Case study: Design-build of a cement-bentonite groundwater cutoff wall in Fort-McMurray

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ABSTRACT
In 2018, Canada Geo-Solutions Inc. (CGSI) completed a design-build project for the installation of a groundwater cutoff wall in Fort McMurray, AB. The purpose of the cutoff wall is to minimize off-lease seepage of process affected water (PAW) beneath the planned Northeast Closure Dam (NECD). The PAW is generated during the mining and processing of synthetic crude at a large oil sands mine. The requirements of the cutoff wall included a maximum hydraulic conductivity of 10^{-9} m/sec, a minimum unconfined compressive strength of 1 MPa, a 2 m penetration into the underlying McMurray Formation, and tie-in to an existing cut off wall previously installed for an existing tailings settling basin. Based on the complex project requirements, CGSI selected a self-hardening cement-bentonite slurry wall as the groundwater barrier. This paper provides details of this project from the design and bench scale study to completion of the cutoff wall installation and provides lessons learned through the performance of the project.

RESUME
En 2018, Canada Geo-Solutions Inc. (CGSI) a mené à bien un projet de conception-construction visant à installer un mur anti-eaux souterraines à Fort McMurray, en Alberta. Le mur de protection a pour but de minimiser les infiltrations hors bail des eaux affectées par le processus sous le barrage de fermeture nord-est (NECD) prévu. Le PAW est généré lors de l'extraction et du traitement du brut synthétique dans une grande mine de sables bitumineux. Les exigences du mur à découper incluaient une conductivité hydraulique maximale de 10 à 9 m / s, une résistance à la compression minimale sans contrainte de 1 MPa, une pénétration de 2 m dans la Formation de McMurray sous-jacente et le raccordement à un mur à découper existant précédemment installé. pour un bassin de décantation existant. Sur la base des exigences complexes du projet, CGSI a choisi un mur de coulis de ciment-bentonite auto-durcissant comme barrière pour les eaux souterraines. Ce document fournit des détails sur ce projet, depuis la conception et l'étude à l'échelle en passant par la réalisation de l'installation du mur coupe-circuit, et présente les enseignements tirés de l'exécution du projet.

1 INTRODUCTION

1.1 Project Background

In 2017, Syncrude Canada Ltd (Syncrude) solicited qualified contractors to complete the detailed design and construction services for a 1225 m long, seepage cut-off wall (COW) at their East Pit at the Aurora North Mine near Fort McMurray, Alberta. The Aurora North Mine is located approximately 65 km north of Fort McMurray, Alberta. The proposed COW was constructed across a pre-existing valley located in the northeast of the Aurora North Mine Lease. The COW was installed within the Stanley Creek, which is located between the Fort Hills Moraine and the Aurora Settling Basin. The Stanley Creek originates in the Fort Hills Moraine and flows eastwards towards the Muskeg River and ultimately, the Athabasca River.

Canada Geo-Solutions, Inc. (CGSI) was contracted by GKJV (a joint venture of Graham Construction and KMC Mining) to install a self-hardening COW along the alignment of the future tailings dam. The COW is required to minimize the off-lease seepage of process affected water (PAW) beneath the planned Northeast Closure Dam (NECD). The COW was installed from an earthen platform that will eventually become a mining haul road and will be located immediately downstream of the tailings dam. An overhead view of the COW alignment is provided in Figure 1 below:

Figure 1. Aerial view of COW alignment. (Image from Syncrude Project Documents via GoogleEarth™)

1.2 Site Geology

The surficial geology consisted of Muskeg overlying glacial fluvial sands and gravels. The geotechnical investigations previously encountered discontinuous lenses or zones of frozen ground (in some cases permafrost) along the COW alignment. These zones needed to be accounted for in the design modeling and be considered in the proposed installation method and mix design. The bedrock beneath the proposed COW alignment was expected to be the McMurray Formation. Some geotechnical investigations in the area have indicated that the Upper McMurray Member will be locally encountered. This includes interbedded mudstones and sandstones deposited in a near-shore, drowned channel to off-shore environment. The elevation of the bedrock ranges between El. 285 and 276 m. according to the project documents.

1.3 COW Requirements

The properties of the COW were established by the Owner's consultant prior to the solicitation for contractors. The key requirements of the COW were a maximum hydraulic conductivity of 10^{-9} m/sec when cured and a minimum strength of 1 MPa at 28 days. The COW also was required to be continuous with a minimal quantity of cold joints, be keyed a minimum of 2 m into the McMurray Formation, tie into another existing COW at the site, and be able to withstand traffic loading from future mining trucks up to 560 tonnes.

1.4 Design Work

The design work required included the following:

- Technical approach for the method of installation.
- A laboratory mix design of the self-hardening slurry to meet the project requirements.
- Shop drawings with the dimensions of the COW.

This paper only addresses the laboratory mix design element.

1.5 Scope of Field Work

The scope of work for the GKJV included the following:

- Site preparation including creek diversion and grading of the area.
- Survey of the COW alignment.
- Surface water management.
- Installation of the COW.
- Capping of the COW with un-compacted soil cover.

CGSI's scope of work as a subcontractor to GKJC was limited to the installation of the COW. This paper addresses only the COW installation element of the field work.

1.6 Method Selection

The solicitation allowed contractors to propose either a Slurry Wall method or Deep Soil Mixing (DSM) method to create the COW. The Slurry Wall method was proposed due largely to the site geology. The zones of permafrost, and the nature of the McMurray Formation would provide difficulty in successful completion using the DSM method. Further, the presence of Muskeg made the Slurry Wall method a preferred approach. The DSM method incorporates the in-situ soils in the soil-mix matrix to create the vertical barrier and the organic nature of the Muskeg included in the matrix could have interfere with cementation effecting both the strength and permeability of the COW (FHWA, 2013).

The Slurry Wall technique selected is a “full replacement” method. The in-situ soil along the alignment is completely removed and replaced with the engineered slurry. Only a small amount of soils are suspended in the slurry (generally 10-20% by volume) as a result of the excavation, and are well dispersed throughout the mix. This method allows the contractor greater control over the final properties of the cured slurry.

2 MIX DESIGN

2.1 Selection Criteria

The primary requirements used to guide the creation of candidate mixes for the COW were the permeability and UCS. Mixes consisting of Ground-Granulated Blast Furnace Slag (slag), Portland cement (PC), and bentonite have been frequently used for similar projects to achieve a combination of low permeability and moderate to high strength.

2.2 Considerations

The primary considerations in developing the mix design included the temperature of the source water and the potential for contact of the slurry with the permafrost layers. Previous research (Lea et al. 2013) indicates that cold temperatures have a negative effect on strength development.

2.2.1 Long Term Performance Considerations

The strength and hydraulic conductivity, k, of self-hardening slurry backfill mixes containing slag, referred to as slag-CB herein, continue to improve well past 28 days of cure (e.g. Coughenour et al. 2018). However, despite this common knowledge, specifications continue to be based on performance of the material after 28 days of curing with no consideration of further improvement. Previous research shows that strengths will continue to increase out to more than 90 days (Jefferis 1981, Opdyke and Evans 2005, Soga and Joshi 2010, and Coughenour et al. 2018). Studies show that the k of these mixes continues to decrease out beyond 90 days (Opdyke and Evans 2005; Soga and Joshi 2010) and some data suggests there could be further decreases as far out as 3 years (Soga and Joshi 2010). This long-term strength and k improvement can be attributed to the pozzolanic reaction provided by the slag. Slag reacts more slowly than Portland cement and ultimately develops a denser microstructure as it cures (Soga et al. 2013).

However, based on the requirements of this project, the initial mix design studies where performed to achieve the strength targets at the 28-day cure time.

2.3 Candidate Mixes (First Round)

A total of 24 first-round mixes were created in April of 2018. The variables in the mixes included:

2.3.1 Total Cementitious Material

The total cementitious material was measured by weight of water. This was varied from 20% to 30% in different mixes.

2.3.2 Ratio of slag to PC

This was varied from 90:10 to 60:40. For example, in a mix with 20% total cementitious material and a 75:25 ratio, the mix included 15% slag and 5% PC, each by weight.

2.3.3 Type of PC used.

A number of types of PC were used in the mixes. These included Type I/II, a designation typically used in the US for cement meeting both General Purpose and Moderate Sulfate Resistance standards (ASTM C150). This was used because the cement supplier indicated at the time the source of PC could be from either the US or Canada. Type GU Cement (ASTM C1157) was also used in some mixes. Several mixes were made using Type HE Cement for High Early strength. These were made to try to accelerate the curing to achieve the required 1 MPa strength at 28 days.

2.3.4 Slag

The type of slag used in all mixes was Grade 100 slag.

2.3.5 Blended Cement

Several mixes were created using a pre-blended slag-PC product provided by the cement vendor. The product, known as Terraflow 90 (or T90), is a blend of 90% slag and 10% PC.

2.3.6 Bentonite

The bentonite in the various mixes was 90 bbl material meeting the requirements of Section 9 of API 13B. The bentonite was included at a rate of either 3.0% or 4.5% to weight of water.

2.3.7 Additives

Three commercially available additives were tested in a total of 5 of the mixes. Each additive was an accelerant which were used to try to accelerate the curing to achieve the required 1 MPa strength at 28 days.

2.4 Testing

The testing on the mix design samples was initially focused on the strength tests. In general, samples were tested at 7, 14 and 28 days.

2.5 Analysis

Based on the first-round mixes, the following conclusions were drawn:

- None of the mixes were close to the required 1 MPa at 28-days
- A ratio of 90:10 slag to PC resulted in the best performance, regardless of the total cement content
- The accelerator additives resulted in a higher strength at 28 days

Due to the fact that none of the mixes reached the target strength at 28 days, an additional 10 mixes were created, all using a 90:10 slag to PC ratio. Also, a Request for Information (RFI) was submitted to the Owner to extend the target age at which the fully cured strength would be evaluated.

2.6 Second Round Mixes

Second-round mixes focused on a 25% cementitious content and a 90:10 slag to PC ratio. Variables in these mixes included variation in temperatures of the source water and curing. Accelerants were used in some mixes, and some where made with HE cement. Some mixes were created using extraordinarily high cement contents (30%, 40% and 50%). Although mixes this rich were unlikely to be used in the field due to economic considerations, they were created to see if it was feasible to achieve 1 MPa at 28 days.

While the second-round mixes were curing, the Owner approved the RFI that removed the 28-day time frame for reaching the target strength. The requirement was changed to require strength to be achieved before haul trucks crossed the site, which was scheduled to be over a year after the work was to be completed.

2.7 Second Round Results

The second round UCS tests were limited to samples at the ages of 7, 14 and 28 days. The field work was scheduled to start prior to 56 days of curing for these samples. However, the first-round samples were tested at 56-days. Past trends were used to project the expected UCS performance of the second-round samples after a 56-day curing period and the expected ultimate performance of all samples. These projections were based on strength gain trends from previous studies (Coughenour, et al. 2018).

2.8 Mix Selection

None of the candidate mixes that were deemed viable for full scale production reached the required strength at 28 or 56 days. Given the project schedule deadlines, additional mixes could not be cured and tested.

The contract for the full-scale work was based on a total cementitious content of 23%. Although the 23% total cementitious mixes did not achieve the requirements in 56 days in the laboratory study, the mixes containing 25% cementitious material did not perform appreciably better and all the higher cement contents were not considered economically feasible. Ultimately the mix was selected largely on data from previous work.

Another factor in mix selection was the availability of material. Prior to mobilization, the cement supplier indicated that the pure slag product was not being imported into Canada. The only products available were Terraflow 90, and Portland cement. Given that the 90:10 ratio performed best in the mix study, this product was selected for use at a total cementitious dosage of 23%.

3 FIELD WORK

3.1 Batch Plant Mixing

The slurry was created in the field using a series of mixers. The first step was to create and pre-hydrate bentonite slurry. Once the bentonite slurry is hydrated, second step is to add the cementitious material. The bentonite slurry and cementitious material are mixed together and the mixed slag-CB slurry is pumped to the trench as needed.

3.1.1 Mix Water and Slurry Heating

Mix water for the slurry was drawn from an on-site pond. This water was fed by the diverted Stanley Creek that runs through the site. At the start of the project, in July of 2018, the water temperature was generally 15-22 °C. Previous studies indicate that source water above 10 °C does not have a negative effect on the early curing of the slag-CB slurry (Lea 2013). As the project carried into late September, the source water dropped consistently below 10 °C. In order to prevent any adverse effects on the slurry, fluid heaters were mobilized to the site. The heaters used were diesel fired, and use a fluid-to-fluid (glycol) heat exchanger to continuously heat the bentonite slurry as it is circulated through it.

3.2 Excavation

Excavation of the slurry trench was completed using a 125 tonne excavator, fitted with custom-built long reach stick and boom attachments. The excavation rig is designed specifically for slurry trench excavation. Excavation is performed as the fresh slag-CB slurry is pumped to the trench from the batch plant maintaining the slurry level within a few feet of ground surface. Since the majority of the excavation is performed in the “blind”, under the slurry level, the excavator operator needs to be specially trained for this type of work. The excavation was carried to the top of the McMurray Formation, which is verified from the bucket cuttings. The excavation was then carried an additional 2 m into the bedrock layer. The total depth of the barrier wall ranged from 15.5 m to 23.9 m.

In order to assure wall continuity, each panel is overlapped horizontally with the previous panel. When panels are installed in the same day, the previous panel is generally still liquid slag-CB slurry and it is obvious to the operator and the inspector that the panels are continuous. On installations done on subsequent shifts, the tie-in to the previous panel is verified by re-measuring a location on the trench back into the previously installed panel. The consistency of previously installed panels ranged from a very viscous fluid to a very soft gel-like material.

Figure 2 below shows the beginning of the COW excavation. The COW alignment continues directly behind the excavator.

Figure 2. Excavation of the COW under slurry

3.3 Differing Conditions

In the course of excavating the barrier wall, a differing site condition was encountered. The condition was the presence of both sandstone and siltstone above the McMurray Formation. When initially encountered, this unit was a thin sandstone layer, which was able to be excavated with the slurry trench excavator. Once that layer was penetrated, the McMurray Formation appeared to be directly beneath it. A short distance later, a siltstone layer was encountered. This formation could not be penetrated with the excavator.

The barrier wall trenching operation was relocated to another area of this site to continue installation while further investigation was completed. The Owner was able to quickly hire another contractor to complete drilling and sampling work to determine the extent and thickness of the siltstone layer, and to determine if that unit was embedded in the McMurray Formation. It was determined that the siltstone was not embedded in the McMurray and needed to be removed so there was no risk of seepage under the siltstone. The removal required another contractor to be mobilized to the site to disaggregate this rock to allow for easier removal during subsequent slurry trenching activities. Disaggregation was completed with a large rotary drill rig fitted with a 1 m rock-grinding auger.

3.4 Sampling and Curing

During the production work, samples of the slag-CB slurry were collected at a minimum of once per shift. The samples used for evaluation of the project were collected from the trench, at various depths. Each sample was cast into multiple specimens, for UCS testing, permeability testing and for archives. Plastic pipe (PVC) was used as sample molds. Each mold had an approximate diameter of 50 mm and were 200 mm long. The long sample molds are used to better model what happens it the trench, where the density of the slurry increases slightly with depth, as suspended soil particles slowly migrate toward the bottom of the trench during curing. The samples were cured in coolers and stored in the site trailer at the site.

Early in the project, some samples were sent to the laboratory for UCS testing, at ages between 14 and 28 days. In addition, testing was completed at a frequency of about 3 times what was required by the specification. All of these early samples tended to be on the order of twice the UCS of the comparable mix design samples. Therefore, most samples after the first 3 weeks or so, were held until the 28 days age before the first UCS tests were conducted. All samples designated for testing at the project required frequency were also tested at 56 and 182 days.

3.5 Test Results

The UCS test results of the field samples are presented in Table 1 below. In general, the strength tests were what was expected based on previous project experience.

Table 1. UCS results of field samples

Sample Age (days)	UCS (kPa)		
	Sample Size	Average	Standard Deviation
14	12	647	130
21	7	910	126
28	49	1076	200
56	30	1481	285
182	20	2011	298

As expected, the UCS of the slag-CB samples continued to increase out to 182 days (approximately 6 months). The 6 month UCS results were nearly double that of the 28 day results and nearly 40% higher than the 56 day results. These are significant increases that would be very beneficial to both the owner and the contractor if considered in the specifications, specifically the sample age at which the target parameters must be met.

4 LESSONS LEARNED

4.1 Material Considerations

A number of types of cement were used in the mix design, and many were blended with pure slag material. However, during the mix design process, it was learned that the pure slag product was not available in Canada. Had this been known prior to the start of the mix design, many of the mixes would not have created, and more variations on the T-90 mixes would have been created.

4.2 Field Results vs. Bench Scale

Figure 3 below illustrates the field results vs. the bench scale results, with the "ultimate" strength of the selected mix design projected. The conclusions on these results are as follows:

- The strength curing curve was well predicted.
- The average of the field samples was slightly better than the target strength of 1MPa at 28 days of curing.
- All field samples achieved at least 1MPa at 56 days of curing.

The average of the field samples was approximately 2 MPa at 182 days.

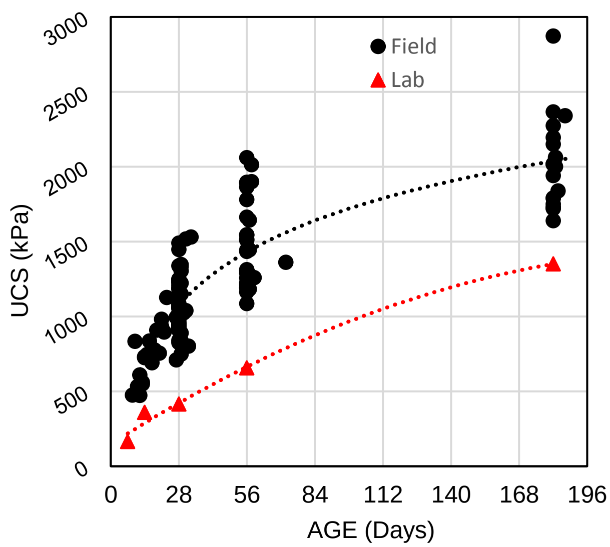

Figure 3. Field vs Lab UCS Results

The likely factors in the much greater strength observed in the field as compared to the laboratory mixes include the following:

4.2.1 Inclusion of Soil Particles

During the excavation of the trench, a small fraction of the in-situ soils become suspended in the slag-CB slurry. This portion is generally seen to be approximately 10% be weight of the slurry. Soil inclusions in slag-CB slurry are typically considered undesirable because they can cause defects and preferential failure planes (Ruffing et al. 2018). However, inclusions of certain types, sizes, and percentages can also be beneficial to strength and permeability. For instance, sands and gravels suspended in slag-CB slurry can act similar to aggregates in concrete and result in a higher than expected UCS. Suspended fines can also have a similar positive impact on permeability. It is possible then that the mixes created in the lab resulted in lower strengths than the field samples because of the lack of soil inclusions.

4.2.2 Human Factor

When creating the slag-CB slurry in the field, there is a tendency for the plant operator to be conservative in the addition of cement to the mix. The operators tend to "over-dose" the cement, especially early in the project until there is some feedback from management, either that the usage is too great based on analysis of the overall throughput, or that the laboratory results show the project goals are being met or exceeded. On this project, the target cement addition rate was 23%, however the actual calculated cement addition rate was approximately 24.4% as measured by the total cement deliveries used for slurry creation.

4.3 Slurry Heating

The use of slurry heaters was an effective method to overcome the potential negative effects of cold source water. The heaters resulted in the fresh slag-CB slurry being on the order of 8 °C to 15 °C warmer than the source water. The water in October tended to range from 2 °C to 8 °C, and the slag-CB slurry ranged from 11 °C to 19 °C. By heating the water, the slag-CB slurry temperature was similar to the room temperature slurry used in the mix design study.

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