Paste backfill of shallow mine workings for land reclamation in Canmore, Alberta



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ABSTRACT:

Land above abandoned coal mines is often attractive for re-development, being in areas of historic settlement, often with great natural beauty. However, voids and collapsed rubble in shallow underground workings present a risk of future ground subsidence that can adversely impact the stability of surface structures and infrastructure as well as public safety. This paper presents the objectives, criteria, methods and results of a mitigation program for about 1.0 hectares of land in Canmore, Alberta using flowable paste backfill material made from local soils and Portland cement.

RÉSUMÉ

Les terrains situés au-dessus des mines de charbon abandonnées sont souvent intéressants pour le réaménagement, étant dans des régions anciennement habitées et souvent d'une grande beauté naturelle. Cependant, les vides et les débris dus à l'effondrement des galeries peu profondes présentent un risque d'affaissement futur et peuvent avoir un impact néfaste sur la stabilité des structures et des infrastructures de surface ainsi que sur la sécurité publique.Cet article présente les objectifs, les critères, les méthodes et les résultats d'un programme de mitigation, sur environ 1.0 hectares de terre à Canmore, qu utilise un matériel de remplissage liquide composé de la terre locale et de ciment Portland.

1 INTRODUCTION

Coal mining in Canmore began in 1886 and continued until 1979 when the last mine ceased operation. Reclamation activities required by the mine regulations were carried out following closure of the mines. The coal mines were primarily underground operations and the coal was generally extracted by the room-and-pillar method of mining. In the Canmore area, as many as seven seams have been mined commercially. The coal seams extend geologically over distances of a few hundred feet. However, the seams are not continuous, and at many locations, faults have displaced the coal locally limiting the extent of some mines. The locations of workings within the various seams overlap and commonly two and occasionally three coal mines exist at the same plan location. The coal is characterised as being low volatile bituminous to semi-anthracitic in rank and demonstrates an increase in coal seam rank with depth. Approximately 16 million tons of coal was extracted over the life of the mines.

The Three Sisters Mountain Village development comprises approximately 2000 acres (800 hectares) of land and is planned to include residential housing for 10,000 people, two world-class golf courses and a resort centre. The study site for the mitigation program was in Stewart Creek Phase 1 of the Three Sisters Mountain Village development and comprises approximately 2.5 acres (1 ha) of land. Stewart Creek Phase 1 is underlain by abandoned coal mine workings in the upper No. 4 Mine, No. 4 Seam and lower Wilson Mine, Wilson Seam. The No. 4 Mine, No. 4 Seam was mitigated between November 2004 and March 2005, which is the topic of this paper. The mitigation program was carried out for the owner of the land at the time, Three Sisters Mountain Village Ltd. (TSMV).

Drilling data indicate that the No. 4 Seam is up to 3.5 m thick and, typically, 3 m of this was extracted. This seam comes to subcrop within the northern portion of the site where the floor is a minimum of 7.6 m below ground surface. In the vicinity of the development, this seam dips at an angle between 12° and 18° to the southwest and strikes approximately northwest-Within the mitigation area, the mine is southeast. above the water table. Drilling into the mine indicated that the workings are largely collapsed, with little remnant void; however due to the loose nature of the rubble mass, the risk of future ground movements could not be discounted. Prior to mitigation, the possible future subsidence movements as a result of collapse in this mine included sinkhole-type formations and block subsidence resulting in abrupt step deformations. These movements are anticipated to occur when there

is less than 10 m of intact rock cover over the roof of the mine or zone of mine-induced fracturing. These movements cannot be effectively mitigated through structural modifications to building foundations and/or basements. Therefore, the workings overlain by less than 10 m of intact rock cover were mitigated. The maximum depth encountered during this mitigation program based on the criterion of 10 m intact rock cover was 36.5 m and the average depth was around 22 m.

The Wilson Mine, Wilson Seam also underlies Stewart Creek Phase 1 and is, on average,50 m below the No. 4 Seam. Drilling has shown that this mine is partially collapsed with some void and rubble remaining. Also, the mine is completely submerged. Mitigation of this mine was not considered necessary as the estimated possible future subsidence due to further collapse of this mine can likely be accommodated more economically through structural design of planned buildings.

The mitigation program for the Stewart Creek Phase 1 subdivision was carried out for residential development, roads and municipal reserves. At the time of the mitigation program, the subdivision layout provided was in an early stage of planning with the understanding that internal details were preliminary. For that reason, the locations of planned roads on the preliminary layout were treated to the same standard as residential development during this program. Between November 2004 and March 2005, over 8,300 m³ of soilcement backfill was injected into the mine by either pressure injection or gravity injection.

2 MITIGATION PROGRAM DESCRIPTION

The mitigation program for residential development included drilling of primary injection boreholes on a 15 m grid pattern. An investigative drilling program consisting of forty-four boreholes was carried out in 2004 prior to the mitigation program and most of these boreholes were also used as primary injection boreholes for the purposes of mitigation. Boreholes that encountered mining or mining-induced fracturing with less than 10 m of intact rock cover or with large voids that could cause large, localized movements on the ground surface were injected with paste backfill under pressure. Boreholes that encountered coal with no significant fracturing in the rock above or encountered mining with more than 10 m of intact rock with no significant potential for sinkholes to develop at the surface were filled with paste under gravity to refusal. Prior to injection, boreholes were classified as mitigation or abandonment boreholes based upon the drilling results.

During the mitigation process, a cement content of 4% by weight and a slump of 150 mm were targeted for the paste backfill, although these values varied slightly in the field. The injection was carried out as described in the above section. Proof drilling was carried out and the majority (65%) of proof holes encountered paste and/or coal. Secondary injection was carried out in proof boreholes in the same manner as the primary injection.

3 MITIGATION OBJECTIVES

The objective of the mitigation program in Stewart Creek Phase 1 was to recover additional land for development by reducing the potential maximum subsidence movements predicted to result from sinkhole formation and block failure as well as decreasing the probability of those events occurring as a result of the No. 4 Mine below the subject site.

The reduced potential for subsidence-related ground movements was achieved by the injection of a soilcement mixture, termed "paste backfill", into boreholes by means of either pumping or gravity. The paste backfill was used to accomplish two objectives:

1. The stabilization of rubble by filling the void space between the rubble fragments and, thereby, to reduce the magnitude and likelihood of subsidence of the ground surface.

2. The reduction of the potential for sinkhole or block failure formation at the ground surface by filling in horizontally extensive voids or localized voids.

The criteria described in the following section were used to achieve the objectives.

4 MITIGATION CRITERIA

When determining subsidence mitigation criteria, various land uses and ranges of subsidence hazards were considered to be compatible with each land use (i.e. the land is considered to be 'suitable' for its designated use when it contains hazards within the specified range). Also, the mitigation methods that could be applied to limit the hazard to a given magnitude were considered. The subsidence estimation methods used in the application of these criteria are described elsewhere (Whittaker and Reddish, 1989).

As an example, it has been established that subsidence of 0.1 m is a suitable limit for residential backyards. The magnitude of subsidence is unlikely to cause a physical danger, it will probably not cause immediate loss of functionality, and it will be repairable at much more modest cost than the cost of mitigation required to prevent it. However, it was recognized that there may be instances in which the perception created by subsidence of this magnitude and its impact on land value and corporate image are not acceptable. Therefore, the guidelines are accepted as being general in nature and, where appropriate, the guidelines will be adapted for specific purposes. Table 1 shows the subsidence mitigation criteria guidelines used in the Stewart Creek Phase 1 mitigation program.

Table 1. Subsidence Mitigation Criteria

Land Use	Minimum Ratio of Intact Rock Cover to Remnant Void	Minimum Thickness of Intact Rock Cover (m)	Maximum Predicted Ground Deformati on (ft)
Residential	>12 times	10	0.1
Municipal Reserves	N/A	N/A	0.3
Roads	>8 times	N/A	0.1

Boreholes that encountered conditions that did not meet the required subsidence mitigation criteria were considered to be injection boreholes and used for backfill injection under pressure using pumps. Otherwise, boreholes were considered to be abandonment boreholes and were used for backfill injection under gravity head.

To determine when to terminate pumping during the field mitigation program, criteria were used for pump and gravity injection, as calculated from drilling results and shown in Table 2.

Table 2. Injection Criteria

Injection Type	Volume	Pressure
Pressure	90% of void volume 30% of rubble volume Occupying a 7.5 m radius around the hole	2 times overburden pressure
Gravity	Volume of bored hole	N/A

The pressure criteria of two times overburden pressure was adopted based upon monitoring and experience, and that it is possible to exceed overburden pressure with a given paste mix based head losses due to friction down the hole and out into the formation. Observations of paste backfill coming from adjacent boreholes indicates that the pressure is usually at or less than the hydrostatic head of paste 15 m away, and thus less than the overburden pressure.

It should be noted that if, during gravity injection into a borehole that encountered an intact pillar within the mitigation area, the injected volume was more than double the amount calculated for the borehole then gravity injection was halted and pressure injection was carried out. This was to fill any extensive fracturing above or around the coal pillar that interconnected with the borehole.

5 MITIGATION METHODS

The methods used to achieve the objectives based on the established criteria are discussed in the following subsections.

5.1 Injection Point Installation

Boreholes were drilled on a 15 m grid pattern, as discussed in Section 2.0. The No. 4 Mine plan with site layout and boreholes overlain is shown in Figure 1.



Figure 1. No. 4 Mine plan with site layout overlain. Injection boreholes are shown in small font in the upper (subcrop) portions of the mine above the thick dashed line.

Conditions within both the bedrock and the mine, including height of void, amount and condition of rubble, extent of fracturing and presence of coal, were recorded. In general, very little void was encountered during the drilling program with the exception of a few isolated tunnels. The majority of the material at mine level was rubble resulting from historical roof collapse, with some fracturing above. Figure 2 shows an example of the nature of the rubble encountered as recorded on borehole camera footage The photographs shows an area of approximately 12" square.



Figure 2. Still photograph of rubble encountered through borehole camera survey.

All boreholes were 5.25" (133 mm) diameter and drilled using a truck-mounted ReichDrill R650 reverse circulation air rotary drill rig supplied. The borehole locations were selected and surveyed prior to drilling on the basis of past investigative drilling as well as mine plans. The majority of boreholes were drilled vertically; however, where physical constraints existed such as overhead transmission lines, boreholes were drilled at an angle from the vertical to target a specific location within the mine. Schedule 40, 100 mm PVC casing with a working pressure of 220 psi was installed in each borehole. The PVC casing was generally installed 1 m into bedrock.

5.2 Cemented Paste Backfill Injection

Between November 2004 and March 2005, approximately 8,373 m³ of paste backfill was placed into the No. 4 Mine workings. The paste backfill equipment consisted of a Komat'su 200LC backhoe, a 9 cubic yard Standard Dial-a-Mix concrete system mounted on a tandem truck chassis and a Concorde hydraulic piston drive concrete pump truck. Water and cement were delivered to site via trucks from local sources.

The aggregate used in the paste mixture was a locally available native till overburden. The overburden was screened and the material finer than 19 mm was used in the paste mixture. This material, which has a significant silt content, naturally possessed the properties of a paste backfill aggregate, which typically require greater than 15% finer than 20µm.

The paste backfill was mixed on site in the mixer truck, which directly monitors aggregate (overburden) feed, cement feed and water volume and mixes the materials via a 300 mm diameter delivery auger. The majority of the injection of backfill was performed using a positive-displacement concrete pump connected by 100 mm diameter pressure hose to the PVC borehole

casing. The paste backfill operation is shown in Figure 3 with a close-up shown in Figure 4.



Figure 3. Photograph of operation set-up



Figure 4. Injection set-up at well-head

A gravity injection method was utilised for backfilling boreholes that did not intersect the mine and boreholes that intersected over 10 m of intact rock cover.

For gravity injection, the delivery auger was placed immediately above the PVC casing and the paste was poured through a screened funnel into the top of the PVC casing. The metal screen had holes 100 mm by 50 mm and was used to avoid obstruction of the borehole with debris or frozen lumps of material. Table 3 summarizes the paste mixes used for different injection applications.

Injection Method	Slump	Cement Content (wt%)	Pressure
Pressure Injection (Building footprint and developable lots)	6"	4	Twice overburden pressure
Gravity Injection – Abandonment	6"	4	Hydrostatic
Gravity Injection – Municipal Reserve	8"	4	Hydrostatic

Table 3. Design Injection Parameters

5.3 Confirmatory Methods

Throughout the mitigation program, several methods were used simultaneously to help determine whether boreholes were filled to their maximum capacity. During injection these methods included monitoring of: maximum pressure criterion, maximum volume criterion and presence of paste backfill in adjacent boreholes. A borehole camera as well as manual sounding of boreholes with a weighted tape was used to confirm the presence of paste backfill in boreholes adjacent to the injection borehole. Also, the ground in the vicinity of the injection, proof drilling was used as a confirmation method. Each of these methods is described further in the following sub-sections.

5.3.1 Maximum Volume and Pressure Criteria

Prior to injection, boreholes were classified as mitigation or abandonment boreholes according to the criteria listed in Table 2 based on drilling and borehole camera inspection results. Volume and pressure criteria were established for each borehole (see Table 1). During injection, a pressure gauge was connected to the top of the casing to monitor wellhead pressure. The data from the pressure gauge was transmitted in real-time to a laptop and recorded for future reference. Readings were recorded manually at 30 minute intervals. An example of the data acquired is shown in Graph 1 which is a plot of pressure in psi versus time in minutes. This example shows a typical profile of very low pressure at the beginning of injection while the open void space can be filled by gravity alone, followed by progressively higher pressure as pump pressure is required to push paste into more distant or less permeable voids and finally up to a pressure spike of approximately 300 psi when the borehole reached the injection capacity.



Graph 1. Wellhead pressure in primary injection borehole with approximately 360 m³.

The volume of paste backfill injected was measured by a gauge monitoring auger rotation on the mixer truck and recorded at least every 30 minutes. The rate of pumping was varied as required to maintain a wellhead casing pressure less than the working pressure of the PVC pipe or twice the overburden pressure. Generally, maximum injection pressure was reached before the volume criteria and the injection was terminated on that basis. At the completion of the injection, the final volume and maximum wellhead pressure were recorded for each borehole.

5.3.2 Survey for Uplift of Ground

During the first two weeks of injection, the ground surface adjacent to the injection borehole was monitored for regional uplift of the ground by means of visual observation and elevation survey using a construction level. No uplift was measured by the surveying and it was determined that the risk of jacking the ground was low, so visual observation alone was used to monitor for uplift during injection for the remainder of the mitigation program. Cracking of the ground surface was observed at two locations, which was attributed to loose soil conditions and very shallow mining conditions near the subcrop.

5.3.3 Borehole Camera and Manual Checks for Cemented Paste Backfill in Adjacent Boreholes

Prior to mitigation, a borehole camera was used in all boreholes where a void was logged during drilling to confirm the existence of the void as well as the extent of fracturing and condition of rubble. The borehole camera was also used in a selection of boreholes which did not encounter voids to determine the extent of fracturing and condition of rubble. This aided in more accurate volume estimates for injection. During mitigation, the boreholes within 15 m of the injection borehole were observed periodically for the presence of paste. In some cases, paste filled up adjacent boreholes and flowed up onto the surface. The borehole camera was used to monitor boreholes that were anticipated to have connection to the injection borehole based on drilling results or interpretation of mine plans. The real-time video image was observed throughout the injection and digital video tapes were collected when paste backfill was observed in the borehole. Figure 5 shows paste backfill filling a void in a borehole adjacent to the injection borehole.



Figure 5. Still photograph from borehole camera footage of paste flow.

5.3.4 Proof Drilling

Secondary boreholes were drilled to confirm that the paste backfill had adequately filled the void and rubble. The proof holes were generally drilled between primary holes; approximately 1 secondary hole was drilled for every 4 primary holes. The majority of proof holes encountered paste backfill, paste backfill and rubble, and/or coal.

Secondary injection was carried out in proof boreholes in the same manner as the primary injection. It was anticipated that, if the primary injection was successful, the volume of the secondary injection would be an order of magnitude less than the primary injection volume. The majority of secondary boreholes injected encountered refusal due to pressures exceeding the working pressure of the casing within a very short time (5 - 10 minutes). An example of this is shown in Graph 2 where a secondary injection borehole was full within a few minutes with a total volume injected of 0.2 m^3 . This demonstrates that the majority of the backfilling was completed during the primary injection.



Graph 2 – Wellhead pressure in secondary injection borehole with 0.2 m^3 volume injected.

Some secondary boreholes had large secondary injection volumes (greater than 10 $\mbox{m}^3)$ due to reasons such as:

• Primary boreholes in the vicinity encountered intact coal pillars

• Problems occurred during primary injection due to rubble collapse into angled PVC pipes

• Injection into primary boreholes filled unrecorded mine workings

These holes were included as second-pass primary injection locations in the volumetric analysis below.

5.3.5 Quality Control

Quality control testing was carried out every 100 m³ during injection by means of slump tests and the casting of 100 mm diameter cylinders. The cylinders were tested for unconfined compressive strength (UCS) according to ASTM D2166, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. A UCS value of 100 kPa was selected as a minimum strength criterion after 28 days of curing. During the injection programs, 197 samples were tested for unconfined compressive strength and results are shown in Table 4.

Table 4 . Summary of UCS Test Results

Mitigation Program	Minimum	Maximum	Average
	Strength	Strength	Strength
	(kPa)	(kPa)	(kPa)
Residential (pressure and gravity injection)	110	930	480

It should be noted that on days when little volume was injected, or the volume per borehole was less than 10 m^3 , concrete cylinders were not cast.

6 MITIGATION RESULTS AND CONCLUSIONS

A summary of mitigation results is shown in Table 5.

Table 5. Summary of Residential Development Mitigation

	Primary injection Volumes				ent e	
	1 st Pass	2 nd Pass	Total Primary Injection	Total Secondary Injection	Total Abandonme	Total Volum
# Boreholes	71	7	78	42	73	193
Volume Injected (m ³)	8,158	1,778	7596	72	59	7727
% Volume of Total	80.7	17.6	98.3	0.9	0.8	100

¹Total Volume includes primary injection volume, secondary injection volume and abandonment volume

Less than 1% of the total injection volume was placed during secondary injection. This would imply that primary injection provided almost complete filling of available voids. Secondary injection was shown to be necessary only for confirmation and there is a high level of confidence that the mitigation has backfilled the majority of interconnected and large voids. It has been assumed that only large voids are capable for forming sinkholes and that block failures require laterally extensive, though perhaps vertically small, voids. Voids of both these types are successfully filled by the mitigation methods described.

In conclusion, it was found that a cemented paste backfill mix could be successfully used to stabilize abandoned mine workings for land recovery.

7 REFERENCES

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