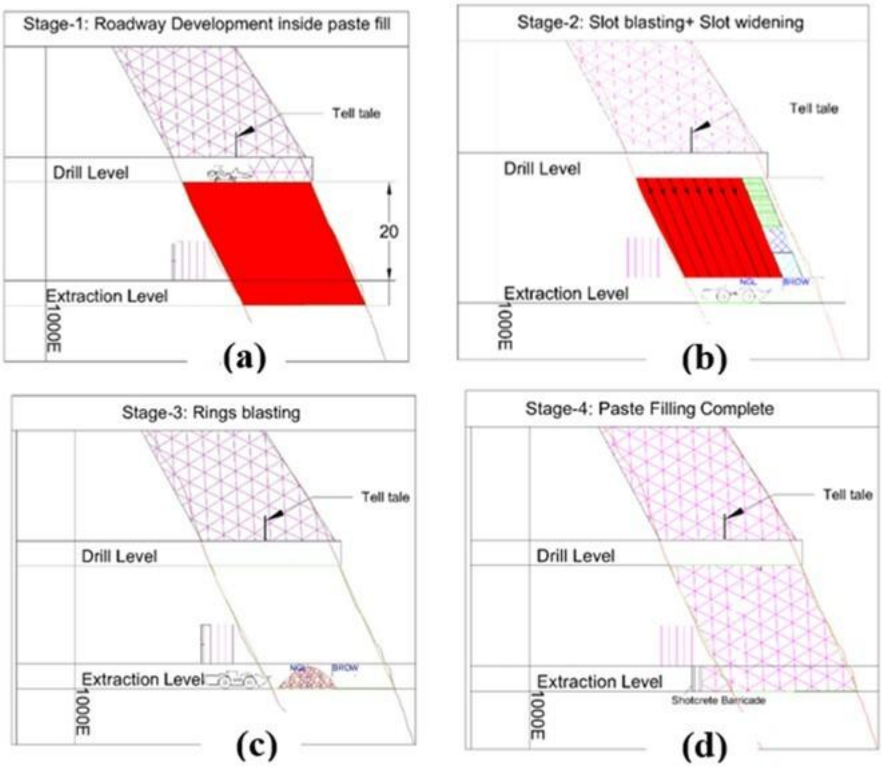

Fig. 1 Underhand mining using paste back fill (a) redevelopment of a drill level in paste mass (b) drill level used for production drilling and charging (c) extraction level used for ore mucking (d) stope is backfilled with cemented paste fill

1.2 Properties of Cemented Paste Fill and Rock

The mechanical properties of CPF casted samples (plug fill and bulk fill) are determined at different curing durations 24 hours, 72 hours, 7 days, 14 days, 28 days, and 35 days. The tests are performed as per ISRM-suggested methods and the properties are shown in Table 1. These results were used as the inputs for the elastoplastic analysis in numerical modeling using FLAC3D. The mechanical properties of the ore and surrounding rock were also determined, and their values are shown in Table 2.

Table 1 Properties of Plug fill and bulk fill

Material Property	**CPF type**	**Curing time**					
		24 hrs	**48 hrs**	**7 days**	**14 days**	**28 days**	**35 days**
Density (kg/m^3)	Plug fill 10% OPC	2010 to 2070					
	Bulk fill 4 % OPC						
Cohesion (kPa)	Plug fill 10% OPC	74.38	98.54	151.72	289.62	349.44	492.67
	Bulk fill 4 % OPC	25.04	35.19	51.26	81.36	124.73	160.56
Friction Angle (Deg.)	Plug fill 10% OPC	29 to 31					
	Bulk fill 4 % OPC						
Tensile strength (kPa)	Plug fill (kPa) 10% OPC	37.51	50.03	74.83	144.46	176.38	245.47
	Bulk fill (kPa) 4% OPC	12.57	17.56	25.04	40.94	62.52	80.61

Table 2 Properties of rock mass

Rock Type	Density (Dry) (kg/m3)	Uniaxial Compressive Strength (MPa)	Tensile Strength (MPa)	Young's Modulus (Average) (GPa)	Cohesion (MPa)	Friction Angle (Degree)	Poisson's Ratio
Ore (Dolomite)	2877	89	7.72	14.41	4.17	33.23	0.214
Hanging wall (Quartz mica schist)	2704	95	8.86	17.81	5.27	36.00	0.223
Foot wall (Biotite schist)	2842	79	5.22	11.89	3.4	35.65	0.227

2 Numerical modelling

Numerical modeling was carried out using FLAC3D software to simulate the development of a 4.8 m x 4.8 m roadway inside the paste mass. In modeling, the stope dimensions of 20 m width, 25 m length, and 25 m height, at 800 m depth, are used. The Mohr-Coulomb failure criterion is used for elastoplastic analysis.

The modeling procedure was done in 5 stages; where the initial stage involves the generation of a grid based on the stope dimensions and mining boundaries, as shown in Fig. 2. In the 2nd stage, boundary conditions are fixed, and in-situ stresses are applied. At this stage, the model is solved under the elastic condition. In the 3rd stage, the stope was excavated, and the model was solved in elastoplastic analysis. After that, the excavated rock mass was backfilled with a plug fill to 9 m, and the remainder of the stope was filled with a bulk fill. The material properties from Table 1 were assigned to the backfill. After backfilling the stope, the development of the roadway through the plug fill is simulated, and the stability of the roadway is assessed. These assessments were completed with and without support. The support used in the model was a 100mm thick layer shotcrete of M35 grade.

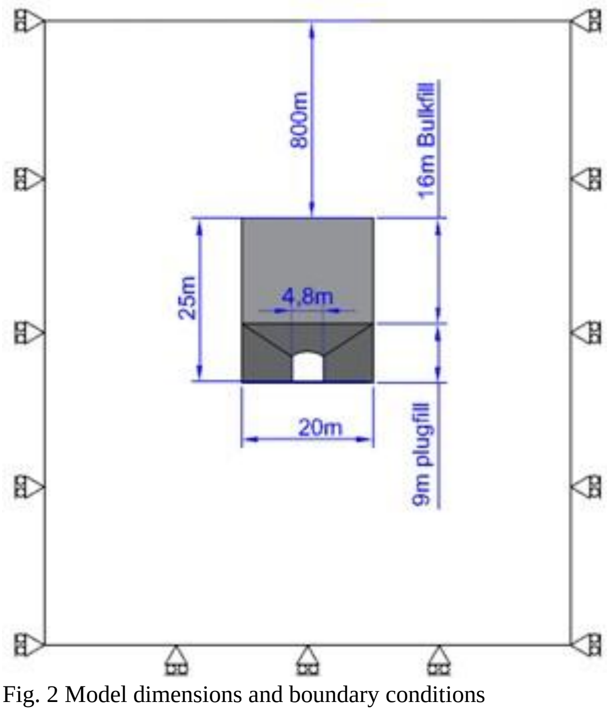

Fig. 2 Model dimensions and boundary conditions

3 Results and discussion

The numerical simulation results are analyzed for two cases: Case 1: The stability of the roadway within CPF without the shotcrete lining, and Case 2: The stability of the roadway within CPF with the shotcrete lining.

3.1 Case 1: Stability of roadway within CPF without shotcrete lining

The yielding of the CPF roof was analyzed at different combinations of cohesion for plug and bulk fill (Fig. 3). It was observed that some zones in the backfill are yielding by shearing and tension. Stable roadway conditions were obtained for a plug-fill cohesion of 150 kPa and a bulk-fill cohesion of 50 kPa. A line A-A' was drawn just above the drive roof and another B-B' at the center height of the drive, as shown in Fig. 3. The profile of maximum and minimum principal stress along lines A-A' and B-B' are shown in Fig. 4 and Fig. 5, respectively.

In Fig. 4, the following observations are evident: the maximum principal stress increases away from the CPF rock interface at the stope edge (0 m) because of stope wall confinement. At 5-6 m distance from the stope edge, the stress decreases as CPF to CPF interactions occur before the stress starts to increase again as it concentrates in the excavation side wall. In the roof of the drive, the stress becomes tensile and reaches its maximum tensile value at the mid-section of the drive. The same phenomenon is observed along the B-B line, but at the center, the maximum principal stress is zero because the CPF has been excavated. Fig 5 shows the minimum principal stress along lines A-A' and B-B' following the same trends as maximum principal stress.

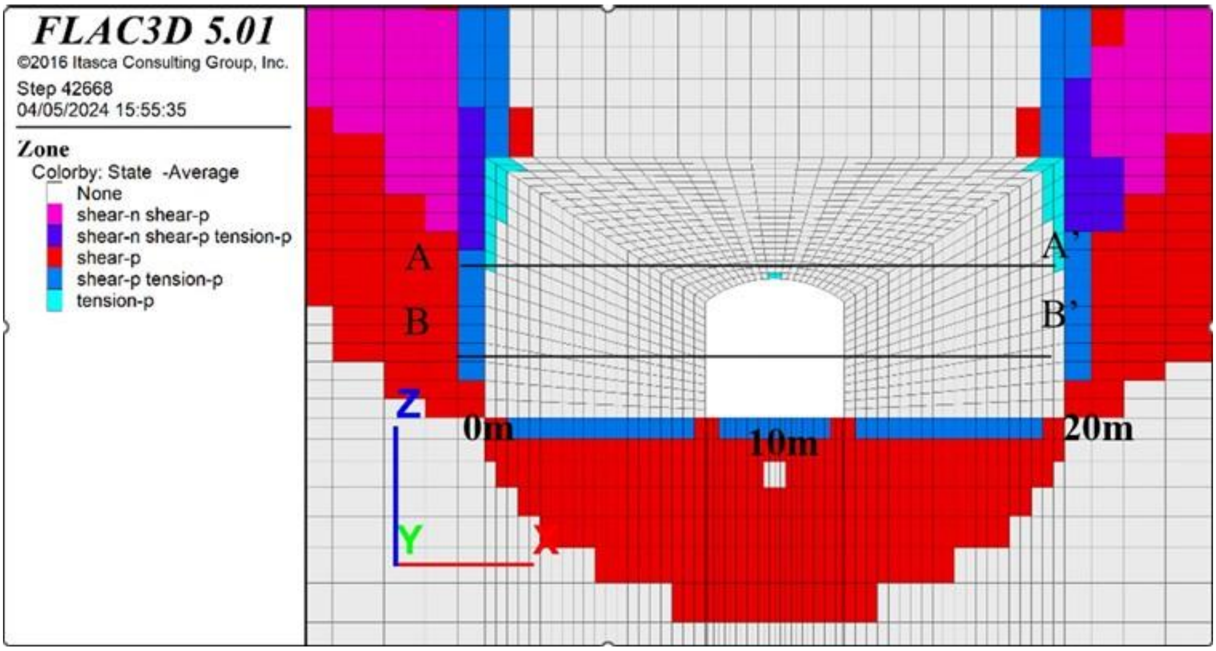

Fig. 3 Yielding in roadway roof with 150 kPa plug fill cohesion and 50 kPa bulk fill cohesion

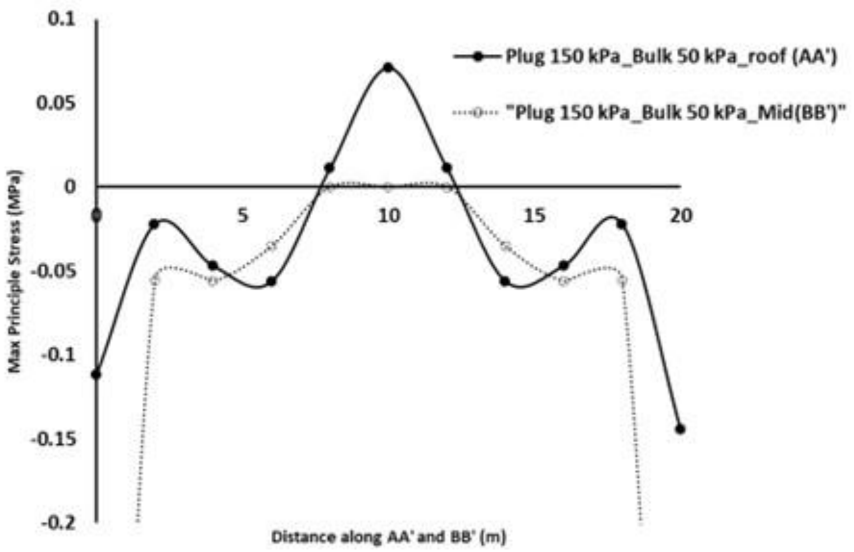

Fig. 4 Profile of maximum principal stress along line A-A' and B-B'

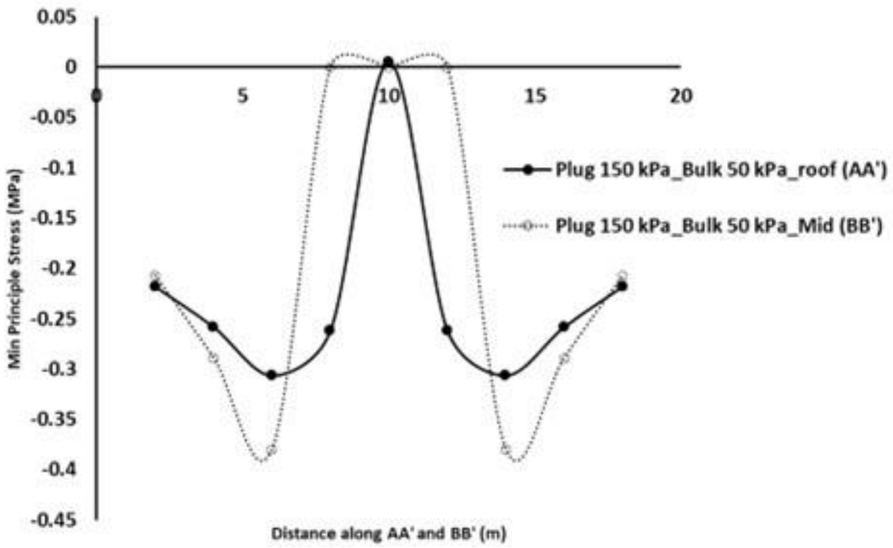

Fig. 5 Profile of minimum principal stress along lines A-A' and B-B'

3.2 Case 2: Stability of roadway within CPF with mesh reinforced shotcrete lining

After the development of the roadway inside the CPF, a lining consisting of 50 mm of shotcrete, then a wire mesh layer, followed by another 50 mm of shotcrete, is applied. Sprayed shotcrete in the roof must support its own weight within minutes of being applied. The minimum UCS required for shotcrete to support its own weight is typically 0.4 MPa. For safety and to prevent equipment damage, a shotcrete strength of 1 MPa is required before re-entry is permitted. It is observed that M35 grade fiber-reinforced shotcrete reaches a strength of 1 MPa in one hour. The values shown in Table 3 were used in the modeling.

Table 3 M35 Shotcrete grout properties for one hour of curing time

Property of M35 Shotcrete	Friction Angle (Deg.)	Cohesion (MPa)	Density (Kg/m^3)	Tensile strength (MPa)
	25	0.35	2539	0.35

The shotcrete lining increases the internal pressure over the CPF roadway, which prevents the deformation of the roof and reduces the amount of yield in the CPF. With increasing cohesion of the plug fill and bulk fill, the yielding height in the excavation roof is observed to decrease for both Case 1 and Case 2, and the results are shown in Table 4. It is observed that at higher cohesion values (150 kPa plug fill cohesion and 50 kPa bulk fill cohesion) with the shotcrete lining, the yielding height is reduced to zero (Fig. 6). The percentage yielding in CPF is calculated using the ratio of the number of zones under plasticity and the total volume of CPF. The percentage yield within the CPF for the cases with and without the shotcrete lining is shown in Fig. 7. This shows that the use of shotcrete reduces the number of yielded zones across all the strength values assessed of plug-fill cohesion, with the reduction most significant at lower cohesion values (75 – 150 KPa).

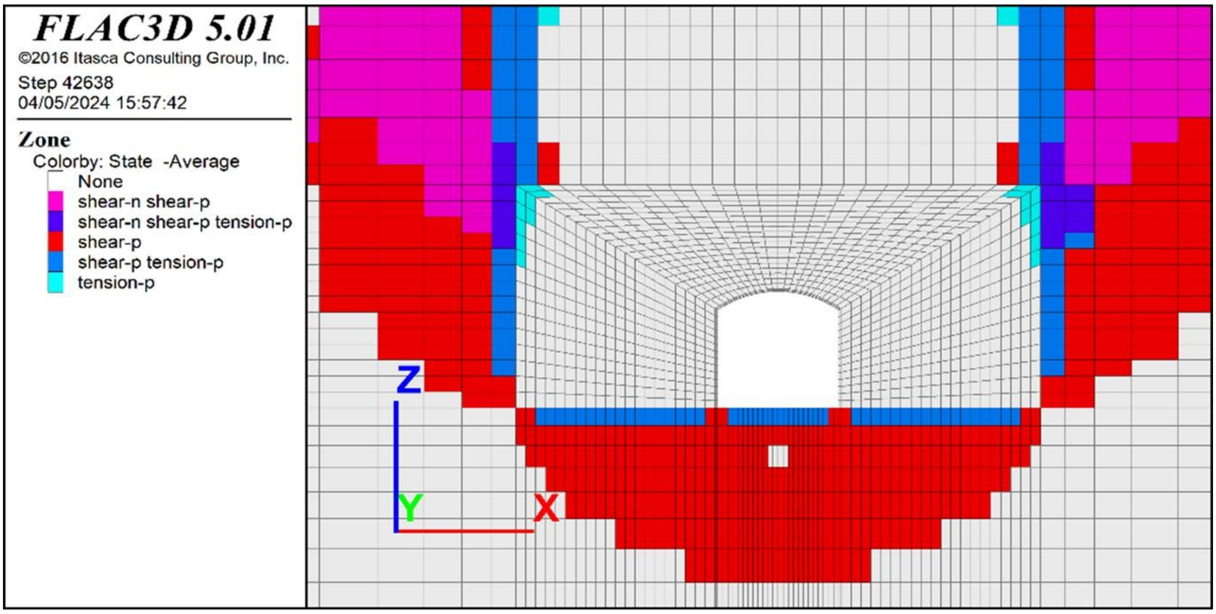

Fig. 6 Yielding in roadway roof with 150 kPa plug fill cohesion and 50 kPa bulk fill cohesion after shotcrete

Table 4 Height of yielding zone in roof

Cohesion (MPa)		**Height of yielding zone in Roof (m)**	
Plug fill	**Bulk fill**	**Without Shotcrete**	**With Shotcrete**
75	25	2.5	2
100	35	2	1.2
150	50	0.2	0
290	80	0	0

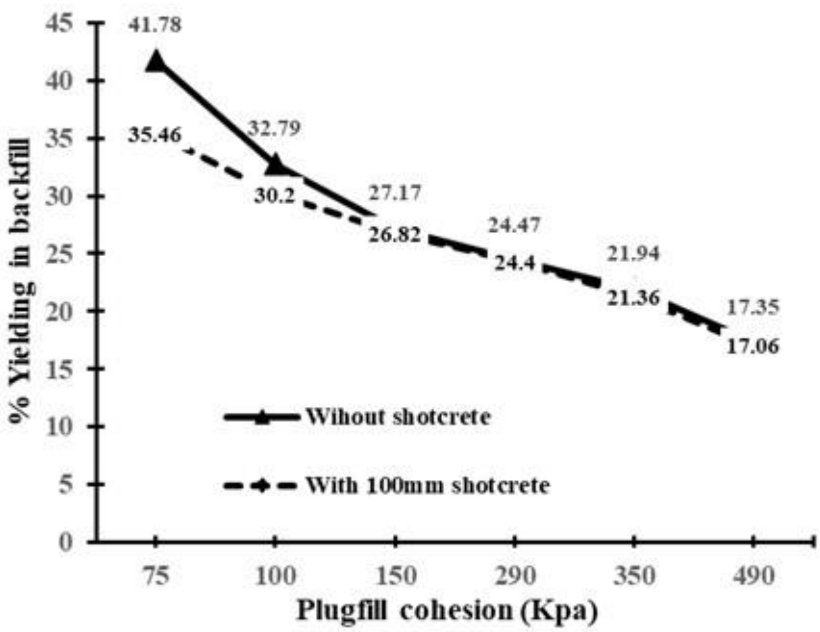

Fig. 7 Percentage yielding of CPF after roadway development

4 Conclusion

This study focused on the development of a roadway through the paste backfilled stopes in underhand mining. The mechanical properties of CPF casted samples (plug fill and bulk fill) were determined in the laboratory, and the development of a 4.8 m x 4.8 m roadway inside the paste mass is numerically simulated in FLAC3D. The numerical simulation results show that the roadway is safe to use if CPF has an internal angle of friction of 30° and a cohesion of 150 kPa and 50 kPa for plug fill and bulk fill, respectively. Further, in numerical models, when a shotcrete lining of 100 mm thickness and M35 grade is applied, the yielding zone becomes negligible. This situation provides stable and safe working conditions for development through the CPF. In essence, this study also offers the minimum requirements for cohesion and internal angle of friction when development is done through the cemented paste fill.

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