Dam Construction at Diavik using Bituminous Geomembrane Liners



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ABSTRACT

The Diavik Diamond Mine is located in a region of continuous permafrost on East Island in Lac de Gras, Northwest Territories. Following diamond extraction from the kimberlite ore, the remaining "Processed Kimberlite" material is permanently stored in the Processed Kimberlite Containment (PKC) Facility consisting of lined perimeter dams which are raised in stages throughout the mine life. The design and construction of the first three phases of the East and West Dams included an HDPE liner installed on sand bedding. Following experience gained on the site using bituminous geomembrane liner for construction of collection ponds, the design and construction of the fourth and fifth phases of the PKC facility dams were changed to use a bituminous geomembrane liner. The bituminous geomembrane liner allowed for a greater range of bedding material options and easier installation over a greater range of sub-zero temperatures than the HDPE liner. This paper will present the general dam design and discuss the range of materials used for liner bedding and cover in the dam construction. The condition of the bituminous geomembrane liner exposed and cut out of a collection pond dam which was no longer required on the site will be presented.

RÉSUMÉ

La mine de diamant Diavik est située dans une région de pergélisol continu, sur l'île de l'Est du Lac de Gras, NT. Suite à l'extraction des diamants du minerai kimberlitique, les rejets sont empilés définitivement dans un parc à résidus circonscrit par des barrages dont l'étanchéité est assurée par une géomembrane. Ces barrages sont fondés sur le pergélisol et sont construits au fur et à mesure de l'évolution de la mine. Le design et la construction des trois premières phases des Barrages Est et Ouest comprenaient l'installation d'une geomembrane PeHD sur une couche de sable. Suite à l'expérience acquise sur le site lors de la construction des étangs collecteurs en utilisant une géomembrane bitumineuse, le design et la construction des quatrième et cinquième étapes de construction des barrages ont été modifiées afin d'utiliser cette géomembrane bitumineuse. La géomembrane bitumineuse permet d'utiliser une grande variété de matériel de scellement et peut être installée sous un plus grand éventail de température comparativement à la geomembrane PeHD. Cet article présente le design général des barrages. Cet article présente aussi les performances d'une géomembrane bitumineuse exposée et coupée d'un barrage d'un étang collecteur qui n'était plus utile sur le site.

1 INTRODUCTION

The Diavik Diamond Mine is located on what is informally named "East Island", a 17 km² island in Lac de Gras, Northwest Territories (NT), approximately 300 km northeast of Yellowknife (64° 30' North, 110° 20' West). Figure 1 presents the location of the Diavik Diamond Mine. The Diavik Diamond Mine was approved around open pit and underground mining of up to four diamondbearing kimberlite pipes, designated as A154 North, A154 South, A418 and A21, are all located off the shore of East Island, under the waters of Lac de Gras.

The mine site lies within the Arctic Climatic Region where daylight reaches a minimum of 4 hours per day in winter and a maximum of 20 hours in summer. The climate is extreme, with long, cold winters and very short, cool summers. Temperatures are cool, with an average temperature in July of 10°C and in January of -31°C. The mean annual air temperature at the site is approximately -10°C. Snow falls in every month, although rain generally only occurs between about May and October. The mine site is located about 100 km north of the diffuse boundary between the widespread discontinuous and continuous permafrost. Based on deep thermistor installation measurements, the permafrost has been confirmed to a depth of 380 m below the East Island. Temperature data from shallow thermistor installations indicates a range of mean annual ground temperatures of between -3 and -6°C. The active layer in the vicinity of the mine site is about 1.5 m to 2.0 m deep in till soils and about 5.0 m in bedrock. In some poorly drained areas and areas with thicker vegetation cover, the active layer can be less than 1 m in depth. The depth of the permafrost decreases towards Lac de Gras, and permafrost is absent beneath the lake itself.

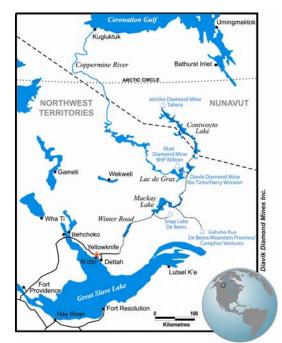


Figure 1. Diavik Diamond Mine Site Location Plan

The Diavik Diamond Mine site is remote with year round access only by air transport. Between late January and early April a winter ice road allows transport truck access to the mine to deliver supplies.

The diamond extraction process includes crushing the kimberlite ore and mixing with ferrosilicon and water as a transport media during processing. Following extraction two main by-products are created which are the coarse processed kimberlite (CPK) consisting of crushed kimberlite particles with grain size between about 8 mm and 1 mm, and fine processed kimberlite (FPK) consisting of crushed kimberlite particles less than about 1.5 mm grain size. The CPK material is trucked to the Processed Kimberlite Containment (PKC) facility and the FPK is transported as a low-density slurry in a pipeline from the process plant to the PKC facility.

2 PKC FACILITY DESCRIPTION

The PKC facility provides permanent storage for the processed kimberlite (PK) by-products produced during diamond extraction from the kimberlite ore. Figure 2 presents a satellite photo view of the facility in August 2007. Since mining and diamond recovery began in late 2002, a total of approximately 10 million tonnes of the PK product have been deposited into the PKC facility. Current Life of Mine planning requires storage for up to 26 million tonnes of PK.

During operation, in addition to providing permanent storage for the PK products, the PKC facility is used to temporarily manage water, and a year round pond is maintained in the PKC facility. Water within the PKC facility includes the excess process water from the FPK slurry transport and a large portion of the site wide run-off water from the numerous sediment management ponds constructed around the island. Run-off water from any disturbed area of the mine site is collected in these ponds and then pumped to the PKC facility pond. A reclaim barge is located in the central PKC pond and ongoing ore processing is carried out using as much reclaim water as is possible. Maximizing the use of reclaim requires detailed site wide water management planning and FPK deposition planning to ensure sufficient water quantity and quality are available at the reclaim barge.



Figure 2. Satellite View of PKC Facility

The facility dams have been designed to provide for containment and storage of the FPK and CPK products and the reclaim water pond within geomembrane-lined rockfill perimeter dams which are keyed into the frozen foundation.

Two starter dams, the East and West Dams, were constructed in 2002 to close the ends of the small valley running approximately east to west across East Island. The dams have been raised in stages and extended to the North and South Dams in stages throughout the mine operation. Following four phases of dam raising since the starter dams were built, the facility now consists of a continuous perimeter dam which is about 5.5 km in length, as shown in Figure 2.

Two Internal rockfill spigot dikes, one on each of the north and south sides of the FPK pond, have been constructed. Each provides a support bench for the FPK discharge pipes allowing perimeter discharge around the central pond. The north spigot dike also separates the FPK area from the CPK storage area to the north. CPK was originally deposited against the height of land to the north, and now CPK is contained by the North Dam and the north section of the East Dam. Waste rock from the open pits is placed north of the North Dam.

As shown in Figure 2, the area south of the south spigot road has not yet been utilized for PK storage. This cell was recently constructed in 2007, and is planned to be commissioned for FPK deposition starting in summer 2008.

3 PKC FACILITY DAMS

The PKC Facility Dams consist of broad rockfill shells which support the upstream liner system. The crest width of the dams was selected to allow two-way haul truck traffic. At the starter stage of each dam section, the upstream liner is keyed into a cut-off trench in the frozen ground upstream of the rockfill shell. The cut-off trench was constructed using a drill and blast method followed by excavation to remove any ice rich foundation soils and achieve the design depth. Excavation is to a sufficient depth to found the trench backfill material in a frozen icepoor till or on bedrock. Till stripped from the open pits is used for trench backfill. In 2007, the cut-off trenches for the North and South Dams were completed and joined to the existing trenches for the East and West Dams, making the cut-off trench continuous around the upstream perimeter of the facility shown in Figure 2.

The liner is installed into the cut-off trench till backfill and then raised up the upstream face of the rockfill shell on a suitable liner bedding layer and anchored at the current crest. Additional raises to the downstream shell are carried out and the next phase of upstream liner is tied into the previous liner at the previous crest and installed up the upstream face of the new raise.

Figure 3 presents a section which is typical of the design concept for the PKC Facility dams. The downstream rockfill shell is constructed over a range of foundation conditions including ice poor till, ice rich till, and bedrock. Vertical thermistor strings have been installed for continued monitoring of the foundation temperatures below the dams. Inclinometers have been installed to monitor dam shells on ice rich foundation soils, and downstream seepage and run-off collection systems exist at low points along the dams.

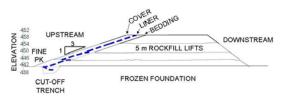


Figure 3. Typical PKC Facility Dam Cross Section showing the wide rockfill shell supporting upstream liner system

The first three stages of construction of the East and West Dams incorporated a 1.5 mm (60 mil) thick, doublesided textured high density polyethylene (HDPE) liner system. A rockfill shell and a till fill liner support zone were raised 5 m for each stage, and the till zone was resloped to a 2.5H:1V slope angle. Liner bedding material consisted of a locally borrowed esker or coarse sand which was placed over the till. The liner was installed down the slope. The liner was covered with the same esker or coarse sand which was used for bedding. With the limited warm weather season at the site, there were many challenges in constructing the PKC Facility dams with the HDPE liner system. Modified welding procedures were developed to continue with HDPE work at sub-zero temperatures. However, excavation and placement of the till followed by the coarse sand for the bedding layer was limited to the short warmer weather seasons at site.

Revisions to the construction technique and liner system design were undertaken for the Phase 4 construction which was carried out in 2006. This included changing the type of membrane from HDPE to bituminous, using a liner bedding material comprising crushed granular material and re-sloping the upstream face to 3H:1V.

Phase 5 construction is currently on-going, scheduled over a 3 year period between 2007 and 2009. Phase 5 has made use of a range of liner bedding materials and range of grades of the bituminous geomembrane.

As shown in Figure 2, at August 2007, the PKC Facility consists of a continuous perimeter dam system. Following completion of Phase 5 construction in 2009, all dams will have been raised to a crest elevation 460 m, which results in a maximum dam height of about 35 m for each the East and West Dams and about 25 m for each the North and South Dams.

4 BITUMINOUS GEOMEMBRANE LINER

Construction experience using bituminous geomembrane (BGM) liner at the Diavik site was first gained during the spring of 2005 with the construction of a series of new water management collection pond dams. Details of the performance of the BGM liner used in the collection pond dam construction at Diavik are presented in Breul et al. (2006) and Eldridge et al. (2008).

Temporary collection Pond No. 14 was the first dam on the Diavik site to be constructed with a BGM liner. The pond was required to be constructed in a short period during late winter to early spring in advance of the spring run-off. There was little bedding material available at this time of year to allow use of an HDPE liner system, and a high cost was estimated to weld the HDPE liner seams under enclosed and heated conditions, leading to the decision to utilize a BGM liner on a coarse granular bedding for construction of this pond. Subsequently, two additional ponds were constructed with a BGM liner.

The BGM liner selected for use at Diavik was the Coletanche ES grade liner supplied by Soprema Inc. BGM ES liner consists of a non-woven polyester geotextile with an elastomeric bituminous binder. The geotextile provides mechanical resistance and the elastomeric type bituminous binder provides chemical and aging resistance to the BGM ES liner, as well as its water tightness. The Coletanche ES liner comes in a range of thicknesses, from 3.5 mm for ES1, to 5.6 mm for ES4. A sanding layer is applied to the surface and an anti root film is applied to the base during the liner production. The hydraulic conductivity of the liner is less than 10⁻¹⁴ m/s. The friction angle between the liner and dry granular soils is in the range of 35 to 40 degrees depending on liner grade and bedding gradations. Values are lower for saturated or clav materials.

ES liner is delivered in rolls of 5.15 m width, with roll length being 55 m for ES4 and 90 m for ES1. Each roll is 2000 kg and deployment is conducted using a hydraulic beam attached to a backhoe which can unroll the liner while the installation crew aligns it in the required position down the slope. Sheets are joined by welding with a propane torch. Figure 4 presents the welding of BGM sheets of ES2 liner during sub-zero temperatures and winter conditions at Diavik.



Figure 4. Propane Torch Welding BGM ES2 liner at Diavik in winter

Advantages of the BGM liner include: good mechanical resistance, low coefficient of thermal expansion (allowing liner to be deployed in sub zero temperature conditions), heavy weight material (not prone to disturbance during installation under high winds typically experienced at the Diavik site), propane torch welding at low temperatures. The key advantage to using the BGM liner at Diavik was the influence on the construction schedule, giving Diavik a longer construction season. The BGM allowed for installation under colder temperatures due to lower allowable temperatures for welding and due to the ability to use a range of liner bedding materials, making use of crushed rockfill materials for liner bedding rather than borrowed esker sands for HDPE.

Figure 5 presents a summary of the range of air temperatures at the Diavik site and the periods over which the BGM liners were installed for three water collection pond dams and for two phases of the PKC Dam construction.

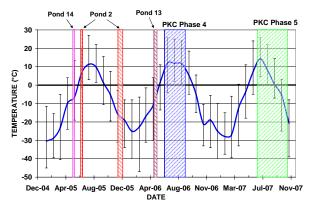


Figure 5 Range of Air Temperature during periods of BGM liner installation at Diavik

5 BGM LINER AND PKC DAM RAISES

During the fourth phase of construction for raising the PKC Facility dams, which was carried out in 2006, significant extensions were required for each of the East and West Dams. Following the experience gained on site in collection pond construction, the use of a BGM ES3 liner installed on a crushed rockfill liner bedding zone was selected for the Phase 4 PKC dam raises.

The construction sequence involved the mine haul fleet of 100 and 240 t trucks placing a wide rockfill shell. Rockfill was placed starting in November of 2005 through the following winter to allow upstream liner works to be carried out by summer of 2006.

The site contractor re-sloped the upstream face of the rockfill zone to 3H:1V to prepare for liner bedding placement. The width of the rockfill remaining at the crest was 40 m, considered suitable for two-way haul truck traffic. Liner bedding was then placed and compacted on the slope and then the ES3 liner was installed and a cover layer placed. The 3H:1V slope was selected for efficiency of re-sloping and placing and compacting the granular materials on the slope.

For the design of the Phase 4 dam raise, ES3 liner was selected for placement on a jaw run crushed rockfill bedding (200 mm minus crushed rockfill). Figures 6 and 7 show the liner being placed on the jaw run bedding. For the extension sections of the East and West Dams, excavation of the cut-off trench was completed and backfilled with till, with a section of the ES3 liner installed in the till backfill. The sloped section of ES3 liner was joined to the liner installed in the trench, as shown in Figure 7.



Figure 6. 3H:1V slope with jaw run 200 mm minus crushed rockfill bedding for the ES3 liner during Phase 4 construction.



Figure 7. ES3 liner on jaw run bedding, joining ES3 liner in till filled cut-off trench during Phase 4 construction.

During Phase 4, the sections of the East and West Dams with existing HDPE liner were raised. The ES3 liner was joined to the existing HDPE liner using a mastic and flam stick system. Figure 8 shows bonding of a flam stick to the HDPE which then allowed the new sheet of ES3 liner to be welded to the flam stick.



Figure 8. Attaching a Flam stick to the existing HDPE liner to which the BGM ES3 liner is welded.

Following the Phase 4 liner placement, esker sand was available from a local borrow and was used as the liner cover. Figure 9 shows the cover zones. Following liner placement starting in spring, esker sand was available and was placed as the first layer for liner cover, followed by a layer of jaw run and then run of mine rockfill. Rockfill was placed over the jaw run at spigot locations for erosion protection from the hydraulic deposition of FPK.



Figure 9. Liner cover zone, esker sand, jaw run and run of mine rockfill for FPK spigot erosion control.

Construction of the fifth stage of the PKC Facility required small extensions and raises to the East and West Dams, and starter dam construction for the North and South Dams. At the start of this construction phase in 2007, Diavik was pre-stripping the A418 open pit which provided a large source of unfrozen till. Till was used to backfill the cut-off trench upstream of the North and South Dams.

For the areas where liner was placed in 2007, the till was placed on the slope for liner bedding, followed by placement of an ES2 BGM liner system. Two lifts of till were placed each with a nominal thickness of 0.75 m each and compacted. With the till having a maximum particle size of 150 mm and a fines content from 20 to 40%, a very smooth bedding surface was established, as shown in Figure 10.



Figure 10. ES2 Liner being installed on the Till Bedding Zone.

Construction of the North Dam required installation of a large area of liner which was required to be installed as early as possible in the 2008 construction season. Work began in April on the North Dam, and at this time, unfrozen till for liner bedding was not available. The North Dam liner bedding system was constructed using a jaw run crushed rockfill placed on the re-sloped rockfill and covered with a layer of coarse sand to allow for BGM ES1 liner to be used. The North Dam contains the CPK material, is a significant distance from the PKC pond, and the mine waste rock is stockpiled downstream of the dam; therefore, ES1 liner was deemed suitable for lining the North Dam. Figure 11 presents the coarse sand bedding placed over jaw run on the North Dam, followed by placement of the ES1 liner.



Figure 11. North Dam placing coarse sand over crushed rockfill followed by BGM ES1 Liner.

A summary of gradations used for liner bedding is provided in Figure 12.

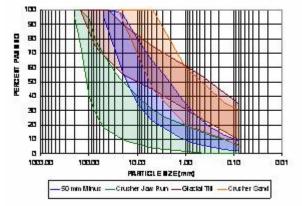


Figure 12 Summary of BGM Liner Bedding Layer Gradations

6 EXCAVATION OF ES1 LINER USED IN POND 14

BGM liner was first used in May 2005 at the Diavik site for the construction of temporary water collection Pond No. 14. The dam design included a downstream rockfill shell, which was re-sloped on the upstream side to a 3H:1V slope for an upstream liner system. A cut-off trench was excavated at the toe of the upstream slope. Under winter conditions, no till was available to backfill the trench, and a mix of bentonite and 50 mm minus sand and gravel was used to tie the liner into the cut-off trench excavation. The Liner bedding consisted of a layer of 50 mm crushed rockfill and a BGM ES1 3.5 mm thick Liner was installed and covered with 50 mm crushed rockfill.

The temporary Pond No. 14 Dam was used to collect runoff from its catchment for two seasons. The pond dam is located upstream of the A418 open pit and in 2007 was no longer needed for surface water management. By August 2007, the A418 pit was being stripped to its limit in the area of Pond 14 Dam and a section of the dam was planned to be excavated for the pit development.

This allowed the opportunity to expose the BGM ES1 liner and observe its condition.

A Cat 450 backhoe was used to excavate a test trench to remove the 50 mm crushed rockfill cover zone and expose the ES1 liner. Observations were made on the condition of the unearthed liner and bedding.

Figure 13 presents a view of the ES1 liner exposed in the Pond No. 14 Dam. An area of about 4 m along the slope and about 1 m wide was excavated. The backhoe was used to remove the majority of the cover zone, followed by hand excavation to complete the unearthing of the liner. The liner was found to be intact and without penetrations.

The liner was cut and folded back, as shown in Figure 13, to expose the underside of liner and the bedding zone. In at least two locations, gravel sized bedding material of up to about 50 mm size was embedded in the ES1 liner. On the surface side of the liner, this was observed as a smooth bump where it appeared the bituminous liner had conformed to the underlying bedding. The gravel sized pieces were physically attached to the liner and required force to be removed for further inspection. Following removal, no penetration through the liner was observed. The condition of the ES1 liner observed was consistent with the design intent of elastomeric bituminous geomembrane which is expected to allow 70% stress relaxation in 3 hours time. ES1 Liner installed on a crushed rockfill bedding is expected to achieve a 40 degree friction angle (Coletanche Design and Application Handbook), based on the observations of the condition of the liner the there is a significant frictional resistance to sliding as a result of the stress relaxation around the granular bedding.

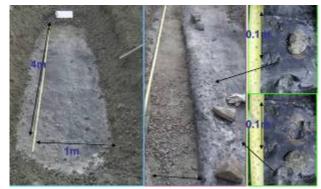


Figure 13. ES1 liner with 50 mm minus crushed rockfill bedding and cover, excavated to observe condition of liner.

7 CONCLUSIONS

The PKC Facility Dams at Diavik have been constructed using a Coletanche BGM Liner. The use of a BGM liner allows for a wider range of materials to be used for the liner bedding and cover zones and significantly extends the construction season.

BGM Liner grades of ES1, ES2 and ES3 have been used for Phase 4 and 5 construction, and bedding materials ranged from coarse sand, to till to jaw run crushed rockfill material.

BGM ES liners have been installed throughout the year, even in winter conditions at the Diavik site. Liner installation production rates range from up to about 3000 m^2 per day in summer to 2000 m^2 per day in winter.

Observations of an excavation to expose a ES1 liner installed in the temporary Pond No. 14 dam indicated that the liner performed as expected in the dam structure, exhibiting a stress relaxation around the gravel size bedding and displaying a high frictional bond between liner and bedding.

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