MINE SUBSIDENCE CONTROL PROJECTS ASSOCIATED WITH SOLID WASTE DISPOSAL FACILITIES[1]

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Abstract: Pennsylvania environmental regulations require applicant's for solid waste disposal permits to provide information regarding the extent of deep mining under the proposed site, evaluations of the maximum subsidence potential, and designs of measures to mitigate potential subsidence impact on the facility. This paper presents three case histories of deep mine subsidence control projects at solid waste disposal facilities. Each case history presents site specific mine grouting project data summaries which include evaluations of the subsurface conditions from drilling, mine void volume calculations, grout mix designs, grouting procedures and techniques, as well as grout coverage and extent of mine void filling evaluations. The case studies described utilized basic gravity grouting techniques to fill the mine voids and fractured strata over the collapsed portions of the deep mines. Grout mixtures were designed to achieve compressive strengths suitable for preventing future mine subsidence while maintaining high flow characteristics to penetrate fractured strata. Verification drilling and coring was performed in the grouted areas to determine the extent of grout coverage and obtain samples of the in-place grout for compression testing. The case histories presented in this report demonstrate an efficient and cost effective technique for mine subsidence control projects.

Additional Key Words: subsidence, grouting, solid waste, deep mines.

Introduction

As required by the Pennsylvania Department of Environmental Resources (DER) regulations for municipal solid waste (MSW) disposal facilities, an applicant for a solid waste disposal permit must provide information regarding the extent of deep mining under the proposed landfill site. In fulfillment of the regulations, the applicant is required to provide evaluations of the maximum potential for subsidence at the site and designs of measures to be utilized to mitigate the potential for adverse impact on the facility due to subsidence. This paper presents case histories of deep mine subsidence control projects associated with the development of three solid waste disposal facilities. Each case history presents site-specific mine grouting project summaries that include evaluations of the subsurface conditions from drilling, mine void volume calculations, grout mix designs, grouting procedures and techniques, grout coverage, and extent of mine-void filling evaluations.

The case studies presented utilized basic gravity grouting techniques to fill the mine voids and associated subsidence fractured strata over the collapsed portions of the deep mines. Based on the anticipated conditions of the deep mine voids as determined from preliminary drilling information, grout mixes were designed to maximize filling of the mine voids and fractures. The grout mixtures were designed to achieve compressive strengths suitable for preventing future mine subsidence while maintaining high flow characteristics to penetrate fractured strata. A variety of grout mix designs were developed using varying proportions of sand, fly ash, cement, and water. Control of the grout mix designs during grouting operations was maintained by compression testing of grout test cylinders. In addition, coring was performed in the grouted areas to determine the extent of grout coverage and obtain samples of the in-place grout for compression testing.

Regional and Local Geology

All three of the case study sites are located in the Appalachian Plateau physiographic province of southwestern Pennsylvania. Regionally, the geologic structure of this area is characterized by subhorizontal bedrock strata and gently plunging northeast-southwest-trending folds. Geologic strata encountered at the sites consist primarily of interbedded sandstone, siltstone, and shale and range in age from Lower to Upper Pennsylvanian. These case studies deal with subsidence control projects associated with deep mining on the Upper Kittanning and Pittsburgh coal seams.

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Subsidence Evaluations

As required by the MSW regulations, an evaluation of the maximum potential for subsidence at landfill sites underlain by deep mines must be performed. In addition, the design measures incorporated into the landfill design to mitigate the potential for adverse impacts on the integrity of the landfill facility must be presented. Subsidence predictions were performed for each of the sites presented in this paper during the landfill permitting process. The subsidence calculations were typically generated using the National Coal Board (NCB) method for subsidence predictions (Peng, 1986). This method of subsidence prediction bases the calculation on the minable thickness of the coal (void height) times a subsidence factor. The determination of an appropriate subsidence factor is critical to the prediction. In England the NCB has developed empirical subsidence factors based on observation of subsidence over active coal mining operations. Subsidence factors in the United States are generated based on research and field observations. A typical maximum subsidence factor for U.S. bituminous coalfields is 0.5 (GAI, 1974). Other assumptions regarding the type of subsidence (sinkhole versus trough) relative to the depth of overburden are also applied to the subsidence predictions (Jones & Kohli, 1985). The end result of the subsidence evaluation is that if the site is underlain by deep mines, some form of subsidence mitigation under the waste disposal area to protect liner and leachate control systems is typically required by the regulatory agencies. In Pennsylvania, typically mine subsidence mitigation is required where overburden thickness is less than 30.5 m (100 ft). The determination of the areas requiring subsidence control includes factors such as angle of draw, in addition to the overburden depth criteria.

Subsidence Control Projects

In central and southwestern Pennsylvania two basic mine subsidence control techniques have been utilized: overexcavation-backfilling and grouting. Since the Pennsylvania MSW regulations require that no waste be placed within 7.6 m (25 ft) of a coal seam, overexcavation and backfilling is the most common mine subsidence control technique for shallow-overburden deep-mined areas. Often the overexcavation techniques will be extended to some economical overburden depth limit. Areas of deep mining beyond the excavatable limits which require subsidence control are then grouted.

Grouting projects for the mitigation of deep mine subsidence potential have been performed on a number of landfills in southwestern Pennsylvania. The overexcavation and grouting techniques are the predominate, if not the only, subsidence mitigation methods known to have been used. These mine grouting projects typically use fly ash and cement grout mixtures placed into the deep mine voids and subsidence fractured strata via boreholes. Grouting is typically performed using gravity placement techniques. To minimize environmental and logistical problems at the landfills, the grouts are typically mixed at local commercial concrete plants and delivered to the sites via standard concrete ready-mix trucks. Three mine grouting projects representative of this type of mine subsidence control technique are presented in the following sections.

Case Studies

Site 1

The mine subsidence control project at Site 1 was performed as part of a permitted expansion of the landfill to mitigate potential subsidence effects on the landfill liner and leachate collection systems. The liner system in this area was to be installed on an approximately 167.6 m (550 ft) long 3 horizontal to 1 vertical (3H:1V) slope, along the southern perimeter of the waste disposal area.

Four coal seams, the Upper Freeport, Lower Freeport, Upper Kittanning, and Lower Kittanning, occur within the strata in the project area. The Lower Kittanning Coal and Upper Kittanning Coal are the two prominent coal seams within the vicinity of the site. Both beds have been stripped and deep-mined. Based on available mine map information, it appears that both the Lower and Upper Kittanning Coal were mined using the room-and-pillar method. The mine maps also indicate that extensive retreat mining was performed in this area. Only the Upper Kittanning Coal required grouting in the area below this portion of the landfill expansion. The seam thickness of the Upper Kittanning averages 92 cm (3 ft) within the project area, with a maximum thickness of 107 cm (3.5 ft). Previous geologic investigations described in the landfill permit application indicated that substantial collapse of the mine voids had occurred. Based on these investigations, it appeared that in most of the project area, the mine voids were completely collapsed or gob-filled, with open voids averaging less than half of the mine void volume based on seam thickness and typical mining extraction ratios.

Substantial excavations were required in the project area to remove coal within 7.6 m (25 ft) of the liner systems and to achieve the proposed liner grades in the 3:1 slope area. To facilitate the grouting operations, the blasting and excavation operations were designed to create two wide flat benches at elevations just above final landfill grades. Grouting operations were performed from these two benches. The lower bench, which was created by required overexcavation of the Lower Freeport Coal (to provide minimum 7.6 m (25 ft) separation between the landfill liner and coal seams), occurs approximately 10.6 to 15.2 m (35 to 50 ft) above the Upper Kittanning deep mine. The upper bench associated with the overexcavation of the Upper Freeport Coal occurred approximately 28.9 to 41.1 m (95 to 135 ft) above the Upper Kittanning deep mine. After overexcavation of the coal within 7.6 m (25 ft) of the liner grades, approximately 3.2 ha (8 acres) of Upper Kittanning deep mines remained which required grouting.

Grout Hole Drilling. The perimeter of the grouting area was located and staked by survey. Locations for grout barrier holes were marked at 4.6 m (15 ft) centers along the perimeter of the grouting area. The actual locations of the grout barrier wall grout placement holes, installed around the perimeter of the grout area, were adjusted during drilling operations to achieve the minimum 30.5 m (100 ft) liner subgrade-mine separation requirements.

Production grout hole locations were staked within the grouting area on approximately 12.2 m (40 ft) centers. The 12.2 m (40 ft) spacing was based on observations of the travel distance of the grout during previous mine stabilization programs at this site. Some of the production holes could not be drilled on the 12.2 m (40 ft) grid spacing due to the highwall created by coal isolation barrier excavations. To achieve grout coverage in these areas, production hole locations were adjusted and additional production holes were drilled around the locations of known voids in an attempt to target high grout take areas. As a result, many production holes were drilled at spacings less than 12.2 m (40 ft).

A total of 541 barrier and production grout holes were drilled within the project area. All production and barrier wall grout holes were drilled using air rotary drill rigs equipped with a 16.5 cm (6-1/2 in) diameter air percussion hammer drill bit. Drilling records were maintained by the field engineer documenting the depths at which the coal, void, or fractured strata were encountered and the thicknesses of these zones. The intact coal seam (assumed coal mine pillars) was encountered in only about 20% of all drill holes. This suggests that the extraction rate in this area was much greater than that normally associated with room-and-pillar mining and confirms that retreat mining was common in the area. Collapse of the mine roof in the retreat mined area substantially reduced the mine void volume to be grouted. The extent of the collapsed mine voids and remaining void spaces is variable throughout the stabilization area. However, of the 541 holes that were drilled, only 26 (5%) encountered open void space at the Upper Kittanning Coal elevation.

The Upper Kittanning mine conditions interpreted from the drilling activities were observed and documented visually at the base of the highwalls created by the overexcavation of coal in the project area. The exposed deep-mined areas were observed to be totally collapsed with a few, highly deformed pillars and a small amount of void space remaining as delaminations along bedding planes within 3 to 6 m (10 to 20 ft) above the mine floor.

Grout Production. A fly ash-cement grout mixture was used for this mine stabilization project. The fly ash was supplied from a local coal-fired powerplant. This fly ash source was preapproved for use by the DER, based on chemical analyses to identify pollution potential and physical characteristics. A grout mixture of 5 parts fly ash to 1 part cement (by weight) was used throughout the mine grouting project. This mixture was selected to meet a minimum grout strength of 0.7 Mega-Pascal (MPa) (100 psi) as required by the landfill permit. Test cylinders for compressive strength testing were made from the grout mixture delivered to the site on a daily basis. Compression testing of the grout cylinders was performed after a 7-day curing period. Compressive strengths of the grout ranged from 0.8 to 6.1 MPa (113 to 877 psi) with an average of approximately 3.8 MPa (556 psi).

The fly ash, cement, and water were mixed at an offsite commercial concrete batch plant and delivered to the job site in standard concrete ready-mix trucks. The dry weights of fly ash and cement were recorded and enough water was added at the batch plant to provide a uniform mixture. Additional water was added at the site to provide the correct consistency (slump) depending on the conditions of the area being grouted. Grout barrier holes were filled using a stiffer grout mix, typically with a slump in the range of 20.3 to 25.4 cm (8 to 10 in). Production grout holes were filled with a more fluid grout mix, usually with slumps ranging around 30.5 cm (12 in), so as to promote greater coverage and more complete filling of the fractured overburden conditions encountered in many of the boreholes.

Grout Placement. Grouting of the deep mine voids and associated fractured rock strata was performed by gravity placement. The fly ash-cement mixture was delivered directly into the uncased barrier-production grout boreholes by the ready-mix trucks. The barrier grout holes were filled first, beginning at the lowest portions of the mined area (downdip end) and continuing around the perimeter of the grout area. This order of filling was observed so as to construct a barrier grout wall around the perimeter of the project area to contain the production grout. Grout was placed into each barrier hole until it was filled to the surface. The grout level was observed for at least one-half hour after initial placement; if the grout had settled, more grout was added until the hole was again filled to the surface. All barrier holes were filled in this manner with records kept of the hole number, date(s) of grouting, and grout take volumes.

Production grout holes were filled in the same manner as the barrier holes, except that the slump was typically 27.9 to 30.5 cm (11 to 12 in). The higher slump grout was used to increase the distance that the grout would flow within the area contained by the barrier holes to promote filling of fractures and smaller spaces within the gob-filled seams and fractured overburden. The production grout holes were filled systematically beginning at the downdip or lower portions of the deep mine within the project area. Once grouting placement began in a grout hole, every attempt was made to complete the grouting of that hole before moving to the next hole. This procedure was adopted since discontinuous grouting typically resulted in the grout holes sealing off prematurely. If this condition was encountered, additional grout holes were drilled in the immediate area to complete the grouting of that area.

Grout Take. The records of grout used in this mine stabilization program indicate that a total of approximately 6291 m^3 (8,228 yd^3) of grout was placed within the project area. Approximately 60% of the grout was used in the northern half of the project area and 40% in the southern half. Both areas were approximately 1.6 ha (4 acres), so grout takes averaged 589.7 m^3/ha (1,234 yd^3/acre) in the northern area and 392.8 m^3/ha (822 yd^3/acre) in the southern area. The grout takes for the northern portion of the project area are very similar to those that were seen in previous mine stabilization projects on the Upper Kittanning at this site, while those in the southern area are somewhat lower. A review of the deep-mine maps indicates that the southern area contained more retreat-mined areas than the northern area. More complete subsidence in the southern area associated with the retreat-mining would explain the lower grout takes observed.

Verification Coreholes. Verification coring was performed at 49 locations within the project area. NX-sized cores were obtained from approximately 6 m (20 ft) above the mine elevation to at least 0.6 m (2 ft) below the bottom of the coal seam. As indicated on the corehole logs, grout was observed filling voids within the collapsed mine roof materials and filling fractures in the strata above the level of the Upper Kittanning Coal Seam. Where suitable lengths of intact grout cores were obtained, they were used for compressive strength testing. These core samples had compressive strengths averaging 7.1 MPa (1,025 psi), significantly exceeding the permit requirements. These higher compressive strengths are a direct result of the age of the samples, which was in excess of 28 days.

Some of the verification coreholes did not encounter grout in the rock cores. The majority of the coreholes that did not encounter grout showed the presence of solid rock, indicating a complete roof collapse where whole blocks of mine roof collapsed into the void space. These coreholes were characterized by core runs with good core recoveries of 80% to 100%. Only two verification coreholes encountered small voids or highly fractured rock strata that had not been sufficiently grouted. In these instances, the verification coreholes were grouted and additional production holes were located around the coreholes and grouted to ensure good grout coverage. Additional verification coreholes were then drilled, which showed the area to be grouted completely.

Site 2

The mine stabilization program at Site 2 was also performed as part of a permitted expansion of the existing landfill and was similar to Site 1 in that the mine grouting area was associated with a lined area on a 3H:1V slope. This mine stabilization project took approximately 6 weeks to complete.

Based on geologic investigations conducted as part of the landfill permitting efforts, two coal seams are found within the project limits. These coal seams are identified as the Pittsburgh Coal and the Redstone Coal. The Pittsburgh Coal has been both surface-mined and extensively deep-mined in the area, and the Redstone Coal was only surface-mined. This mine subsidence control project deals with deep mines on the Pittsburgh Coal Seam. According to information contained in the landfill permit, it appears that the Pittsburgh Coal was mined using the room-and-pillar method, with some retreat mining. According to drilling information, the thickness of the

Pittsburgh seam ranges from 2.4 to 3 m (8 to 10 ft). Under the permit area, it was determined that an approximate 8-ft thickness of the Pittsburgh Coal was removed at extraction rates of approximately 70%.

On this project it was decided that the majority of the deep-mined areas would be overexcavated in conjunction with removal of coal within 7.6 m (25 ft) of the landfill liner system. The remaining deep-mined areas, consisting of approximately 0.6 ha (1.5 acres), which occurred along the perimeter of the expansion area at the top of the 3H:1V slope, were to be grouted. This mine grouting project was performed from two benches prepared as part of the overexcavation operations. These two benches ranged from 7.6 to 24.4 m (25 to 80 ft) above the deep mine.

Grout Hole Drilling. The drilling program was started at the eastern (downdip) end of the mine stabilization area. Drilling progressed from this point around the perimeter of the area at 4.6 m (15 ft) spacings. These perimeter (barrier) holes were located so that relatively stiff grout injected into these areas would form a barrier around the mine stabilization area and prevent the loss of the thinner grout that was to be injected in the interior (production) holes. Production grout holes were drilled in a 4.6 m (15 ft) grid pattern across the interior of the mine stabilization area. Drilling progressed across the area from east to west to the western corner of the mine stabilization area, where previously excavated and backfilled mined areas were encountered. All production and grout barrier holes were drilled using air rotary drill rigs equipped with a 16.5 cm (6-1/2 in) diameter air percussion hammer drill bit. Drilling records were maintained by the field engineer documenting the depths at which the coal, void, or fractured strata were encountered and the thickness of these zones. These records were used to guide and assist in the evaluation of the grout program.

A total of 510 grout holes were drilled within the project area. Coal pillars were encountered in about 27% of all drill holes (barrier, production, or verification holes). This suggests that the extraction rate in this area was comparable to that normally associated with room-and-pillar mining (about 70%). Of the 510 holes that were drilled, only 61 (about 12%) encountered open void space at or above the Pittsburgh Coal elevation. The drilling information suggests that mine roof failures have occurred over much of the area and the associated subsidence has substantially reduced the remaining open mine void space. It is also believed, based on drilling observations, that many of the mined rooms were backfilled during mining with mine tailings or gob. These conditions were confirmed by the downhole video camera survey (discussed later in this section).

The mine conditions described above were observed and documented at the site in the Pittsburgh Coal overexcavation areas. The majority of the deep-mine voids in the area exposed by overexcavation were observed to be totally collapsed and/or backfilled with gob materials. The extent of the collapsed mine voids and remaining void spaces was variable throughout the stabilization area. However, based on the drilling information, it was determined that the Pittsburgh mine voids were substantially collapsed and/or backfilled and only a fraction of the original mine void volume remained to be grouted.

Grout Production. A sand-cement grout mixture was used for this mine stabilization project. Prior to the start of the project, mix designs and test batches of grout were prepared to determine the appropriate proportions of sand, cement, and water needed to achieve a minimum compressive strength of 0.7 MPa (100 psi). A grout mix consisting of 1193 kg (2,630 lb) of sand, 213.2 kg (470 lb) of cement, and 219.5 l (58 gals) of water per cubic yard of grout at a 25.4 cm (10 in) slump was determined to be optimal for the required strength. The sand, cement, and water were mixed at a local offsite batch plant and delivered to the job site in ready-mix concrete trucks. Weights and volumes of the mixture were recorded for each load. Additional water was added, as needed, at the site to provide the correct consistency (slump) prior to injection.

Grout test cylinders were collected from each 38.2 m^3 (50 yd^3) of grout mixture delivered to the job site. The 28-day compressive strengths of the grout ranged from 6.4 to 12.8 MPa (928 to 1,863 psi), with an average of about 9.7 MPa (1,405 psi).

Grout Placement. The grout was poured into each barrier or production grout hole using a small hopper with a funnel end to direct the material into the grout holes. The barrier grout holes were filled with grout having a 20.3 to 25.4 cm (8 to 10 in) slump, which was determined to be appropriate to allow the mix to flow down the hole and fill the void space. Grout was placed into each barrier hole until it was filled to the ground surface. The grout level was observed for at least one-half hour after initial placement; if the grout had settled, more grout was added until the hole was filled to the surface.

Production grout holes were filled in the same manner as the barrier holes, except that the slump was typically 27.9 to 30.5 cm (11 to 12 in). The higher slump grout was used to increase the distance that the grout would flow within the mine voids and to promote filling of fractures and smaller spaces within the gob-filled seams and fractured overburden.

Grout Take. Estimates of the amount of void space existing in the mine stabilization area were made utilizing the information collected during the drilling portion of the project. The drilling logs indicated that the average height of the void based on the cumulative height of all voids encountered was approximately 1.2 m (4 ft). It was also determined that only about 12% of the holes contained voids. Assuming an average 1.2 m (4 ft) void space, over 12% of the area, and a grout area of 0.6 ha (1.5 acres), the existing void volume can be estimated to be approximately 886.9 m^3 (1,160 yd^3). Additionally, some of the holes logged as voids during drilling did not have the larger grout takes typical of boreholes drilled into an open mine void. It was determined by the downhole video camera survey that, in fact, some holes logged as having voids actually were localized fractures or soft gob zones. This means that the actual void volume is somewhat less than the 886.9 m^3 (1,160 yd^3) estimated above. The records of grout used in the mine stabilization program indicate that a total of 730.9 m^3 (956 yd^3) of grout was placed, which is comparable to the estimated void volume based on drilling information.

Verification Drilling and Grouting. Air rotary verification drilling and grout takes were used to evaluate the effectiveness of the grouting program. Following completion of production grouting, the subsurface conditions and grout takes recorded were compared. Based on this comparison, areas with the potential to have ungrouted void space were identified. Additional drilling was performed in these areas and the holes were subsequently grouted. If the grout take in a particular air verification hole was less than 0.76 m^3 (1 yd^3), the area was considered to be sufficiently grouted. Following this procedure, if an area was still suspected to contain ungrouted void space, additional verification holes were drilled and grouted. This procedure was followed until the entire mine stabilization area was sufficiently grouted. In all, 91 air verification holes were drilled in the mine stabilization area.

Verification Coring. Verification coring was completed at seven locations within the mine stabilization area. NX-sized cores were obtained, beginning approximately 6 m (20 ft) above the mine elevation and extending at least 0.6 m (2 ft) below the bottom of the coal seam. The majority of the verification coreholes encountered grout. Grout in the corehole was observed mostly as filling of voids within the collapsed mine and fracture fillings in the rock above the level of the Pittsburgh Coal Seam. Suitable lengths of intact grout cores were collected and used for grout compressive strength tests. The core samples retrieved had compressive strengths ranging from 10.8 to 17.1 MPa (1,560 to 2,480 psi) and averaging about 13.3 MPa (1,925 psi).

Downhole Video Survey. A downhole video camera survey was undertaken to determine the pregrouting conditions within the mine stabilization area and verify the filling of the void space after grouting. The pregrouting downhole video camera survey confirmed that the mine voids were generally collapsed. Many of the intervals that were logged as voids during drilling appeared to be localized, large fractures or soft zones of mine backfill or caved material that were mistaken to be open voids.

A postgrouting video survey of the verification holes was also performed. During these surveys, intervals of grout were observed in previous mine void intervals and as fracture fillings in broken or fractured overburden zones. The postgrouting video survey provided visual confirmation that complete void and fracturing filling had been achieved.

Site 3

The original mine stabilization plan for this site entailed the complete excavation of the underlying Pittsburgh Coal Seam and deep mine workings during excavation for the development of the waste disposal areas. Horizontal placement of backfill materials, by pneumatic stowing, was proposed to fill any mine voids encountered along the base of the exposed highwalls. Previous landfill development construction activities used the horizontal, pneumatic stowing technique to fill mine voids encountered in the base of the highwall in the landfill area adjacent to this project area. However, the horizontal stowing method proved to be difficult, costly, and not completely effective. In addition, work required to prepare the highwall area for stowing created instabilities in the excavated highwall slopes. For these reasons, it was proposed to eliminate the underground mine voids and stabilize the overburden within this project area by grouting, prior to excavation of the highwalls.

Based on previous geologic investigations, it is known that the project site is underlain by the Pittsburgh Coal and the Redstone Coal. Within the project area the Pittsburgh Coal occurs at a depth of 39.5 m (130 ft) and the Redstone Coal occurs approximately 27.4 m (90 ft) above the Pittsburgh Coal. The Pittsburgh Coal has been both surface mined and extensively deep-mined in the area, while the Redstone Coal has been only surface mined. The thickness of the Pittsburgh seam is generally about 2.4 to 3.7 m (8 to 12 ft), and it was determined that approximately 1.8 to 3.7 m (6 to 12 ft) of the Pittsburgh Coal was removed within the project area. An evaluation of available mine maps revealed that the Pittsburgh Coal was mined at the site using the room-and-pillar method with typical extraction ratios of approximately 70%. The mine maps also indicated that a main entryway for the mine existed in the vicinity of the proposed mine stabilization project area, along with large coal pillars which were left inplace to support the roof along this main entry. Excavations in the adjacent project areas also encountered large amounts of in-place coal, as well as large, open, intact mine voids confirming this condition.

This mine stabilization project was conducted along the top of a 39.6 m (130 ft) highwall excavated as part of the landfill expansion and on a bench cut at the Redstone coal elevation. Grouting of the deep mines was performed on mine voids located under and immediately adjacent to the highwall and included areas within the 30° angle of draw. This mine stabilization project took approximately 5 weeks to complete.

Grout Hole Drilling. The drilling plan called for six rows of grout injection holes running parallel to the northern perimeter of the landfill expansion and highwall excavation. The rows were labeled A through F (south to north) and were spaced approximately 4.6 m (15 ft) apart. Rows D and E were spaced 6 m (20 ft) apart to make allowances for the slope of the partly excavated highwall. Holes were drilled along each row at a 4.6 m (15 ft) spacing, and hole alignment was staggered between each row.

Grout hole drilling was performed using air rotary methods and a standard 17.1 cm (6-3/4 in) rock bit. Work was started initially on rows A and F and progressed around the perimeter of the area at 4.5 m (15-ft) spacing. These perimeter (barrier) holes were used to emplace relatively stiff grout to form a barrier around the mine stabilization area and prevent the loss of the thinner grout that was to be grout in the interior (production) holes. Due to the existing surface conditions of the mine stabilization area, access to the exact hole locations as stipulated by the drilling plan was difficult or unsafe due to the highwall. These field conditions dictated slight adjustments of the drilling plan to cover the entire mine stabilization area and maintain adequate spacings. Some of the hole locations along the top and the toe of the highwall in rows D and E were completely inaccessible, or undrillable because of safety concerns. Many of these holes were "angle" drilled. Typically, the angles were less than 6°. Drilling records were maintained by the field engineer documenting the depths at which the coal, void, or fractured strata were encountered and the thickness of these zones.

The drilling defined a very distinct trend of large, open voids within the project area. These voids roughly correlated with the main haulageway as shown on the deep-mine map. Coal pillars were encountered in about 40% of all injection holes, suggesting that the coal extraction rate in this area was less than that normally associated with room-and-pillar mining. Much of the unmined coal appears to be large, closely spaced chain pillars, which protected the mine haulageways from roof collapse. These chain pillars have apparently provided more long-term roof support for the haulageways, resulting in larger, more intact mine voids existing in these areas. Of the 255 holes that were drilled, 92 (36%) encountered open void space at or above the Pittsburgh Coal elevation.

The mine conditions described above were observed and documented at the site in the adjacent Pittsburgh Coal overexcavation areas. The mine in the exposed areas was observed to be partly collapsed with many in-place coal pillars and a few intact rooms and haulageways. However, the extent of the collapsed mine voids and remaining void spaces is variable throughout the stabilization area. Based on these observations and the drilling information, it was determined that much of the Pittsburgh mine voids are intact and a considerable amount of the original mine void volume remained to be grouted.

Grout Production. Two different grout mixes were utilized during this mine stabilization project: a sand and cement mix; and a fly ash, sand, and cement mix. The sand and cement mix consisted of approximately 1338.1 kg (2,950 lb) of sand, 136.1 kg (300 lb) of cement, and 189 to 227 liter (50 to 60 gal) of water. This mix was used for the first 3 days of the project, mostly in the barrier holes. The remainder of grouting was performed with a fly ash, sand, and cement grout mix consisting of approximately 226.8 kg (500 lb) of fly ash, 907.2 kg (2,000 lb) of sand, 147.4 kg (325 lb) of cement, and 189 to 227 l (50 to 60 gal) of water. The mix components and part of the water were mixed at the batch plant and delivered to the job site in ready-mix trucks. Additional water was added, as needed, at the site to provide the correct consistency (slump) prior to injection.

At least one test cylinder was collected each day during the grouting operations. The cylinders were tested and showed compressive strengths ranging from 0.8 to 3.4 MPa (115 to 495 psi), with an average of about 1.4 MPa (196 psi) after a 3-day cure period.

Grout Placement. The grout was placed into each barrier or production grout hole using a small hopper with a funnel end. The barrier grout holes were filled with grout having a 15.2 to 25.4 cm (6 to 10 in) slump. Grout was placed into each injection hole until it was filled to the ground surface. The grout level was observed for at least one-half hour after initial placement; if the grout had settled, more grout was added until the hole was filled to the surface.

Production grout holes were filled in the same manner as the barrier holes, except that the slump was typically greater than 25.4 cm (10 in). The higher slump grout was used to increase the distance that the grout would flow within the project area and to promote filling of fractures and voids within the mine workings and fractured overburden.

Grout Take. The records of grout used in the mine stabilization program indicate that a total of 2153.5 m^3 (2,816.5 yd^3) of grout was placed. Estimates of mine void volumes can be made based on typical mining extraction ratios and coal seam thickness. These estimates are typically greater than the actual remaining mine voids that require grouting, owing to mine roof collapse and subsidence. However, utilizing the information collected during the drilling portion of the project, a relatively accurate estimate of the void volume can be determined. The drilling logs indicate the thickness of all voids encountered, and it was determined that the average height of the void based on the cumulative height of all voids encountered was approximately 1.04 m (3.4 ft). It was also determined that about 36% of the holes contained voids. Assuming an average 1.04 m (3.4 ft) void space, over 36% of the area, and a grout area of 0.44 ha (1.1 acres), the existing void volume can be estimated to be approximately 1586.5 m^3 (2,075 yd^3), which is approximately 40% less than the actual volume of grout placed into the mine voids. This discrepancy is most likely attributed to grout being placed outside the project area during construction of the barrier walls in areas where large voids were encountered. This occurred in rows A and F, where several adjoining barrier holes encountered large, connected voids and had very large grout takes.

Air Rotary Verification Drilling and Grouting. Following completion of production grouting, the subsurface conditions and grout takes recorded were analyzed. From this evaluation, areas with the potential to have ungrouted void space were identified. Additional drilling was performed in these areas, and the subsurface conditions were logged to determine the effectiveness of the grouting program. The verification holes were monitored for the presence of grout, coal, open voids, or fractured rock. Of the 24 air verification holes drilled, 21 encountered grout, 3 encountered fractured material, and none hit voids or coal. Additionally, all of the air verification holes were subsequently grouted. If the grout take in a particular hole was less than 0.76 m^3 (1 yd^3), the area was considered to be sufficiently grouted. Following this procedure, if an area was still suspected to contain ungrouted void space, additional verification holes were drilled and grouted. This procedure was followed until the entire mine stabilization area was determined to be sufficiently grouted.

Verification Coring. The intent of the verification coring program was to retrieve grout samples to verify the grout coverage as well as the insitu strength of the grout. Verification coring was completed at eight locations within the mine stabilization area. NX-sized cores were obtained, from approximately 6 m (20 ft) above the mine elevation and extending at least 0.6 m (2 ft) below the bottom of the coal seam.

Grout was observed in the core as filling of voids within the mine and as fracture fillings in the strata above the level of the Pittsburgh Coal Seam. Seven of the verification coreholes encountered grout, and one encountered coal. Suitable lengths of intact grout cores for testing were obtained from most of the holes that hit grout. The core samples retrieved had (unconfined) compressive strengths ranging from 6.5 to 7.6 MPa (940 to 1,100 psi) and averaging about 7.1 MPa (1,035 psi).

The unique opportunity to observe the grouted zone was presented at this site when the excavation for the highwall in this area was performed. Overexcavation to provide the required 7.6 m (25 ft) coal separation zone for the landfill exposed the grouted zone at the base of the highwall. Visual observations of the grouted mine voids showed complete filling of the open voids by the grout. In addition, the grout was observed to have filled in the small voids within the caved materials, and fractures created by roof falls and subsidence. The extent of the void filling was notably very complete, and only a few small voids could be observed.

Project Comparison

The three grout projects described were designed to utilize readily available materials, locally available standard equipment and services, and simplistic grouting techniques in order to minimize cost and increase productivity. The drilling services employed for the grouting programs were shothole drillers from the coal mining industry who specialize in high production drilling at low cost. Grout materials were selected based on local availability, low cost, and suitability. The decision to mix the grout offsite at local concrete batch plants was based on previous experiences with grouting projects. Grouting projects that stockpile materials and mix grout onsite require large areas for storage, material handling, and mixing equipment. In addition, these projects are difficult to supply, and typically the large water supplies required to mix the grout are not available. Mixing the grout offsite eliminates material storage problems, mobilization and setup of substantial amounts of equipment, and onsite logistical problems.

Grout mixtures were developed based on the availability and cost of the materials. Fly ash was used in the grout mixtures, if readily available, owing to its physical properties, which enhance the flow characteristics of the grout. Fly ash grouts penetrate readily into fractures and loose caved materials in the mine voids providing a greater degree of void filling.

Grout placement techniques were by gravity through uncased boreholes. Since the drilling services were relatively inexpensive, it was more cost effective to drill additional grout placement holes to achieve grout coverage or to replace a collapsed or blocked borehole than to use the more conventional methods of installing casing in boreholes, tremie pipes, and injection of grout under pressure.

A summary of the size, drilling, grout mixtures, drilling for the three grout projects is presented in Table 1.

Table 1. Grouting project summary.

Site	Hectares (Acres)	Grout holes m (ft)	Grout mixture	Grout take m^3 (yd^3)	Verification drilling
1	3.2 (8.0)	541 10,567 (34,668)	Fly ash-cement	6291 (8228)	49 coreholes.
2	0.6 (1.5)	510 9,555 (31,350)	Sand-cement	731 (956)	91 air rotary, 7 coreholes.
3	0.44 (1.1)	255 7,160 (23,491)	Sand-cement fly ash- sand- cement.	2154 (2817)	24 air rotary, 8 coreholes.

The mine subsidence control projects described in the preceding sections, while different in terms of site specifics, have one basic similarity. This similarity is the subsided conditions of the mined voids. Typical estimates of the mine void volumes requiring backfilling to prevent subsidence invariably overestimate the amounts of materials that can actually be injected. These overestimations occur as a result of the failure to consider past subsidence or because the amounts of subsidence that have occurred are underestimated owing to the lack of enough site-specific information. The projects discussed in this paper suggest that mine void volumes remaining in older deep mines requiring grouting to prevent future mine subsidence are in the range of 30% to 40% of the estimated mine void volume, based on typical extraction-mine seam thickness techniques. This percentage is lower at Site 2 due to the fact that a portion of the project area had not been deep-mined.

Cost

The cost of mine subsidence control grouting projects will vary depending on the size of the area to be grouted, thickness of the coal seam, volume of the mine voids to be grouted, and drilling depths. The most significant cost items in the grouting projects presented were the drilling and the grout. Labor cost can be a major item if more conventional grouting techniques are used. However, in these projects the labor costs were low since the majority of these costs are included in the unit prices for the drilling and the grout. A summary of the project costs for the three mine subsidence control projects is included in table 2.

Table 2. Grout project cost summary.

Site	Hectares (Acre)	Drilling cost	Grout cost	Labor cost	Total cost	Cost per hectare (acre)
1	3.2 (8)	$52,000	$288,000	$25,000	$365,000	$114,062 (45,625)
2	0.6 (1.5)	47,000	41,000	15,000	103,000	171,666 (68,700)
3	0.44 (1.1)	23,000	110,000	12,500	145,500	330,681 (132,272)

From the data presented in table 2 it can be seen that the cost per acre for mine grouting can vary greatly. The most variable cost is the grout cost, which is directly related to the mine void volume to be grouted. The degree of mine collapse, relationship of the project area to the mine layout (room-and-pillar areas, main entries, retreat-mined areas), and thickness of the coal seam (mine void height) vary significantly among mined areas and can greatly impact the grout volumes and cost.

Conclusions

The deep mines associated with these projects are representative of the deep mining in this region. Conditions in the deep mines were well documented by the high density of the drilling and visual observations. These investigations show that the mine voids are typically substantially collapsed and are filled with gob or caved material. As a result, the void volume remaining to be grouted is substantially less than estimated by conventional conservative estimation techniques. In addition, subsidence prediction techniques that use original mine void heights and volumes to calculate potential subsidence and estimate potential future damage from these old deep mines will overestimate the potential and be conservative.

Conventional mine grouting projects typically specify high-strength grout mixes, cased grout injection boreholes, grout tremie pipes, and pump or pressure injection systems. These requirements increase the cost of the grouting projects significantly with respect to material costs and are labor intensive. The use of these techniques typically limits grout placement production rates, which increases the length of the project and ultimately the cost. The simplified grout placement methods used in the case studies presented in this paper increase productivity by eliminating labor-intensive activities and decrease cost by reducing labor, materials, and equipment. Another consideration for reducing project cost is the use of low-cost, locally available materials and low-strength grout mixtures. Unless high loads are expected to be superimposed on the project area in the future, high strength grouts are not warranted. As demonstrated by these projects, the use of fly ash in the grout mixes, with minimal amounts of portland cement, produces a grout with considerable strength and good flow characteristics at a reasonable cost.

The simplistic methods used to perform these mine subsidence control projects are the key to their success with respect to cost effectiveness. These projects relied upon inexpensive, high-production drilling as the key to providing the required grout coverage. If a grout production hole collapsed or became blocked during grout placement, an additional hole (or holes) would be drilled in that area to achieve complete grout coverage in the area. An important aspect of this grouting technique is the maintenance of good field records. If drilling records indicated substantial voids were encountered in a particular area and grout takes were low, these areas were targeted for additional drilling and grouting during the verification drilling phases of the projects. The success of this technique is verified by the observations made of the grouted zones in excavations, the degree of void filling observed by the air rotary verification drilling procedures and verification coring activities, and the borehole video camera surveys.

Conventional grouting techniques utilizing more sophisticated procedures, such as cased injection holes, tremie systems, and pressure injection systems, have a definite application in specific situations. However, for large-area mine subsidence control projects, the simplistic grouting techniques used in these projects provide an efficient and effective alternative mine subsidence control technique.

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