Field Trial of Spray-Applied Geopolymer Mortar Used to Repair Large Diameter Corrugated Steel Culverts, New Brunswick Department of Transportation and Infrastructure

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Introduction

The New Brunswick Department of Transportation and Infrastructure (NBDTI) highway network contains over 2100 large culverts with over 75% of this inventory expected to require renewal within the next 20 years. Over half of the inventory requiring renewal are corrugated steel pipes (CSPs), which have shown to have the shortest service life of all culvert types installed since the 1960s.

Conventional cut-and-cover culvert replacements, especially in deep fill embankments, are costly and disruptive to traffic and the environment. It was determined that trenchless methods should be considered for these culverts where conditions are suitable.

In January of 2021, a New Brunswick contractor proposed the trenchless method of lining existing culverts with a spray-applied geopolymer material (Geospray) supplied by GeoTree Solutions.

Subsequently, NBDTI engaged in a field trial of geopolymer mortar. The main objective of the trial is to determine the suitability of this rehabilitation method for ongoing implementation in NBDTI culverts.

NBDTI developed a list of culverts that met the following criteria:

- Culverts located in fill heights greater than 5m
- Culverts in embankments that were stable and not subject to ongoing settlement or large differential movement
- Minimal shape deviation and section loss
- Reasonable property access to both ends of the culvert
- Adequate hydraulic capacity to allow for a reduction in cross-sectional area
- Located on watercourses with characteristics such as small drainage area or significant slope that would eventually preclude the requirement for fish passage provisions in consultation with the Department of Fisheries and Oceans.

From the approved group of culverts, five were selected for repair. The lessons learned from the field trial will determine if this trenchless repair method should be used for NBDTI's ongoing culvert renewal program.

Detailed inspections were carried-out at the proposed sites to measure shape deviation, verify the presence and severity of voids within the culvert backfill, and whether any additional site preparation was required prior to applying the geopolymer. Upon completion of the condition survey, the contractor's engineer supplied the required thickness design to achieve a fully structural, lined culvert with an expected design life of 50 years.

Of the five sites chosen for the trial, four were completed in 2021 and one in 2022. This paper includes details of the culvert selection process, lessons learned during the field trial, results of the quality control and change recommendations for completion of the trial by fall of 2022.

Selection of Culvert Rehabilitation Candidates

The NBDTI overall culvert inventory database, BRDG, was utilized as a starting point to review culvert assets for their suitability as potential candidate culverts. Culverts in the inventory are organized into *Large Culvert* category (diameter 1200mm - 3000mm) and *Bridge Size Culvert* category (diameter > 3000mm).

Beginning in January 2021, relevant data for all 2226 Large Culverts was extracted from BRDG. It was decided by NBDTI that Bridge Size Culverts were too large for the geopolymer repair being trialed. Microsoft Excel spreadsheets were used to sort, screen & filter selected assets, based on key characteristics.

Varying sets of filters and criteria were applied to the group of assets to gain an understanding of the effects and sensitivities. Recognizing some key characteristics are not readily available in BRDG (ie. hydraulic capacity), the goal of the first stage screening exercise was to develop a focused list of best candidates, to bring forward to the second stage screening where a greater level of analysis including site visits could be undertaken. It was anticipated that there would be many culverts meeting the criteria for first stage selection.

The first stage screening criteria consisted of the following:

- Fill Over Pipe ≥ 3.0m - deeper culverts are generally better candidates for rehab vs. replacement due to excavation costs and traffic disruption.
- BCI 30 to 80 - 'bridge condition index' numerical rating ranges from 1-100. Purpose of this filter is to screen out culverts in excellent condition, not yet at a point in the deterioration curve where rehab is warranted, as well as screening out culverts in very poor condition where replacement is more likely to be best of available options.
- Large culverts where detours are difficult and trenchless options are beneficial
- Barrel Comment = YES – Culvert inspectors are required to provide a comment for the barrel component where its rating is below a certain threshold. The purpose of including this filter was to ensure that candidate culverts have documented deficiencies which could be addressed by rehabilitation.
- Culvert Type = All Steel and Concrete Types
- Culvert Shape = All shapes including arch, oval, and circular shaped culverts were considered

It is recognized that quality candidates are potentially 'screened out' using the constraints above, however the set of criteria was found to be appropriate as it yielded roughly 120 culvert candidates that could be further analyzed in stage two screening. The stage two screening process includes;

- Performing desktop reviews of all 120 candidates for environmental aspects, such as fish passage.
- Performing desktop reviews of hydraulic design requirements
- Determining the need for archaeological study
- Determining property and access requirements
- Site visits to determine global stability. If the embankment required major repairs due to settlement, slope instability, or erosion, then the culvert was deemed not suitable for this trial.

Environmental

Knowing that fish passage will be a major consideration in most cases, focus was given to candidates that appeared more likely to be permitted without a requirement for introducing fish weirs. From desktop reviews, the following situations were identified as criteria needed for trial selection:

- Culverts with small drainage areas and/or along steep channels, where a field environmental review and subsequent discussions with DFO would be likely to result in a determination of no fish passage requirements.
- Culverts with relatively flat longitudinal slope, and backwater throughout the culvert, where a field environmental review and subsequent discussions with DFO would be likely to result in the determination that fish passage is already provided, with no additional requirements. **Figure I**, below, shows an example of a candidate culvert with relatively flat longitudinal slope, backwatered.

Figure I: Culvert Rehab Candidate, fully backwatered

Readily available LiDAR data was utilized to approximate drainage areas and stream channel slopes, and past inspection report photos were utilized to review backwatering of culverts, hanging outlets etc.

Upon reviewing these data and findings, the short list of 120 culverts was further reduced to approximately 75 candidates.

During the Environmental screening phase, DFO requested that NBDTI trial the use of added roughness elements at one of the sites. It was decided that this approach would be used at site DE03 as a measure of the Department's intention to cooperate with regulators and to potentially open the possibility to future sites which may have otherwise not been considered. **Figure II** shows the roughness elements design that was eventually agreed-upon with DFO.

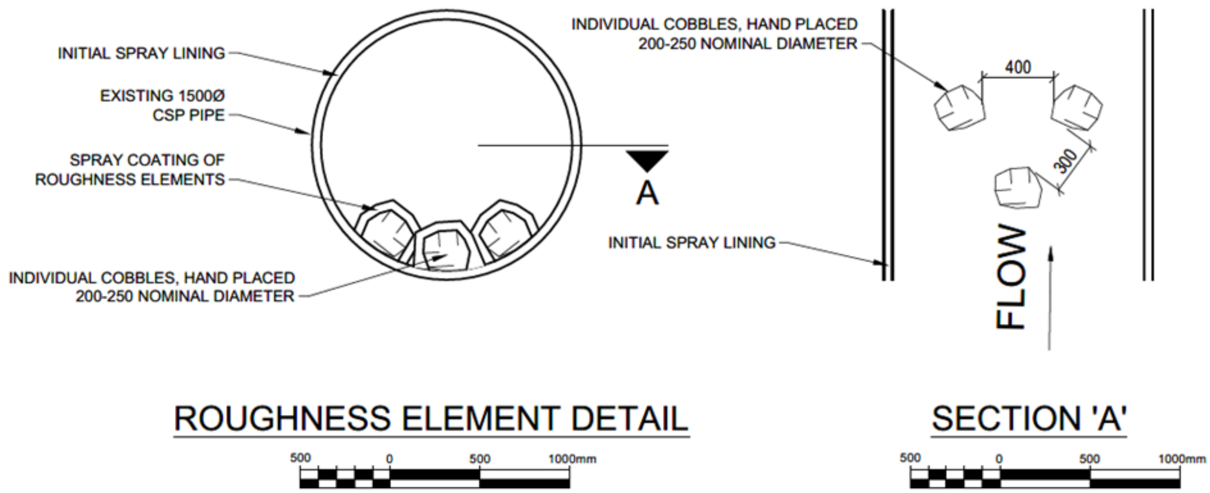

Figure II – Roughness Elements Detail at Site DE03

Hydraulics

The latest NBDTI hydraulic criteria includes specific targets for culvert rehabilitation, which were used to evaluate the 75 culverts identified. Culverts proposed for rehabilitation are required to meet headwater height to culvert depth ratio (H/D) < 1.4 with 1m freeboard in the applicable design storm under inlet control, and headwater differential < 0.3m under outlet control.

The hydraulic review tasks yielded 22 candidate culverts with adequate / reserve hydraulic capacity. This list was supplemented by 7 additional culverts suggested by the Hydraulics Unit based on current knowledge and work ongoing. These 29 large culverts were brought forward for field reviews in spring of 2021 to include:

- topographic surveys;
- culvert barrel / structural condition review;
- environmental field work; and,
- determination of construction access strategies.

Information from these field reviews was utilized to prepare existing plan & profile sketches, engage in discussions with DFO, prepare for submission of Wetland and Watercourse Alteration Permit Applications, depict temporary construction access arrangements, and to identify any property lease or acquisition requirements to facilitate rehabilitations.

The 5 culverts eventually selected as part of the 2021 field trial of spray-applied geopolymer mortar were taken from this list of 29, with consideration given to structural condition, relative ease of construction access, and timing of environmental approvals. **Figure III** shows the geographic location of the 5 culverts included in the field trial of spray-applied geopolymer mortar.

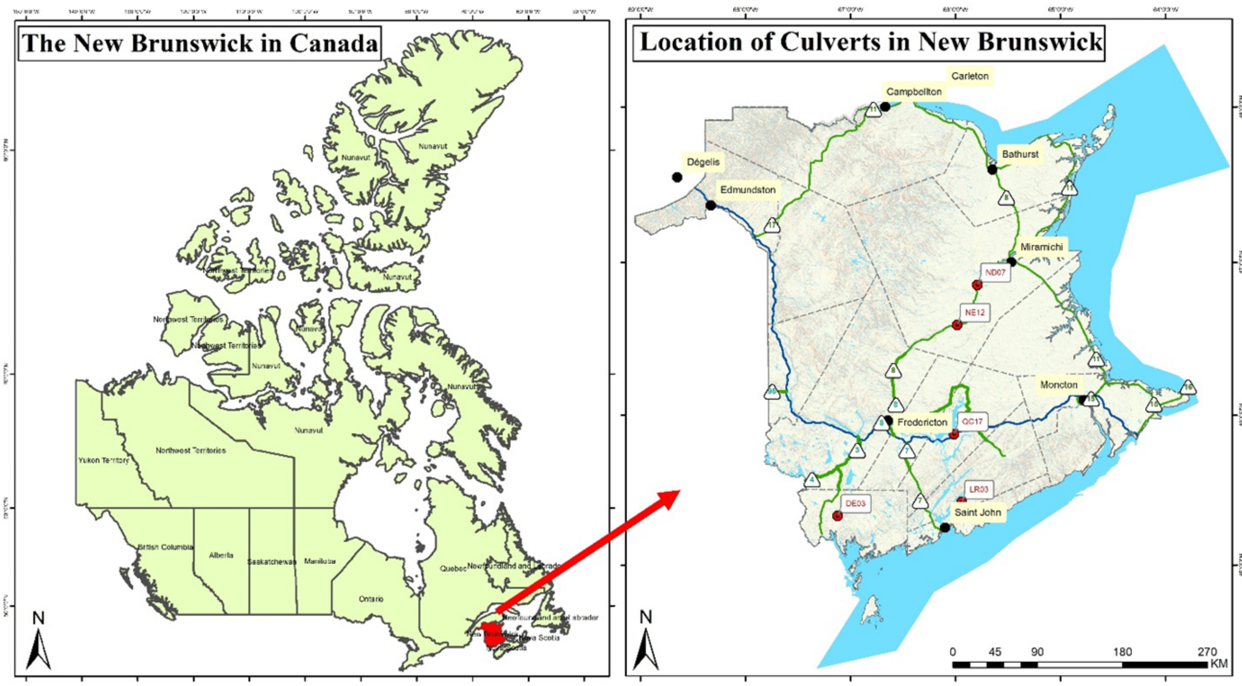

Figure III: Locations of 5 Large Culverts selected

The remaining 24 culverts were then prioritized using NBDTI Hydraulics Unit's culvert triage methodology which ranks and prioritizes culverts based on a set of pre-determined characteristics. It is planned that these culvert assets will be pursued in order of priority under the Department's ongoing rehabilitation program, utilizing a mix of traditional and trial rehabilitation methods.

Going forward, the Department's regular culvert inspection program will include determination of drainage areas and hydraulic capacity on selected assets. This information will be stored in the overall database, leading to a larger proportion of the inventory to be triaged for the purposes of the rehabilitation program.

Geopolymer

To properly discuss geopolymer mortars and materials and help understand their distinct differences in comparison to traditional ordinary Portland cement concrete (OPC), it helps to first discuss OPC, its basic chemistry and some of its perceived downsides.

The manufacture of Portland cement is a complex physical and chemical process, however it can be simply described as the combination and burning of limestone and clay in a rotary kiln at 1450°C. When production is completed, Portland cement powder consists of four main compounds (Neville, 2012):

- Alite – C_3S
- Belite – C_2S
- Tricalcium Aluminate – C_3A
- Tetracalcium Aluminoferrite – C_4AF

Breaking down Portland cement hydration into a very basic discussion; the hydration of both alite and belite with water (H_2O) is predominantly what gives OPC its strength, yielding a product called calcium silicate hydrate (CSH), which essentially provides the "glue" in the system. An abundant amount of calcium hydroxide (CH) is also produced during hydration of OPC, a product that contributes very little to strength. However, with the introduction of pozzolans such as fly ash, metakaolin and ground granulated blast furnace slag (slag), further reactions are created with the CH in the system – thus creating more CSH and providing a denser and more high performance concrete with lower porosity.

Although a durable and widely used construction material worldwide, the production of Portland cement is a significant CO_2 emitter. **Figure IV** below estimates that Portland cement production alone accounts for 5% of the total CO_2 emissions produced worldwide.

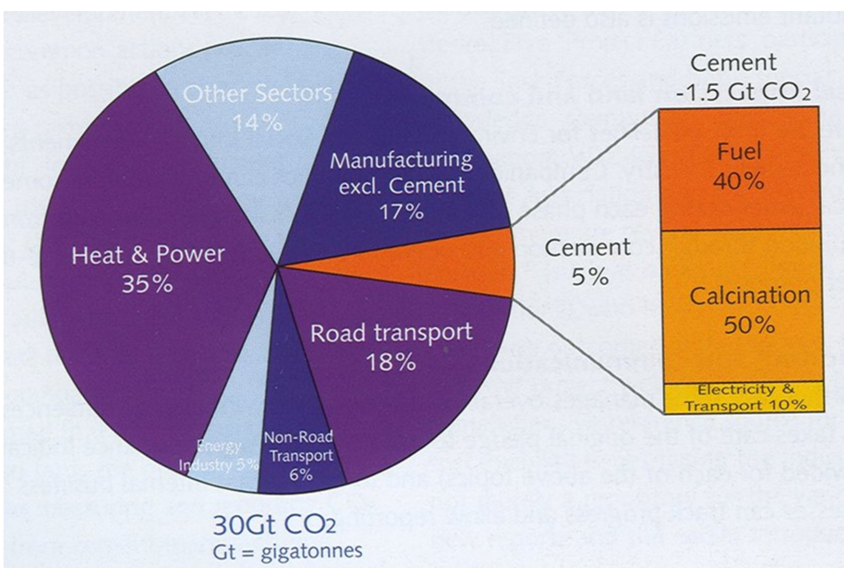

Figure IV: Worldwide CO_2 emissions by Industry (Mihailescu, 2009)

The future use of Portland cement is only predicted to rise, as shown in the figure below. Although predicted to decline in countries such as China or stabilize in other industrialized nations, developing nations will increase the overall demand for Portland cement. This is one reason that alternative binders with a lower carbon footprint, such as geopolymers, are being introduced into the construction industry when feasible.

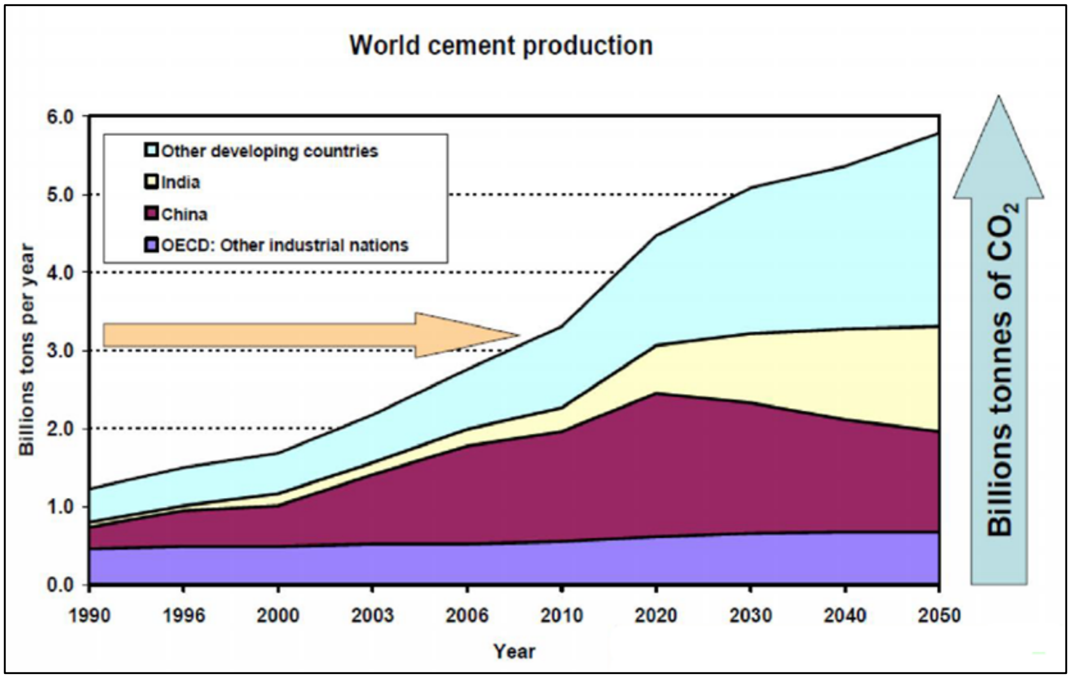

Figure V: Prediction of Future World Cement Production (Scrivener, 2010)

The term "Geopolymer" was first introduced by Joseph Davidovits in 1978 to describe a new class of binder utilizing aluminosilicates that had been activated using an alkali solution. However, research on the alkali activation of aluminosilicate materials dates to as far as the early 1940's (Pacheco-Torgal, 2008). The terms alkali-activated binders and geopolymers are sometimes used interchangeably throughout the industry, however many researchers disagree with the classification of all alkali-activated binders as geopolymers. However, for simplicity, the term geopolymer will be used solely to describe the material discussed herein.

The basic precursor materials used to form geopolymers are pozzolans containing an abundance of alumina and silica such as ground granulated blast furnace slag, metakaolin and fly ash. In comparison, Portland cement contains an abundance of calcium that provides the basis for its hydration. The reaction of pozzolans in the geopolymer system requires the use of an alkali activator such as sodium silicate (Na_2O_3Si) or sodium hydroxide (NaOH). Precursor materials such as slag and fly ash are industrial byproducts, produced from the production of steel and the combustion of coal respectively. These are therefore waste materials that contain an abundant amount of alumina and silica that can be used as precursor materials for the reaction of geopolymers, without creating any further significant environmental impact. Geopolymers are therefore classified as a more environmentally friendly material when compared to OPC.

Although geopolymers are traditionally alkali-activated, the handling of highly alkali solutions to produce geopolymer materials on an every-day construction site creates obvious safety concerns and would therefore limit its usefulness in typical construction applications. Therefore, geopolymer materials capable of activation simply by the addition of water are essential for practical construction use. These "just add water" products have been commercially available since 2011 and include products such as

Geotree Solution's Geospray geopolymer. The reaction of these types of products is performed with the use of precursor materials such as slag and fly ash, as previously discussed, but also with the introduction of a portion of Portland cement and other additives to create the alkaline environment required to activate the precursor materials and form the aluminosilicate geopolymer binder. These materials are sometimes referred to in the industry as hybrid alkali-activated binders or hybrid geopolymers (Royer, 2019 & Provis, 2017).

The reaction mechanism of a geopolymer material differs greatly from the hydration of Portland cement, which was briefly discussed above. The reaction mechanism of a geopolymer relies on the breaking of chemical bonds and condensation to form a cross-linked polymer network consisting of covalent bonds between aluminum, silicon and oxygen molecules that form the aluminosilicate backbone of the structure (Royer, 2019).

In terms of basic hardened properties, both OPC and geopolymers can produce comparable compressive, tensile and flexural strengths however this is highly dependent on the precursor materials used in the geopolymer material (ie. slag vs. fly ash, etc.). Higher amounts of alkali can also produce a higher degree of reaction and curing temperature also plays a role in strength development, similar to OPC (Provis, 2017).

In terms of durability, a geopolymers resistance to acid attack is where it exhibits a distinct advantage over OPC. Geopolymers using lower calcium precursor materials, such as fly ash and metakaolin, appear to exhibit the best resistance to acid attack. This type of resistance makes geopolymers an attractive solution for lining existing sewer pipes where a high resistance to acid and chemical attack is desired. Geopolymers also exhibit increased fire resistance, improved freeze-thaw durability and decreased porosity when compared to most OPC's (Pacheco-Torgal, 2012).

As mentioned above, geopolymers that use a hybrid approach to activation rather than the traditional alkali solutions, allowing just the simple addition of water on site, have been on the market to the industry since 2011 (Royer, 2019). Since that time, according to GeoTree, their GeoSpray geopolymer mortar has been formally approved for use by 19 U.S. highway transportation departments, 2 Canadian highway transportation departments as well as various major cities in Canada and the U.S.

NBDTI Geopolymer Trial

In January 2021, a New Brunswick contractor – Northern Construction Inc. - proposed the culvert rehabilitation method of lining existing culverts with a spray-applied geopolymer material (Geospray) supplied by GeoTree Solutions. The timing of this unsolicited proposal coincided with the beginning of development of the Department's Large Culvert Rehabilitation Program.

The Design Branch at NBDTI obtained approval from the Provincial Government to conduct a field trial with a maximum budget of $1 million. Based on research of past projects in other jurisdictions, it was estimated that the completion of 5 sites could reasonably be completed within the allotted budget.

NBDTI and the Contractor proceeded to negotiate a Time & Materials contract.

Quality Assurance and Quality Control (QA/QC)

QA/QC followed the manufacturer's recommended procedures for testing the product. The Contractor engaged a 3rd party lab testing company – GEMTEC Ltd. – to collect samples on site and test the product's compressive strength in accordance with CSA A23.2.

On-Site Thickness Verification

The Contractor's plan to verify thickness on-site was to install indicators in the CSP. At the first two sites (ND07 and NE12), 38 mm-long screws were attached to the inside of the CSP using an epoxy product. The screws were attached near the 10:00 and 2:00 o'clock positions of the culvert at 5 m intervals.

At the next two sites (QC17 and DE03), the Contractor decided to use zip ties, cut to a 38 mm length, in place of screws. This change was made because workers were running into the screws and causing them to detach from the host culvert.

NBDTI Thickness Tests

Upon completion of the project, NBDTI conducted drilling to verify final thickness. A hammer drill with a 3/8" concrete bit was used to drill into the cured geopolymer at various clock positions until reaching the host CSP. Using a flashlight, it was possible to ensure that the drilling had indeed penetrated the full depth of applied geopolymer.

Application at each site

Each of the first four sites generally underwent application using a spin caster which was pulled through the culverts using a low-speed winch as shown in **Figures VI and VII**.

Figure VI – Spin Caster at Site NE12

Figure VII – Winch at Site NE12

Hand spraying was used in two instances. First, the Contractor experienced an equipment malfunction with the nozzle of the spin caster at site NE12. They attempted to hand spray the pipe while they waited for a replacement part to arrive, however they found that it was too difficult to hand spray due to the limited access to the 1350 mm diameter pipe. The result was an uneven application. Since it was during the first application of the product at the site, it was eventually covered by subsequent applications with the spin caster once it was repaired.

The second instance where the Contractor used hand spraying was to apply a final application at site DE03 over the roughness elements (cobbles) as it would not have been feasible to run the spin caster on top of the cobbles.

Figures VIII and **IX** show the results upon final application in the fall of 2021 at sites ND07 and DE03, respectively.

Figure VIII – Photo of Site ND07 After Final Application

Figure IX – Photo of Site DE03 After Final Application

The results of NBDTI thickness tests completed at the first four sites are shown in Table 1.

Table 1: Design and Applied Geopolymer Thickness

Site	Design Thickness (mm)	Average Measured Thickness (mm)
ND07	38.0	30.5
NE12	38.0	35.9
QC17	40.1	28.4
DE03	44.6	32.8

During NBDTI's thickness testing, it was observed that there was repeated circumferential cracking in all culverts. These cracks all had similar characteristics in that they were 2mm or less in width, and that they extended approximately from the 7:30 to the 4:30 clock positions of the culvert (ie. the invert displayed no cracking). **Figure X** below shows one of the widest observed cracks.

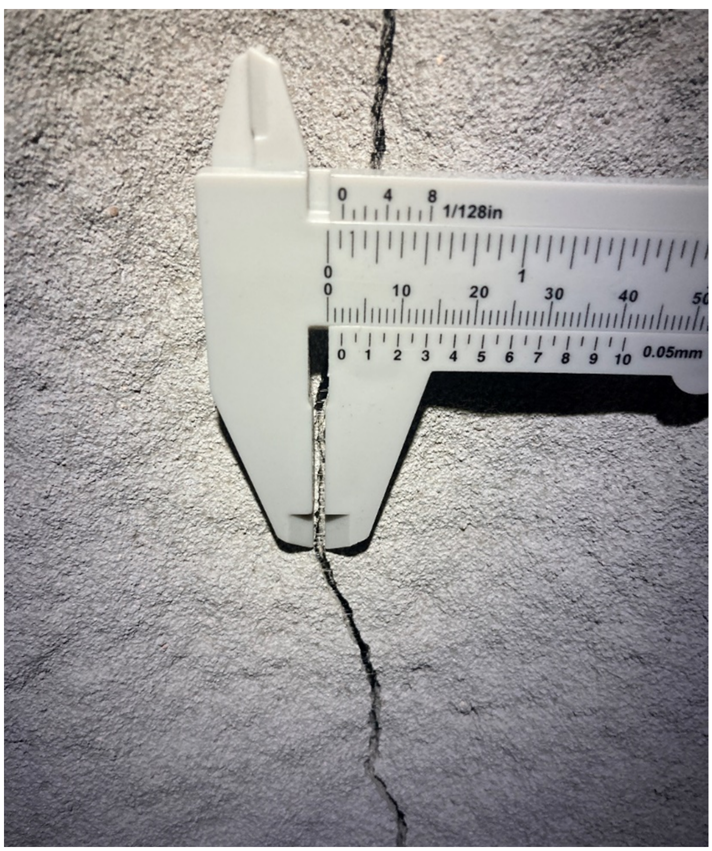

Figure X: Circumferential Cracking Observed at Site ND07

Lessons Learned from application

<u>Thickness Indicators</u>

If using thickness indicators, a rigid item should be used to ensure it maintains its intended position – perpendicular to the host pipe. Zip ties used at two of the sites began to lean over after each application which meant this method of verifying design thickness was not reliable.

<u>Thickness Testing</u>

Final thickness verifications should be completed prior to demobilization. When NBDTI workers went to verify final thickness, it was found that, in general, design thickness was not achieved. By this time, the Contractor had already demobilized. It would have been simpler to complete this testing with the Contractor on site.

<u>Curing</u>

It must be verified that the product has cured sufficiently throughout the *entire* culvert prior to redirecting stream flow through the culvert. The contract stated that "The material must be allowed to cure a minimum of 6 hours or until the material has reached a final set condition - whichever is longer - prior to the release of flow through the pipe."

After applying the final application at the 4th site (DE03), the material was left to cure overnight prior to redirecting the flow through the culvert. The following morning, the Contractor checked the inlet end to ensure it was fully cured, however did not check the outlet end, which was the last segment of the culvert to be sprayed.

Later that morning – after stream flow was returned to the culvert - Design Branch staff visited the site. They entered from the inlet end and walked through the entire pipe. When they arrived near the outlet, they observed that the final application had not cured sufficiently prior to being exposed to the stream flow. This was evident by the presence of rippled bedforms near the outlet of the culvert.

<u>Timing of Work</u>

With governmental approval given in September, the field trial only began in October and was completed November 26. This, combined with malfunctions in the Contractor's rented mixing and spray equipment, meant that there was more pressure to demobilize and move to the next site which led to some quality control measures not being followed. Although the decision was made to delay the 5th and final site to 2022, in hindsight, it is the Department's opinion that this type of work should not extend beyond the end of October in New Brunswick.

The fall season is not an ideal time to complete this type of work. There are fewer appropriate windows of opportunity to apply the product within acceptable ambient temperatures. The duration of the project is increased due to being limited to completing one application per day due to decreased hours of sunlight. The fall season also tends to present higher water surface and groundwater levels which make it more difficult to properly dewater the culvert prior to applying the product.

Change to Process

Upon completion of final thickness testing by Department staff and the ensuing discovery that the product was not uniformly placed and that design thicknesses were not met, a progress meeting was held with the Contractor to discuss the outcome. The Contractor agreed to develop a proposal to address the fact that design thickness was not achieved. The proposal outlines that 3 of the 4 sites that underwent geopolymer application in the fall of 2021 will be revisited to complete an additional application and meet design thickness throughout the entire length of the culverts.

The proposal also outlines that the one remaining site, which was not begun in 2021, will undergo interim thickness verifications after each application while the material is still in the plastic state. This will give a better understanding of the exact thickness of each pass.

The Contractor agrees to ensure the entire application is cured prior to redirecting the stream flow through the culvert and that demobilization will not occur until design thicknesses are verified to have been achieved.

Discussion

For inclusion of this Spray Applied Liner method and geopolymer product on NBDTI qualified product list can be approved in three ways. The first way is that NBDTI design engineers have, for an extended period, used the method and materials and are generally accepting of the result. The results are that NBDTI design engineers or their consultants specify the method and/or product on an on-going basis. This is general acceptance and historical use and the reason that most products appear on the NBDTI qualified product list. This reason could not be used by NBDTI because the geopolymer product was essentially unknown to NBDTI, first being used by industry in 2011. However, contractors in New Brunswick were not routinely using geopolymer products and consultants were not specifying geopolymers. In 2016, NBDTI carried out a trial of the spray applied liner method on two culverts, however the product used was Portland cement. There was no formal inclusion of that method and materials into NBDTI's Qualified product list. This geopolymer material could not be approved under the historically used product reasoning.

The second reason for product qualifications, is that the method and/or product is widely accepted in the industry, on a national or international basis. There needs to be ample indications of other Transportation agencies reporting that their experience or trials are successful. This also should be supported by academic research. Although NBDTI engineers search for these documented success stories, approvals and academic publications, these were difficult to find or not readily available. Agencies such as Ontario Ministry of Transportation and British Columbia Ministry of Transportation were still in their product trial stage. Therefore, NBDTI could not use this second reason to qualify geopolymers for use in NBDTI tenders.

The third avenue for NBDTI to qualify geopolymers was the only one left of the three reasons to qualify a product. It was determined that NBDTI should conduct its own Research Trial. The outcome will inform the decision on whether to add the product to the qualified list or not.

Design recommendations will be produced. This paper outlined this third method. The trial was conducted in-house and our conclusions are intended for use by NBDTI. The conclusions made from the trial are outlined below.

Conclusion

With the great need to repair and replace failing corrugated steel pipes in New Brunswick, it is of much benefit to have many repair options available to NBDTI design engineers and their consultants. The results of the field trial are of great interest to the Department. Conclusions drawn at this stage of the field trial are listed below.

- It is recognized that significant effort in hydraulic analysis, environmental review, liaison with various regulatory agencies, and site access considerations is required to fully understand whether any given method of culvert rehabilitation is appropriate. Due to limitations of time and resources, the selection process outlined in this paper was utilized to focus efforts on a small subset of candidates at the initial screening stages, and in doing so did not uncover a complete set of all culvert rehabilitation candidates within the inventory. It is currently unknown what proportion of NBDTI's overall large culvert inventory are feasible candidates for any given type of culvert rehabilitation method.

- There is not a clear consensus within the industry of the best materials to use on spray applied liner project for highway culverts.

- NBDTI saw the potential benefits of this method and the material used in the trial. The 2022 and 2023 observations of the completed culverts will be necessary before it can be determined if geopolymers should be included on NBDTI qualified product list.

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