DEPARTMENT OF TRANSPORTATION

Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content

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Final Report 2025-32

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The objective of the research project was to compare the performance of corrugated high-density polyethylene (HDPE) pipes manufactured with recycled content to those manufactured with only virgin materials. MnDOT currently requires HDPE pipes to be made with 100% virgin materials. However, recent changes to American Association State Highway and Transportation Officials (AASHTO) M 294 include the option for pipes manufactured with post-consumer and post-industrial recycled content, both of which have been shown to be more sustainable materials than virgin HDPE. The research project involved the installation of two 36-in. diameter corrugated HDPE pipes — one manufactured with 100% virgin materials and the other with a blend of virgin and post-consumer recycled materials — underneath a roadway near Fosston, MN. A life-cycle assessment was conducted to compare the environmental impact of the virgin pipe with the pipe manufactured with recycled content, and a cost analysis was conducted to estimate the cost savings of incorporating pipes manufactured with recycled content to the state of Minnesota. The research project showed that the virgin and recycled pipes are performing comparably and that the pipes manufactured with recycled content offer significant environmental benefits and potential cost savings. Due to installation and measurement issues, both the virgin and recycled pipes appear to be deflected beyond MnDOT requirements, and it is recommended that they continue to be monitored.

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List of Abbreviations

AASHTO: American Association of State Highway and Transportation Officials
ADT: Average daily traffic
AP: Acidification potential
ASTM: ASTM International
CMP: Corrugated metal pipe
EP: Eutrophication potential
EPA: United States Environmental Protection Agency
GWP: Global warming potential
HDPE: High density polyethylene
LCA: Life-cycle assessment
LCCA: Life-cycle cost analysis
LCI: Life cycle inventory analysis
LCIA: Life cycle impact assessment
MnDOT: Minnesota Department of Transportation
OZDP: Ozone depletion potential
RCP: Reinforced concrete pipe
SP: Smog potential
TH: Trunk highway
UMD: University of Minnesota - Duluth

Executive Summary

According to the United States Environmental Protection Agency, approximately 14.5 million tons of plastic containers and packaging were processed as municipal solid waste in 2018 (EPA, n.d.). Recent nationally funded research projects have shown that corrugated HDPE pipes used for highway and railroad drainage applications can be a good use for these recycled plastic materials, keeping them out of our landfills and mitigating the potential for plastic pollution (Pluimer, 2016; Pluimer & Sprague, 2018). Based on this research, the AASHTO and ASTM specifications for corrugated HDPE pipes were changed to allow the use of post-consumer and post-industrial materials in the manufacturing of corrugated HDPE pipes (ibid.). MnDOT currently does not allow the use of corrugated HDPE pipes manufactured with recycled content, and it specifies that corrugated HDPE pipes must be manufactured with 100% virgin materials when used in state DOT applications. The objective of this research project was to compare the performance of corrugated HDPE pipes manufactured with recycled materials to those manufactured with only virgin materials to determine their suitability for culvert and storm sewer applications for MnDOT. In addition, the research project provided an environmental and economic assessment of these materials for MnDOT applications.

To compare the performance of corrugated HDPE pipes manufactured with recycled content to those manufactured with only virgin materials, both types of pipes were procured and installed underneath Minnesota State TH2 near Fosston, MN. The pipes were donated by Advanced Drainage Systems, Columbus, OH, with the virgin pipe manufactured in accordance with AASHTO M 294V and the recycled pipe manufactured in accordance with AASHTO M 294R. The selected site was on the west side of Fosston and involved the replacement of a 140-ft (43 m) long, 24-in. (600 mm) diameter reinforced concrete pipe (RCP) culvert that had been failing due to joint separation and infiltration of backfill materials. The 24-in. (600 mm) reinforced concrete pipe (RCP) culvert was deemed to be too small to accommodate the hydraulic flows in the area, so a 36-in. (914 mm) diameter corrugated HDPE culvert was chosen for the replacement. The culvert replacement was associated with SP 6005-68 on TH2, which was constructed in the Spring of 2022.

Prior to installation, sections from each type of culvert (one manufactured with only virgin materials and the other containing recycled content) were instrumented with strain gauges and string potentiometers to monitor and compare the performance of the virgin and recycled HDPE pipes under live traffic loading. The corrugated HDPE pipes were installed in general accordance with MnDOT specifications, though the contractor used greater lift heights than recommended by MnDOT. The pipes were installed underneath the eastbound lanes on June 2, 2022, and underneath the westbound lanes on August 11, 2022. The pipes underneath the eastbound lanes were not instrumented. The height from the top of the culvert to the bottom of the asphalt pavement was around 4 ft. 9 in. (1.4 m).

Unprecedented rainfall throughout the summer months of 2022 resulted in unsafe conditions to enter the culvert to connect the data acquisition system, and data collection was delayed until spring 2023. Unfortunately, most of the sensors did not survive the harsh winter conditions, and the pipes remained flowing full or nearly full for most of 2023 and 2024. Because of this, we were not able to install new

sensors in the pipes within the timeframe of this project. We are still hopeful to do this in summer 2025, provided the pipes are either dewatered or dry out enough for safe access. These high water levels were not anticipated at the outset of the project, as the previous culvert was not flowing full at the time of the installation.

The pipe deflections were physically measured periodically throughout the project, although measurement was difficult given the high water conditions and presence of sediment at the invert. Some of the vertical deflections appear to have exceeded MnDOT's 5% limit, but the measurement methods were not very precise due to the difficulty in entering the pipes and dealing with flowing water. The reason for the potentially excessive deflections is most likely due to errors in compaction during installation as well as measurement errors due to high water levels and sediment in the invert of the pipes. There were no discernible differences between the virgin and recycled HDPE pipes, and the overall function and performance of the pipes has been satisfactory. The recycled HDPE pipes have slightly lower deflections than the virgin HDPE pipes, but they are comparable within measurement error. The pipes do not appear to have changed in diameter or performance from the June 12, 2023, to the April 28, 2024, inspection dates.

A modified life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) was conducted to compare the pipes manufactured with virgin materials (AASHTO M 294V) to those manufactured with recycled content (AASHTO M 294R). The LCA showed that corrugated HDPE pipes manufactured with recycled materials offer environmental benefits in the majority of impact categories relative to traditional pipe materials based on standard life-cycle assessment methodologies. The LCCA showed potential cost savings associated with the specification of corrugated HDPE pipes manufactured with recycled content. An example LCCA was conducted based on established ASTM methodologies. The example analysis showed that HDPE pipe manufactured with virgin materials offers life-cycle cost savings of 34% over RCP and 45% over corrugated metal pipe (CMP), while corrugated HDPE pipe manufactured with recycled materials offers life-cycle cost savings of 39% over RCP and 49% over CMP.

Based on this research project, it is recommended that MnDOT consider the allowance of corrugated HDPE pipes manufactured with recycled content in accordance with AASHTO M 294R for its culvert and storm drainage applications. The AASHTO M 294R pipes performed comparably to the AASHTO M 294V pipes, and the pipes are still performing well in the 3rd year of service. An LCA showed significant environmental benefits to using corrugated HDPE pipes manufactured with recycled content, and an LCCA showed some potential economic savings.

Chapter 1: Introduction

According to the United States Environmental Protection Agency, approximately 14.5 million tons of plastic containers and packaging were processed as municipal solid waste in 2018 (EPA, n.d.). Recent nationally funded research projects have shown that corrugated HDPE pipes used for highway and railroad drainage applications can be a good use for these recycled plastic materials, keeping them out of our landfills and mitigating the potential for plastic pollution (Pluimer, 2016; Pluimer & Sprague, 2018). The research spanned a period of over 10 years and included testing of hundreds of blends of post-consumer and post-industrial recycled materials, as well as the fabrication and installation of full-scale pipes manufactured with these materials. The research included the development of a new test method (the Un-notched Constant Ligament Stress or UCLS Test, published in ASTM F3181 (ASTM, 2024), to evaluate the effects of contaminants on the stress cracking mechanism of HDPE. The test method is used to determine the service life of corrugated HDPE pipes manufactured with recycled content and was validated on multiple full-scale installed pipes and incorporated into the AASHTO M 294 standard. Based on this research, the AASHTO and ASTM specifications for corrugated HDPE pipes were changed to allow the use of post-consumer and post-industrial materials in the manufacturing of corrugated HDPE pipes (Pluimer & Sprague, 2018; ASTM, 2023). MnDOT currently does not allow the use of corrugated HDPE pipes manufactured with recycled content, as they specify that corrugated HDPE pipes must be manufactured with 100% virgin materials when used in state DOT applications (MNDOT, 2018). The objective of this research project was to compare the performance of corrugated HDPE pipes manufactured with recycled materials to those manufactured with only virgin materials to determine their suitability for culvert and storm sewer applications for MnDOT. Additionally, the research project provided an environmental and economic assessment of these materials for MnDOT applications.

From an environmental standpoint, corrugated HDPE pipes manufactured with recycled content offer several advantages over products manufactured with only virgin materials. First, the incorporation of post-consumer and post-industrial recycled materials into corrugated HDPE pipes allows for the diversion of these materials from landfills and reduces the carbon footprint associated with the manufacturing of raw materials for the pipes. Life-cycle assessment (LCA) research has shown that pipes manufactured with recycled content have a lower carbon footprint than pipes manufactured with only virgin materials (Franklin Associates, 2021). Additionally, plastic pollution has become a growing problem on our planet, and a large driver of this is single-use plastics that make their way into our lakes, streams, and rivers. Allowing post-consumer recycled materials into corrugated HDPE pipes will provide a responsible outlet for this plastic waste that will ultimately serve to clean up our planet.

From an economic perspective, corrugated HDPE pipes manufactured with recycled materials can offer significant cost benefits relative to traditional pipe materials as well as corrugated HDPE pipes manufactured with only virgin materials, based on standard life-cycle cost assessment methodologies (ASTM, 2013, 2014, 2015). One of the reasons for this is that recycled plastic materials typically cost less than virgin plastic materials, though it is often dependent on the current market conditions and supply.

Additionally, the inclusion of recycled products into the transportation market ultimately aids in lowering the overall costs due to competitive bidding of materials (Maher et al, 2015)

To develop a quantitative comparison of the performance of pipes manufactured with and without recycled content, two 36-in. (900 mm) diameter culvert pipes were installed underneath Minnesota State Trunk Highway 2 near Fosston, MN. The first pipe was manufactured in accordance with AASHTO M 294V and contained 100% virgin materials; the second pipe was manufactured in accordance with AASHTO M 294R and contained approximately 60% recycled content. The pipes replaced a 24-in. diameter concrete culvert that was failing due to joint separation and infiltration of backfill materials. Materials and finished product testing were conducted on both pipes to ensure their compliance with their respective AASHTO materials specification. The climate in this region of Minnesota typically has very warm and humid summers, with temperatures exceeding 90 deg. F (30 deg. C), as well as very severe winters, with temperatures often well below 0 deg. F (-17 deg. C). The extreme temperature changes should not adversely affect the performance of corrugated HDPE pipes, as the glass transition temperature of HDPE is around -100 deg. C. Additionally, the corrugated exterior of the pipes serves to mechanically interlock the pipe with the soils, preventing any potential movement of the joints due thermal expansion and contraction.

Additionally, to determine the environmental and economic impacts of the two plastic types, a life-cycle analysis (LCA) and a life-cycle cost analysis (LCCA) were conducted for both the virgin and recycled pipes. While a complete LCA was outside the scope of this project, existing literature was reviewed to provide an estimate of the environmental impacts for each type of pipe given the installation conditions and location of the project.

Chapter 2: Instrumentation and installation of pipes

2.1 Overview of Test Site

The research team at the University of Minnesota – Duluth worked with MnDOT Assistant State Hydraulic Engineer Erik Brenna, P.E. and MnDOT District 2 Water Resources Engineer Rachel Miller, P.E. to identify an appropriate test site for this research project. The selected test site was on the west side of Fosston, MN and involved the replacement of a 24-in. (600) diameter reinforced concrete pipe (RCP) culvert with a 36-in. diameter corrugated HDPE culvert underneath TH2. The RCP culvert was failing due to joint separation and soil infiltration through the joints, and it was also deemed to be undersized. Figures 2.1 and 2.2 show the location of the site in the state as well as an aerial image of the site. The culvert replacement is associated with SP 6005-68 on TH2, which was constructed in the Spring of 2022. The average daily traffic (ADT) on this portion of TH2 was estimated to be 3,800 vehicles per day per MnDOT reports. The climate in this region of Minnesota typically has warm and humid summers and severe winters. The extreme temperature changes should not adversely affect the performance of corrugated HDPE pipes, as the glass transition temperature of HDPE is around -100 deg° C, well below the anticipated low temperatures in this region (a record low in this region of Minnesota would be around -40° C). Additionally, the corrugated exterior of the pipes serves to mechanically interlock the pipe with the soils, preventing any potential movement of the joints due thermal expansion and contraction.

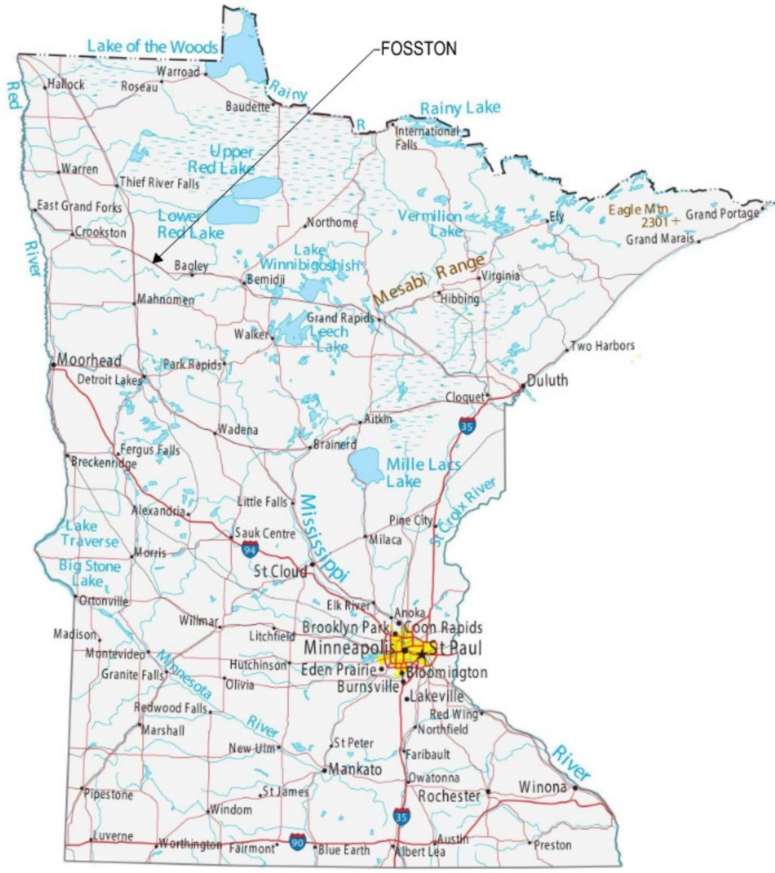

Figure 2.1: Location of culvert on TH2, west of Fosston, MN

Figure 2.2: Location of culvert on TH2, west of Fosston, MN

The pipes for the project were supplied by Advanced Drainage Systems, headquartered in Columbus, OH. Standard corrugated HDPE pipes are manufactured in 20-foot (6 m) lengths, and it was determined that approximately 140 feet (42 m) of pipe were needed for this culvert. Three sticks of 36-in. (900 mm) diameter pipes (60 feet) were manufactured with recycled content in accordance with the AASHTO M 294R specification, and four sticks of 36-in. (900 mm) diameter pipes (80 feet) were manufactured with virgin materials in accordance with the AASHTO M 294V specification. All pipes utilized a bell-and-spigot style watertight joining system. The pipes were shipped to the test site on May 16, 2022. For the installation, it was decided to alternate pipe types to help randomize and mitigate any concerns due to construction variability along the length of the trench.

2.2 Instrumentation of Test Pipes

Due to the aggressive construction schedule, it was decided to instrument the pipes underneath the westbound lanes only, as the eastbound lanes were being constructed first. Both virgin and recycled test sections were instrumented with Celesco string potentiometers to measure deflections and strain gages to measure wall strains. The pipes were instrumented in the Civil Engineering lab at the University of Minnesota – Duluth under guidance from Scott Norr (Electrical Engineering department) and

Instrumentation Resources in Maple Grove, MN. A schematic of the instrumented pipe sections is shown in Figure 2.3 and details of the sensors are shown in Table 2.1.

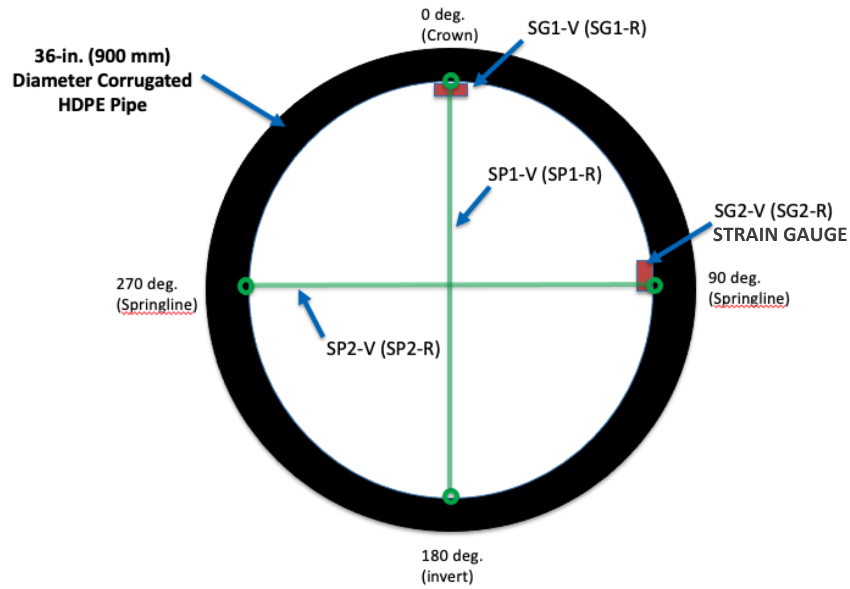

Figure 2.3 Schematic of sensors installed on test pipes

Table 2.1: Description of sensors installed on test pipes

Sensor ID	Sensor Type	Sensor Location	Sensor Model
SP1-V	String Potentiometer	Virgin pipe, vertical	Celesco SP3-50
SP2-V	String Potentiometer	Virgin pipe, horizontal	Celesco SP3-50
SP1-R	String Potentiometer	Recycled pipe, vertical	Celesco SP3-50
SP2-R	String Potentiometer	Recycled pipe, horizontal	Celesco SP3-50
SG1-V	Linear Strain Gage	Virgin pipe, crown (0°)_	MM C4A-06-125SL-350
SG2-V	Linear Strain Gage	Virgin pipe, springline (90°)	MM C4A-06-125SL-350
SG1-R	Linear Strain Gage	Recycled pipe, crown (0°)_	MM C4A-06-125SL-350
SG2-R	Linear Strain Gage	Recycled pipe, springline (90°)	MM C4A-06-125SL-350

Prior to application of the strain gages, the inner wall surfaces were cleaned with isopropyl alcohol. A two-part polysulfide liquid polymer M-Coat® sealant and adhesive strips were used to waterproof and seal the gauges to protect them during service, as shown in Figures 2.4 and 2.5. The string potentiometers were fastened to the pipes with screws, and an eye hook was positioned on the opposite end of the pipe on which to attach the retractable wire while taking measurements, as shown in Figure 2.7. Since the string potentiometers were retractable, they could be retracted during service so as not to impede the flow of water in the pipe. A laser level was used to determine the horizontal, vertical, and diagonal positioning of the instruments within the pipe during installation to ensure the sensors were positioned properly for each pipe, as shown in Figure 2.6.

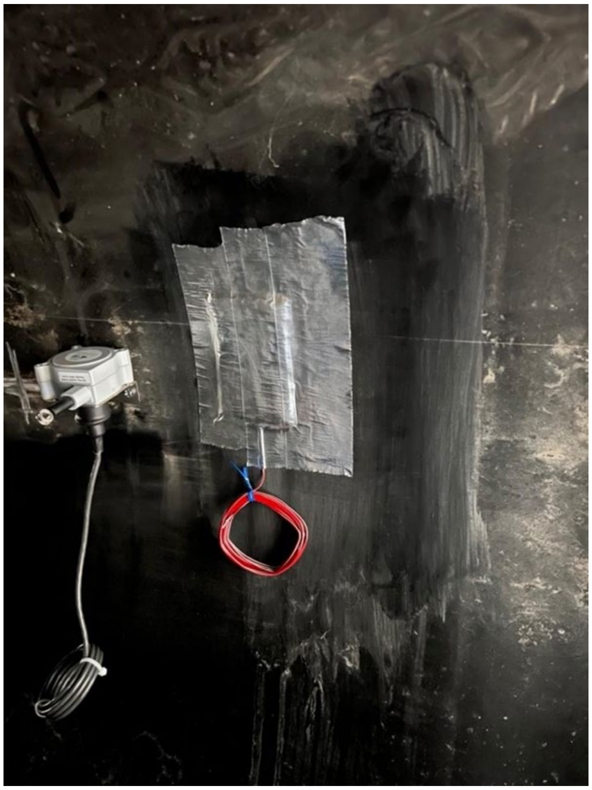

Figure 2.4 Vertical strain gauge on crown of recycled pipe (SG1 R)

Figure 2.5 Vertical strain gage on crown of recycled pipe (SG1-R)

Figure 2.6 Using lasers to align instrumentation

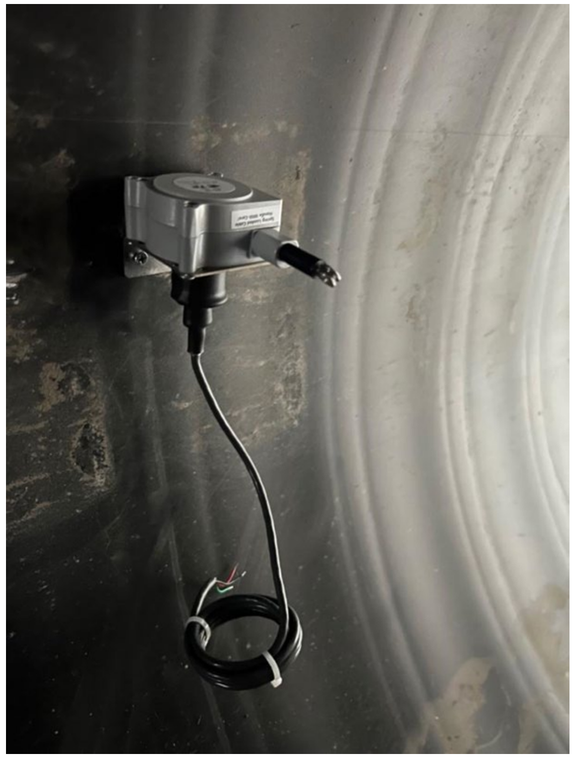

Figure 2.7 Horizontal string potentiometer in recycled pipe (SP2-R)

Following the instrumentation of the test pipes, they were loaded onto a truck and shipped to the test site near Fosston, MN. Figure 2.8 shows the pipes loaded onto a truck and departing UMD.

Figure 2.8 Instrumented test pipes loaded onto a truck at UMD to be shipped to test site

2.3 Installation of Test Pipes

Since the primary objective of this research project was to compare the performance of corrugated HDPE pipes manufactured with recycled materials (AASHTO M 294R) to those manufactured with only virgin materials (AASHTO M 294V), it was paramount that both types of pipes were installed in a similar manner. Since approximately 140 feet (42 m) (seven sticks) of pipe were needed for the culvert, it was decided to alternate pipe types to help randomize and mitigate any concerns due to construction variability along the length of the trench.

The eastbound lanes of TH2 were constructed first, and it was decided to install uninstrumented sections of pipes underneath these lanes so that the instrumented sections of pipes would be easier to access from one side of the culvert. The installation of these pipes took place on June 2, 2022, and was supervised by MnDOT personnel as well as the UMD research team (Professor Michael Pluimer and Graduate Student Katie Padden). The instrumented pipe sections were installed underneath the westbound lanes on August 11, 2022, and the installation was monitored by MnDOT personnel as well as Katie Padden and Mahsa Salimigamasaei (UMD Graduate Students).

The steps of the installation process are detailed below, with a focus on the installation of the instrumented sections under the westbound lanes.

2.3.1 Installation of Pipes Underneath the Eastbound Lanes

The uninstrumented pipes were installed underneath the eastbound lanes on June 2, 2022. Figures 2.9 – 2.16 detail the installation process. The pipes were installed in general accordance with MnDOT specifications, though a few exceptions were made based on consultation with the pipe manufacturer. The trench was wrapped in geotextile fabric (SKAPS GT-112) to mitigate the migration of fines into the structural backfill materials (Figure 2.9), and an 18-in. (450 mm) layer of MnDOT Class 5 fine aggregate bedding materials was placed and compacted onto the fabric to ensure proper support to the pipes, followed by a 6-in. layer of uncompacted material to provide a cradling effect for the pipe (Figure 2.10). Care was taken to knife the backfill materials into the haunch zone (Figure 2.11) to ensure adequate support for the pipes, and the backfill materials were compacted in approximately one- to two-foot lifts (Figure 2.12) until the materials were approximately 12 inches (300 mm) above the pipe, based on recommendations from the contractor. It should be noted that MnDOT specifications require installation and compaction of backfill materials in 6-in. lifts, per Technical Memorandum 17-05-B-02 Attachment D, rather than the one- to two-foot lifts used by the contractor. The same installation process was followed for the pipes installed underneath the westbound lanes (Section 2.3.2), and additional details of the installation process are described in that section.

Figure 2.9 Wrapping the trench in geotextile to prevent mitigation of fines into backfill

Figure 2.10 Installation of first stick of pipe (M 294 V) onto uncompacted bedding

Figure 2.11 Knifing backfill materials into the haunch area to ensure adequate support

Figure 2.12 Compaction of backfill materials in lifts with vibratory compactor

The second stick of pipe (M 294 R) was joined to the first M 294 V pipe via the standard bell-and-spigot watertight joint utilizing an elastomeric gasket in accordance with MnDOT standard 2501 C.4

specifications (Figure 2.13). The pipe was installed in a similar manner to the first stick of pipe, with care being taken to ensure knifing of backfill materials into the haunches as well as compaction in two-foot (600 mm) lifts along the sides of the pipe. A third stick of M 294 V pipe was then installed (Figure 2.14), and a small adapter of M 294 R pipe was installed to connect to the existing 24-in. (600 mm) diameter reinforced concrete culvert that was being replaced (Figure 2.15). After installation, the joints were inspected to make sure the pipes were properly seated (Figure 2.16).

Figure 2.13 Joining of second stick of pipe (M 294 R) to first stick (M 294 V) via bell-and-spigot watertight joint

Figure 2.14 Installing a third stick of pipe

Figure 2.15 Installation of temporary connector of M 294 R pipe to existing 24-in. RCP culvert until westbound lanes are constructed

Figure 2.16 Inspection of joint gaps to ensure proper seating of joints

2.3.2 Installation of Pipes Underneath the Westbound Lanes

The installation of the pipes underneath the westbound lanes took place on August 11, 2022. Due to unforeseen flooding located at the construction site west of Fosston, MN, accommodations for the higher water levels were needed to mitigate the surrounding soil from becoming too saturated. Such accommodations included the use of flood bags and compacted black dirt and clay to hinder the flooding. It is not believed that any significant saturation of soils beds resulted from the temporary culvert attachment.

After removal of the pre-existing 24-in. (600 mm) diameter reinforced concrete culvert pipe that was being replaced due to capacity insufficiency and failures at the joints, the trench was extended to a width of ten feet to accommodate the 36-inch (900 mm) diameter corrugated HDPE pipes. This is in compliance with MnDOT's minimum trench width specifications for plastic pipes, which requires a minimum trench width of 9 ft. 6 in. (2.9 m) for a flexible pipe of this diameter.

The pipes underneath the westbound lane were installed in accordance with the drawing shown in Figure 2.20, with an M 294 R pipe being coupled to the previously installed pipe from the eastbound lanes, followed by an instrumented virgin pipe, an instrumented recycled pipe, a non-instrumented recycled pipe, and a partial non-instrumented virgin pipe. As described in Section 2.3.1, a SKAPS GT-112 geotextile fabric was laid down to mitigate migration of fines into the structural backfill material. MnDOT Class 5 fine aggregate bedding was placed on the geotextile fabric to serve as a bedding for the corrugated HDPE pipes, with a bedding thickness of 18 inches in accordance with MnDOT Specification 2106. The bedding was compacted with the bucket on a Komatsu PC270LC hydraulic excavator. Next, six inches of additional Class 5 materials were loosely placed to grade on the previously compacted 18 inches of bedding, establishing a cradling effect for the corrugated flexible pipe, which complies with MnDOT specification 3149.2.G.1. After the grade was finalized, the culverts were set into place using nylon straps connected to the D-ring attached to the excavator. Figure 2.18 shows some images of the placing of the bedding material and the initial M 294V pipe.

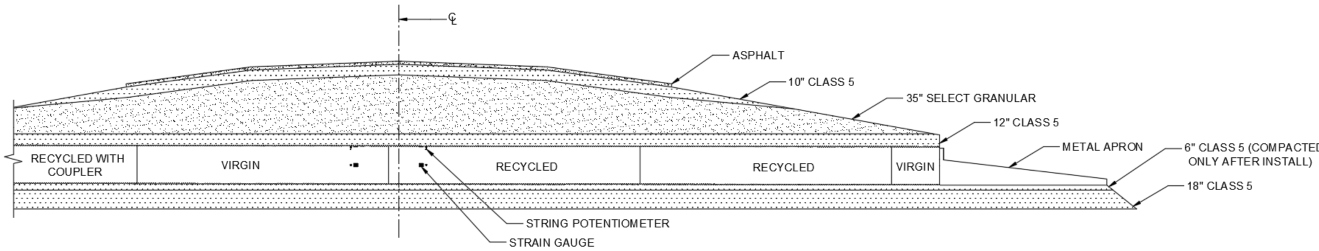

Figure 2.17 Layout of the pipes installed underneath the eastbound lanes

Figure 2.18 Placement of bedding material and initial pipe for installation underneath westbound lanes

The split coupler that was used to connect the existing M 294 R recycled pipe underneath the eastbound lanes to the M 294 R pipe underneath the westbound lanes was wrapped in geotextile fabric to mitigate soil migration into the joint, as shown in Figure 2.19.

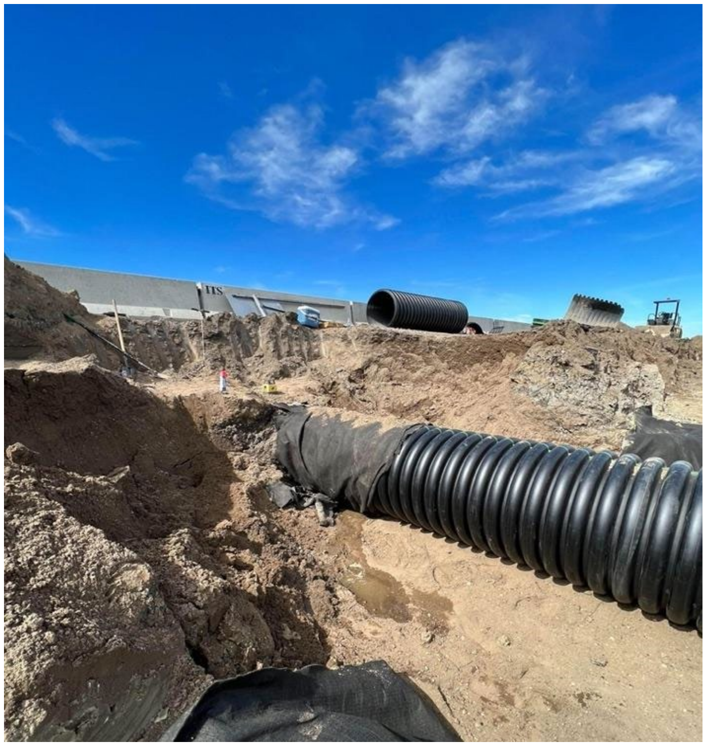

Figure 2.19 Split coupler joining pipe underneath westbound lanes to that previously installed underneath eastbound lanes

For ease of construction, the green lines that were printed on the exterior of the pipes by the manufacturer and run longitudinally along the entire length of the culverts were aligned vertically to ensure the sensors receive the correct directional loading for testing. As discussed in Section 2.3.1, the Class 5 backfill was to be installed in a series of 6-inch (150 mm) lifts in accordance with MnDOT specifications, with each lift being compacted with a jumping jack. However, based on contractor recommendations, greater lift heights of fill were used (it was estimated that the lift heights were one to two feet). The initial lift was shoveled into the haunch zone (a process also known as "knifing") to ensure support, and the handle of the shovel was used to ensure materials were compacted into the valleys of the corrugations. See Figure 2.20 for some images of the installation of the backfill materials.

Above the springline, the backfill materials were uniformly compacted in lifts across the entire span according to MnDOT specification 2106 (MNDOT, 2018). This process continued until the final lift was 12 inches (300 mm) above the crown of the culvert. The remaining backfill above this was composed of select granular material, which was then compacted using a single drum vibratory compactor directly above the culvert. The subgrade above the backfill was constructed of 10 inches (250 mm) of Class 5 soil, and an asphalt surface was paved on top. The asphalt composition consists of a non-wearing course bituminous mixture with a wear course bituminous asphalt. A graphic of the installation cross-section is shown in Figure 2.21. There was approximately 4 ft. 9 in. (1.4 m) of cover from the top of the pipe to the bottom of the asphalt.

Figure 2.20 Installation of backfill materials around culvert pipes; a shovel was used to knife backfill materials into the haunch area, and a jumping jack compactor used to compact lifts

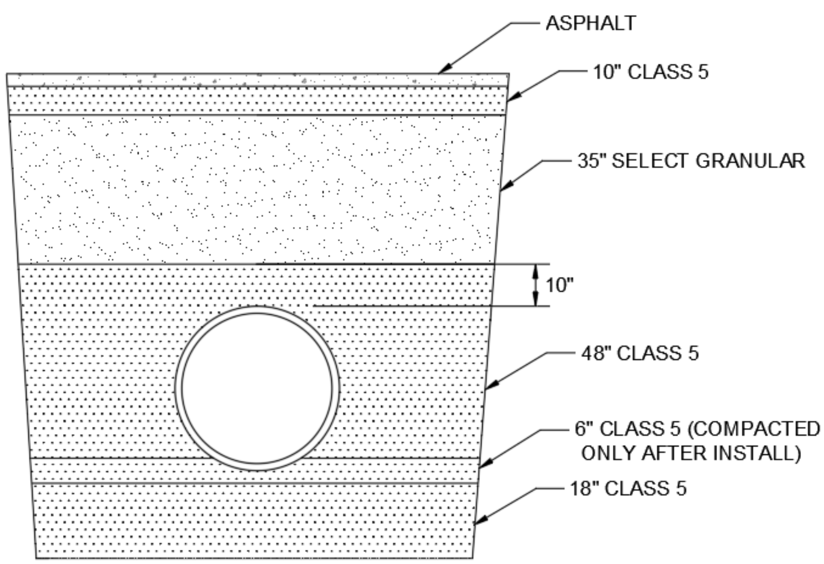

Figure 2.21 Cross-section of culvert installation

2.3.3 Sensor Positioning with Respect to Traffic Loading

The location of the string potentiometers and strain gauges are based on an AASHTO design truck, with an axial width of 6 ft. (1.8 m) Each lane width is 12 ft (3.7 m) across; therefore, assuming the design truck will be located roughly in the center of each lane, the sensors were placed three feet on either side with respect to the centerline (AASHTO 3.6.1.2.2). See Figure 2.22 for an illustration of an AASHTO HS-20 design truck used for placement of sensors.

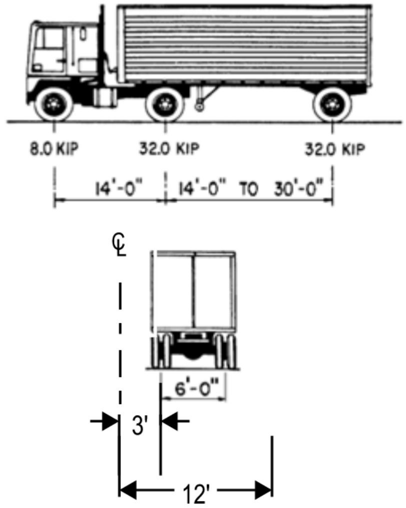

Figure 2.22 AASHTO HS-20 truck used for placement of instrumentation

2.3.4 Initial and Post-compaction Deflection Measurements

In-situ deflection measurements of the westbound instrumented pipes were taken using a Bosch BLAZE digital measuring tape, which is accurate to 1/32 of an inch. To ensure the measurements were taken in the same location prior and post-installation, markers were lightly etched into the sides of the culvert. Table 2.2 shows the initial vertical, horizontal, and diagonal measurements of each pipe, both before and after construction, as well as the calculated deflections. As demonstrated in the table, the deflections were below MnDOT's required 5% limit. Figure 2.23 depicts a visual comparative analysis of the deflection experienced prior to and post-installation.

Ultimately due to severe flooding of the Fosston area abruptly after installation, interior water levels were too high to initiate deflection measurements within thirty days due to hazardous working conditions (Figure 2.24). This was a deviation from MnDOT standard 2501 C.4.

Table 2.2: Physical measurements of pipes before and after construction

Virgin HDPE Pipe (AASHTO M 294 V)			
Direction of Measurement	**Pre-Construction Diameter**	**Post-Construction Diameter**	**Deflection (Percent)**
Horizontal	35.72 in.	36.81 in.	3.1
Vertical	36.06 in.	34.44 in.	-4.5
Diagonal	35.91 in.	35.00 in.	-2.5

Recycled HDPE Pipe (AASHTO M 294 R)			
Direction of Measurement	**Pre-Construction Diameter**	**Post-Construction Diameter**	**Deflection (Percent)**
Horizontal	35.81 in.	36.25 in.	1.2
Vertical	35.91 in.	35.00 in.	-2.5
Diagonal	35.94 in.	36.38 in.	1.2

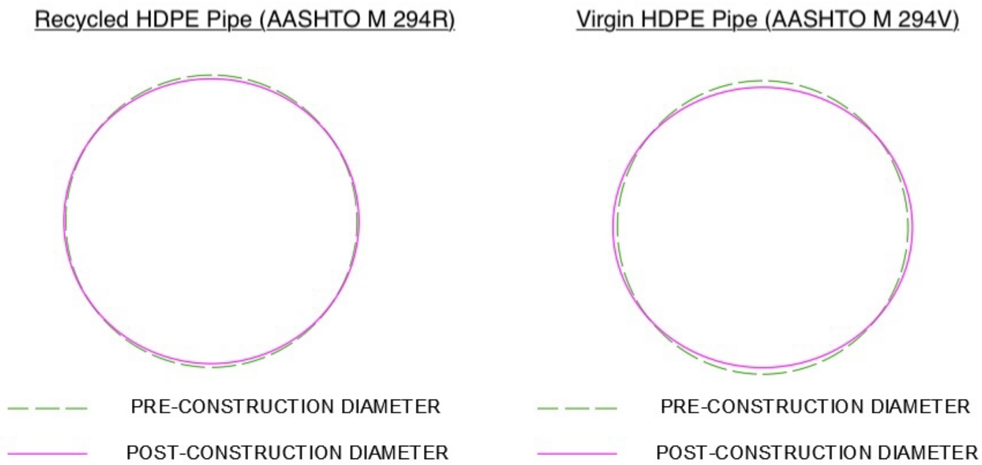

Figure 2.23 Illustration of culvert deflection prior and post construction

Figure 2.24 Photograph of culvert taken 30 days after installation

Chapter 3: Monitoring and Analysis of Pipes

3.1 Project Overview

The primary objective of this research project was to compare the performance of corrugated HDPE pipes manufactured with recycled resin (AASHTO M 294R) to those manufactured with only virgin resin (AASHTO M 294V) for culvert applications.

To quantitatively compare the effects of dynamic and static loading, one of each culvert type was procured from Advanced Drainage Systems and installed underneath Minnesota State TH2 near Fosston, MN. One section of the M 294R pipe was instrumented with strain gauges and string potentiometers, as was one section of M 294V pipe. The strain gauges and potentiometers were installed on the inner crown and springline of the pipes to compare the wall strain and deflection generated from the effects of live traffic loading. A cross-sectional layout of the culvert installation is shown in Figure 3.1. As indicated in this image, the instrumented pipes are located on each side of the westbound centerline, with the virgin pipe to the south and the recycled pipe to the north. Further details of the installation were provided in the Chapter 2.

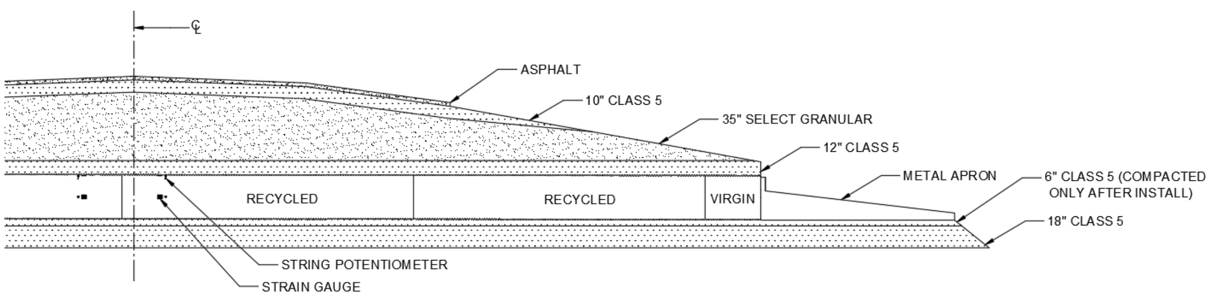

Figure 3.1: Cross section of culvert layout

In the research contract, it was agreed to include approximately eight days of loading analysis to be conducted throughout the fall of 2022 and spring and summer of 2023. However, due to continuously high water levels in the culvert, it was not possible to enter the pipes and hook up the instrumentation throughout this entire time period. These high water levels were not anticipated at the outset of the project, as the previous culvert was not flowing full at the time of the installation.

3.2 Monitoring of Pipes

Throughout the fall of 2022 and the spring and summer and 2023, the culvert's water table was frequently monitored for a safer depth to enter. Figures 3.2 – 3.6 show images of the culvert throughout this timeframe. As indicated in these images, the water depth was too high to safely enter the culvert for inspection. We discussed some dewatering options for the culvert, but we had difficulty identifying a contractor capable of that work, and we did not want to disrupt traffic on the roadway.

Figure 3.2: September 10, 2022 water level

Figure 3.3: October 13, 2022 water level

Figure 3.4: November 10, 2022 water level

Figure 3.5: May 25, 2023 water level

Figure 3.6: June 2, 2023 water level

On June 12, 2023, the water level had finally receded enough to enter the culvert to take some measurements and inspect the instrumentation. Figure 3.7 shows some images of the culvert at this time, indicating that the water level was just below the springline of the pipe, leaving approximately 18 inches of air space above the water to the top of the pipe. While these water levels were still quite high, entry into the culvert was possible, and we were able to inspect the strain gauges, string potentiometers, and joints. Upon inspection, the strain gauges appeared to still be intact, with the two-part polysulfide liquid polymer M-Coat® sealant and adhesive strips holding. However, we were not able to test the electrical function of the gauges as the water levels were too high to safely test. Additionally, due to the continuously high water levels and the subsequent freezing and thawing of the ice over the winter and spring, the string potentiometers were seized up. Specifically, the spring coils attached to the retractable wires in all of the string potentiometers had seized. Therefore, if live-load data is to be eventually collected, the string potentiometers will have to be replaced or a different measurement method employed.

We were able to take some physical measurements of the pipe at this time. A tape measure was used for these measurements, but it was not the most accurate method, especially given the high water depths and sediment at the invert of the culvert. The measurements are shown in Table 3.1.

Figure 3.7 June 12, 2023, water levels and inspection

The pipes were again inspected on July 19, 2023. Figure 3.8 shows an image of the pipe inlet at the time of inspection. Again, the water levels were very high, but the pipes were deemed marginally safe enough to enter. Due to the previously-mentioned issues with the instrumentation, physical measurements were taken using a Lufkin wooden ruler with brass extensions, allowing a more accurate measurement than the tape measure used on the June 12 inspection. Figures 3.9 and 3.10 show the process used to measure the horizontal and vertical diameters, respectively. A summary of the data is shown in Table 3.1.

Figure 3.8 July 19, 2023 water level

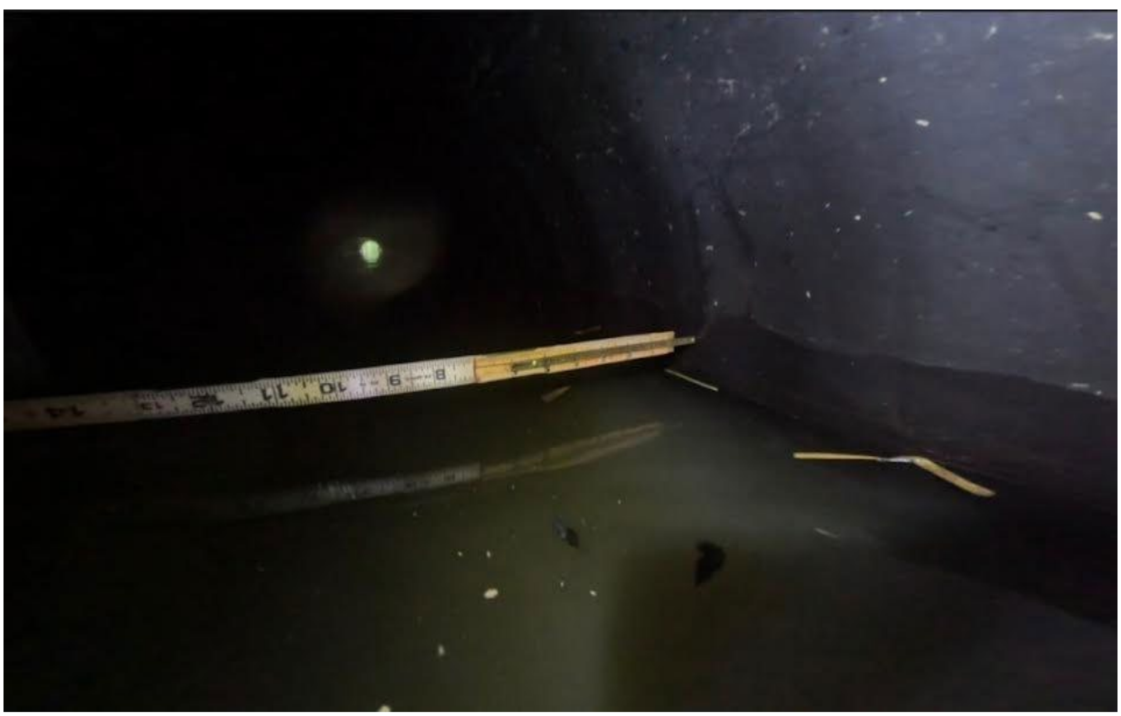

Figure 3.9 July 19, 2023, horizontal measurement using Lufkin wooden ruler with brass extends

Figure 3.10 July 19, 2023, vertical measurement using Lufkin wooden ruler with brass extends

Several additional site visits were conducted between July 2023 and April 2024, and some images are shown in Figures 3.11 – 3.13. Due to high water levels and frozen conditions, the pipes were unable to be adequately inspected during this timeframe.

Figure 3.11 Inspection; 2 in. of ice was estimated, and the culverts were not accessible

Figure 3.12 January 27, 2024, photos - pipes were deemed unsafe to enter

Figure 3.13 April 28, 2024, site visit - water level was over 60% full, and the pipes were deemed unsafe to enter

3.3 Measurement and Analysis of Pipes

Though accurate measurements of the pipe deflections were not possible due to high water levels and unsafe conditions, a summary of the roughly measured pipe diameters and percent deflections for both the M 294V and M 294R pipes is shown in Table 3.1 and a graphical depiction of the culverts is shown in Figure 3.14. As evident from the measurements, the deflections of both the M 294V and M 294R pipes have apparently exceeded MnDOT's 5% maximum requirements. This could be due to a number of different factors, summarized below.

First, this could be related to the installation of the pipes. The pipes installed underneath the eastbound lanes were monitored by both Michael Pluimer (PI) and MnDOT personnel. It was noted that the backfill around the pipes was compacted in larger lifts than typically recommended. The contractor deemed that this was acceptable for the type of backfill being used. However, soil samples were retained and could be further tested to determine the strength of the materials and validate this assessment if desired by MnDOT. Due to the scheduling of the project, Michael Pluimer was not available for the installation of the pipes underneath the westbound lanes. The installation was monitored and documented by graduate student, Katie Padden, and reported in Task 5. It may be worthwhile to inspect the deflections of the pipes underneath the eastbound lanes to see if there are any differences from those underneath the westbound lanes.

A second reason for the excessive deflections may be faulty measurements due to the high water levels in the pipes. It is difficult to accurately measure vertical and horizontal deflections in a pipe filled with water. Additionally, the high water levels made it difficult to determine how much sediment was present on the invert of the pipe. It will be critical and necessary to dewater the pipes and conduct a more thorough investigation to achieve accurate measurements if desired by MnDOT. Note that the horizontal deflections are generally within or close to MnDOT specification limits, and it is possible that the actual vertical deflections are similar but the measurements were inaccurate due to the sediment in the invert of the pipe. The vertical deflection measurements have a greater potential for error than the horizontal measurements and were likely over-estimated.

It should be noted that while the pipes have apparently exceeded the maximum MnDOT deflection requirements, the pipes did not continue to increase in deflection from the June 12, 2023 to April 28, 2024 measurements. Additionally, visual inspection of the pipes did not show any significant distortions or damage. Finally, there does not appear to be any significant difference in performance between the virgin and recycled pipes. If anything, the recycled pipes are performing slightly better than the virgin pipes, though the deflections are very comparable.

To complete a more thorough analysis and comparison of the pipe performance, it will be necessary to dewater the pipes and reinstall the instrumentation.

Table 3.1: Physical measurements of culvert pipes from 2022 - 2023

Virgin HDPE Pipe (AASHTO M 294 V)					
Dimension	**Pre-Construction Diameter, in. (% Deflection)**	**Post-Construction Diameter, in. (% Deflection)[1]**	**June 12, 2023 Diameter, in. (% Deflection)[2]**	**July 19, 2023 Diameter, in. (% Deflection)**	**April 24, 2024 Diameter, in. (% Deflection)**
Horizontal	35.72 in. (0.00%)	36.81 in. (+3.05%)	38.42 (+7.56%)	37.81 in. (+5.85%)	NA[3]
Vertical	36.06 in. (0.00%)	34.44 in. (-4.49%)	32.38 (-10.21%)	32.13 in. (-10.90%)	NA[3]
Diagonal	35.91 in. (0.00%)	35.00 in. (-2.53%)	34.54 (-3.82%)	35.25 in. (-1.84%)	NA[3]

Recycled HDPE Pipe (AASHTO M 294 R)					
Dimension	**Pre-Construction Diameter, in. (% Deflection)**	**Post-Construction Diameter, in. (% Deflection)[1]**	**June 12, 2023 Diameter, in. (% Deflection)[2]**	**July 19, 2023 Diameter, in. (% Deflection)[2]**	**April 24, 2024 Diameter, in. (% Deflection)**
Horizontal	35.91 in. (0.00%)	36.25 in. (+0.95%)	38.33 (+6.74%)	38.06 in. (+5.99%)	NA[3]
Vertical	35.91 in. (0.00%)	35.00 in. (-2.53%)	32.75 (-8.80%)	33.02 in. (-8.05%)	NA[3]
Diagonal	35.94 in. (0.00%)	36.38 in. (+1.22%)	34.13 (-5.04%)	36.02 in. (+0.22%)	NA[3]

[1]Post-construction measurements were made after the pipes were backfilled with approximately one foot of cover over the tops of the pipes, not after the final backfill.

[2]Measurements in June were taken using a measuring tape and not a brass extends; therefore, these measurements may not be as accurate as the July measurements. Additionally, in both June and July, the pipes were flowing with water and there was sediment in the invert, introducing error into the vertical deflection measurements. Actual deflections may be less than indicated and should be verified with the pipes dewatered.

[3]Measurements were attempted but pipes were deemed unsafe to adequately measure due to high water levels and cold temperatures.

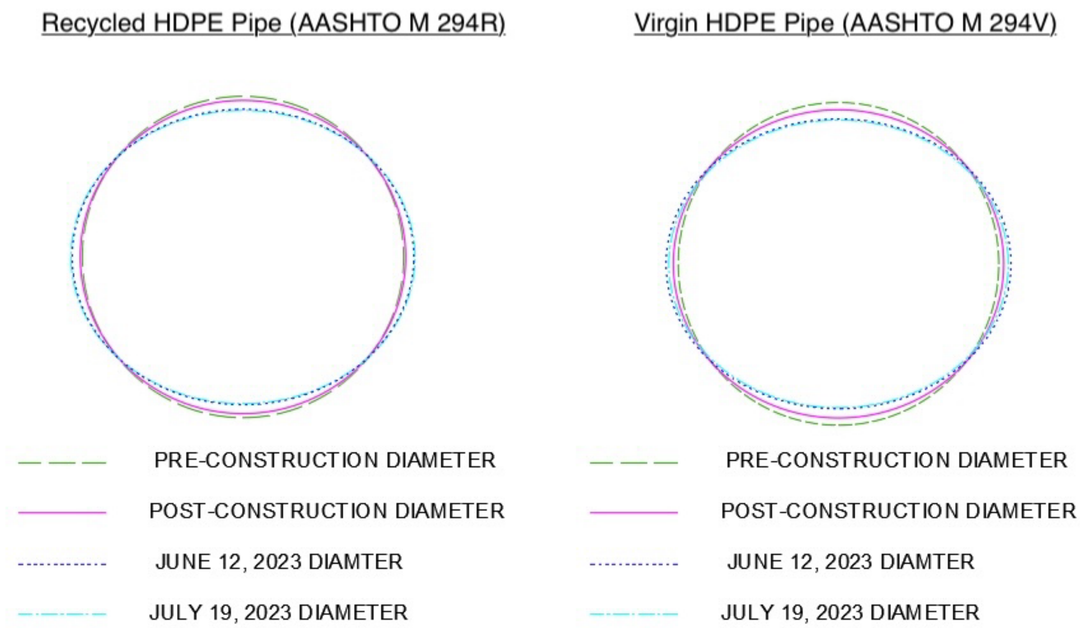

Figure 3.3.14: Illustration of culvert deflection from prior to construction to July 19, 2023

Chapter 4: Materials analysis

Test sections from each pipe were sent to PSILab in Colorado for testing and analysis in accordance with the respective AASHTO M 294 specifications. PSILab is one of two laboratories in the U.S. certified to conduct split sample testing for AASHTO's Product Evaluation and Audit Solutions program. Table 4.1 shows a summary of the test results from the two sets of test pipes that were installed on this project.

Table 4.1: Properties of test pipes for field installation

Property	Test Method	AASHTO M 294 Requirement	AASHTO M 294V Pipe	AASHTO M 294R Pipe
Density	ASTM D 1505	> 0.947 – 0.955 g/cm^3	0.953 g/cm^3	0.954 g/cm^3
Melt index	ASTM D 1238	< 0.4 g/10 min.	0.22 g	0.17 g
Flexural Modulus	ASTM D 790	> 110,000 psi	153,365 psi	154,693 psi
Yield Strength	ASTM D 638	> 3,000 psi	4,080 psi	4,166 psi
Strain at Break	ASTM D 638	> 150% (M 294R only)	692%	791%
Pipe plaque NCLS	ASTM F 2136	> 24 hrs.	62.9 hrs.	62.7 hrs.
Pipe Stiffness	ASTM D 2412	> 22 lb/in/in	27.7 lb/in/in	29.7 lb/in/in
Pipe Flattening	ASTM D 2412	> 20%	Pass	Pass
Pipe ID	ASTM D2122	35.5 – 37.5 in.	35.9 in.	35.9 in.
Pipe OIT	ASTM D3585	> 20 min. (M 294R only)	65.4 min.	74.6 min.
Pipe UCLS	ASTM F3181	> 34 hrs. (M 294R only)	NA	> 159 hrs.

Chapter 5: Life-cycle analysis and life-cycle cost assessment

5.1 Overview

A comparison of the cost and sustainability of the M 294R and M 294V pipes was conducted based on published literature and data gathered from pipe manufacturers for this project. While a complete life-cycle assessment (e.g., ISO 14040) was outside the scope of this project, a literature review of published data was conducted to estimate the impacts (i.e., cost, environmental impact, durability, and sustainability) of using virgin and recycled pipe, and the results of this literature review were summarized for this report. Additionally, a life-cycle cost analysis (LCCA) was conducted using the methodology outlined in ASTM F1765 (ASTM 2022b).

5.2 Life-Cycle Assessment (LCA)

5.2.1 Life-Cycle Assessment Overview

A life-cycle assessment (LCA) is a formalized methodology to evaluate the environmental impacts of a product, process, or service throughout its entire life-cycle. The most widely accepted standardized methodology is outlined in ISO 14040: Life Cycle Assessment – Principles and Framework (ISO, 2006). This comprehensive evaluation spans from the extraction of raw materials, through manufacturing and distribution, to use and disposal or recycling. The goal of an LCA is to identify and quantify the energy and materials used and the wastes released to the environment, and to assess the impact of those energy and material uses and releases on the environment.

The LCA process is typically divided into four main phases: 1) goal and scope definition; 2) life cycle inventory analysis (LCI); 3) life cycle impact assessment (LCIA); and 4) life cycle interpretation. In the goal and scope definition phase, the purpose of the study and the boundaries of the assessment are established, determining what will and will not be included in the analysis. The life-cycle inventory analysis phase involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The life-cycle impact assessment phase evaluates the potential environmental impacts associated with the identified inputs and outputs, such as global warming potential, acidification, eutrophication, and human health effects. Finally, the interpretation phase involves analyzing the results to make informed decisions, improve processes, and support policy and strategy development.

LCAs are valuable tools for businesses, policymakers, and researchers as they provide a standardized and detailed understanding of the environmental implications of different choices and actions. By considering the entire life-cycle, LCAs offer a holistic approach to help avoid shifting environmental burdens from one stage to another or from one type of environmental impact to another. Ultimately, LCAs contribute to the reduction of negative environmental impacts and the promotion of sustainable development.

5.2.2 Life Cycle Assessment Literature Review

While a complete LCA was not conducted for this project, several LCAs were reviewed that compared the environmental impact of different types of drainage pipes. The LCA that was most applicable for this MnDOT project was a study conducted and published by Franklin Associates (2021) comparing the life-cycle impacts of various types of drainage pipes. The report presented a comprehensive comparative study of the environmental impacts of five different piping materials: 1) Corrugated HDPE pipes manufactured with virgin materials (i.e., AASHTO M 294V); 2) corrugated HDPE pipes manufactured with post-consumer recycled materials (i.e., AASHTO M 294R); 3) reinforced concrete pipe (RCP); 4) corrugated aluminized steel pipe (CSP); and 5) corrugated PVC pipe. The analysis was based on 24-in. (600 mm) diameter pipes with a functional unit of 1000 feet (25.4 m) pipe length for a service life of 100 years. The life-cycle impact assessment included impacts related to global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (OZDP), and smog potential (SP).

Regarding global warming potential (GWP), the LCIA results showed that the majority of the GWP was contributed to carbon dioxide emissions from the combustion of fossil fuels. The RCP and CSP pipes had the greatest impacts on the GWP according to the study. Corrugated HDPE pipes manufactured with 50% post-consumer recycled (PCR) materials showed a significant reduction in GWP compared to pipes manufactured with only virgin materials. The reason for this is because the there is less energy used to procure and blend recycled resins compared to the manufacturing of virgin resins.

Corrugated HDPE pipes also were shown to have the lowest impact of the various materials assessed relative to acidification potential (AP), eutrophication potential (EP), and smog potential (SP). Corrugated HDPE pipes manufactured with recycled materials (i.e., AASHTO M 294R) showed slight improvements over those with virgin materials (i.e., AASHTO M 294V). Regarding ozone depletion potential (OZDP), corrugated PVC pipes showed the highest impacts, followed by CSP, RCP, and HDPE pipes.

The life-cycle impact assessment data is summarized in Figure 5.1, and a qualitative ranking summary of the results is shown in Table 5.1. Corrugated HDPE Pipe manufactured with 50% PCR materials (i.e., AASHTO M 294R) was the best ranking material on four of the five categories.

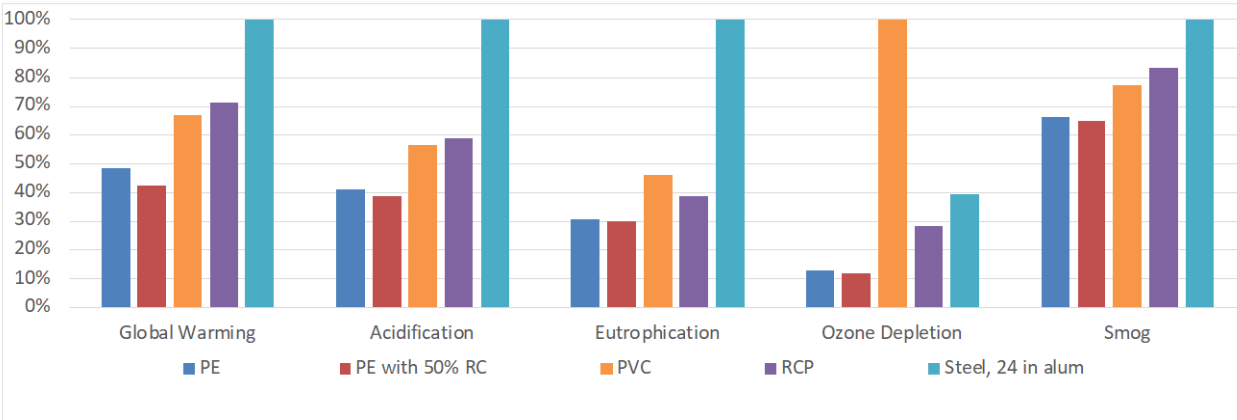

Figure 5.1: Relative life-cycle impact assessment (LCIA) ranking of various drainage pipe materials according to Franklin Associates LCA

Table 5.1: Life cycle impact analysis ranking of various drainage pipe materials according to Franklin Associates LCA

Life Cycle Impact Category	Material Ranking (Scale 1-5, with 1 being the best and 5 the worst)				
	RCP	CSP	HDPE Virgin	HDPE 50% PCR	PVC
GWP	5	4	2	**1**	3
AP	5	4	2	**1**	3
EP	5	3	2	**1**	4
OZDP	4	1	3	**2**	5
SP	5	4	2	**1**	3

5.2.3 Life Cycle Assessment Conclusions

Based on this literature review, it was concluded that corrugated HDPE pipes manufactured with recycled materials (i.e., AASHTO M 294R) offer environmental benefits in the majority of impact categories relative to standard life-cycle assessment methodologies. The primary reason for this is that there is less energy required to obtain and prepare recycled polyethene materials than to manufacture virgin materials. Additionally, the AASHTO M 294 standard includes material performance requirements to ensure corrugated HDPE pipes manufactured with recycled content have a service life that exceeds 100 years, which is greater than MnDOT's current service life requirements for corrugated HDPE pipes.

5.3 Life Cycle Cost Analysis (LCCA)

A life-cycle cost analysis (LCCA) is important to compare the overall present-value costs of various pipe materials. The LCCA considers more than just the material costs of the various pipe systems. It also includes the installation costs, the maintenance and repair costs, the replacement costs, and the anticipated service life as factors to include in the analysis. The LCCA considers the discount rate and converts all costs into present values to determine an accurate comparison of the various systems being evaluated.

There are many available methods currently used to calculate the life-cycle cost of various pipe products. ASTM C1131, *Standard Practice for Least Cost (Life Cycle) Analysis of Concrete Culvert, Storm Sewer, and Sanitary Sewer Systems*, is often specified by the concrete pipe industry (ASTM, 2020a), while ASTM A930, *Practice for Life-Cycle Cost Analysis of Corrugated Metal Pipe Used for Culverts, Storm Sewers, and other Buried Conduits (*ASTM , 2020b), is referenced by the corrugated metal pipe industry. The analysis utilized in this handbook is based on ASTM F1675, Standard Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits (ASTM 2022a).

ASTM F1675 details a procedure to evaluate alternative pipe products with regards to their overall economic impact given the service life of the pipe and the intended design service life of the application. For example, if the given application requires a design service life of 100 years, a product that lasts 50 years would require a replacement (and associated replacement costs) in order to meet the design requirement, while a 100-year product would not need to be replaced. Additionally, ASTM F1675 considers the maintenance and repair costs of each pipe system, as well as the residual value of the pipe systems (this is important for pipes that can be reused or recycled at the end of their intended service life).

To calculate the life-cycle costs for the various drainage systems, ASTM F1675 utilizes Equation 1:

$$PVLCC = PVIC + PVM + PVR - PVT \qquad \textit{(Eqn. 1)}$$

where

PVLCC = Present Value Life Cycle Cost
PVIC = Present Value of Initial Costs
PVM = Present Value of Operating and Maintenance Costs
PVR = Present Value of Replacement or Rehabilitation Costs
PVT = Present Value of Terminal or Residual Costs

The PVIC is taken as simply the initial cost of the pipe system (including material and installation costs) and is not discounted, since this cost occurs at year zero in the analysis. The remaining costs used in the LCCA are discounted to determine their present value given the year (or years) in which the expenditures occur and the intended design life of the pipe system. The following example illustrates how this methodology can be applied to MnDOT pipe infrastructure.

5.3.1 Example Analysis – ASTM F1765 LCCA

In this example analysis, four pipe types are considered: 1) Class III reinforced concrete pipe (RCP); 2) galvanized corrugated metal pipe (CMP); 3) corrugated HDPE pipe with virgin materials (HDPE Virgin); and 4) corrugated HDPE pipe with PCR materials (HDPE Recycled). For the purposes of this analysis, all pipe types have an inside diameter of 24 in. (600 mm).

For this example, it is assumed that all pipe materials require the same backfill materials and have comparable trench widths, so the pipe envelope material are the same for all pipe types. This is an appropriate assumption for some states and applications, though this is not always the case. For example, reinforced concrete pipe can often be installed with select backfill materials only compacted up to the springline of the pipe and native materials in the remainder of the backfill envelope, while flexible pipes typically require select backfill materials to extend 6 in. (150 mm) above the top of the pipe. Also, depending on the hydraulic requirements of the culvert, it is likely that a larger diameter CMP pipe may be necessary to achieve the equivalent hydraulic capacities of the smooth-lined HDPE and RC pipe systems. This would also necessitate a larger pipe envelope. However, for this analysis all pipe envelopes are assumed to be the same.

Since RCP, Corrugated HDPE and Corrugated PP pipes have a smooth inner surface, it is appropriate to assume that the ongoing maintenance and cleaning costs of these pipes will be slightly less than those of the CMP. Additionally, since there are 60% fewer joints on the HDPE pipe systems vs. the RCP systems, HDPE pipe systems should have a slightly lower annual maintenance cost than RCP.

For this example, the desired design service life for the pipe system is assumed to be 100 years, though MnDOT has a design service life of 75 years. RCP and HDPE pipes (virgin and recycled) all have a material service life of 100 years, while the service life of galvanized CMP is typically around 50 years or less, depending on the installation conditions and type of soil and effluent present. As such, the CMP system requires replacement prior to the end of the desired pipe system design life, and this replacement cost must be considered in the LCCA.

The discount rate is used to convert future occurring costs to an equivalent cost at time zero (present). ASTM F1765 defines both a “nominal” discount rate and a “real” discount rate. The nominal discount rate includes the rate of general inflation over the study period, while the real discount rate represents the actual earning power of money over and above inflation. The two values are related as shown in Equation 2.

$$d_r = \frac{1+d_n}{1+I} \qquad \textit{(Eqn. 2)}$$

where

d_r = real discount rate
d_n = nominal discount rate
I = the rate of general price inflation

An inflation rate of 2% and a nominal discount rate of 3% are used in this example analysis, resulting in a real discount rate of 0.98%. These rates are based on historical averages over the past 20 years. The present value of a future cost occurring at a single point in time (e.g. the replacement cost of the pipe system) can be calculated by using Equation 3.

$$PVA_S = A_S * \left(\frac{1}{1+d_r}\right)^n \quad \textit{(Eqn. 3)}$$

where

PVA_S	= present value of a single future expenditure
A_S	= the amount of the future expenditure
d_r	= real discount rate
n	= number of years from year zero to the time of the future expenditure

Similarly, the present value of future recurring costs expected to occur in the same amount at the same frequency (e.g. annual maintenance costs) are discounted into present value dollars according to Equation 4.

$$PVA_r = A_r * \frac{(1+d_r)^n - 1}{d_r(1+d_r)^n} \quad \textit{(Eqn.4)}$$

where

PVA_r	= present value of future recurring expenditure
A_r	= future recurring annual costs
d_r	= real discount rate
n	= number of years over which the recurring annual costs occur

Using Equations 1 – 4 in accordance with ASTM F1765, the present values of the various pipe systems can be calculated given their estimated initial costs and ongoing maintenance costs. While these costs can vary greatly depending on region, material availability, and other factors, the assumed costs for the 24-in. (600-mm) diameter pipes evaluated in this analysis are summarized in Table 5.2. These costs are based on estimates from various highway and railroad installations around the United States, but they may be somewhat dated. The costs are installed costs (including pipe materials, backfill materials, transportation and installation costs) and assumed trench installations, sandy gravel soils for the pipe envelope, and the reuse of excavated native soils for backfill above the pipe. Incorporating recycled materials into corrugated HDPE pipe has been shown to reduce the costs by 15 – 25%, depending on the fluctuations in resin prices (EPA, n.d.). A reduction of 20% was used in this analysis.

Higher maintenance costs were assumed for CMP pipes than HDPE and RCP due to their rough interior, which may require more frequent or time-intensive cleaning. RCP maintenance costs may also be slightly higher than HDPE due to the increased number of joints. Because of this, operation and maintenance costs were assumed to be $1.64/m/year ($0.50/ft/year) for RCP, $2.46/m/year ($0.75/ft/year) for CMP and $1.31/m/year ($0.40/ft/year) for Corrugated HDPE and PP. These costs included video inspections, cleaning and general maintenance of the pipes. They were rough estimates that may vary greatly by region and application. For ease of analysis, the terminal value was set to zero for all of the pipe products. In reality, the Corrugated HDPE pipe could be recycled, and some residual value assigned to it. Likewise, portions of the RCP and CMP products could potentially be salvaged and have some residual value.

Using these factors, the results are summarized in Table 5.2. Additionally, the cost per year for each pipe system given the initial costs and expected service lives of each pipe material was determined by creating a Microsoft® Excel spreadsheet utilizing the PPMT function. This spreadsheet assumed a discount rate of 0.98% and provided the value of an annuity that yields the same present value of the current cost. Using the same assumptions described above, this cost is also included in Table 5.2.

Table 5.2: Life Cycle Cost Analysis in accordance with ASTM F1765 for various 600-mm (24-in.) diameter pipes based on typical average installed operating and maintenance costs

Pipe Type	Material Service Life (yrs)	Initial Installed Cost - $/m ($/ft)	Annual Op. and Maint. Cost - $/m ($/ft)	Replace. Cost - $/m ($/ft)	PV of Op. and Maint. - $/m ($/ft)	PV of Replace. Cost - $/m ($/ft)	Total PV - $/m ($/ft)	Cost per Year - $/m ($/ft)
RCP	100	246 (75)	1.64 (0.50)	0 (0)	104 (32)	0 (0)	350.24 (106.78)	5.87 (1.66)
CMP	50	164 (50)	2.46 (0.75)	164 (50)	156 (48)	101 (31)	421.02 (128.36)	10.47 (3.23)
HDPE-Virgin	100	148 (45)	1.31 (0.40)	0 (0)	83 (25)	0 (0)	230.98 (70.42)	3.87 (1.10)
HDPE-Recycled	100	131 (40)	1.31 (0.40)	0 (0)	83 (25)	0 (0)	214.58 (65.42)	3.35 (1.02)

As evident from this analysis, for the given assumptions and conditions in this example, Corrugated HDPE pipe manufactured with virgin materials offered life-cycle cost savings of 34% over RCP and 45% over CMP, while Corrugated HDPE pipe manufactured with recycled materials offered life-cycle cost savings of 39% over RCP and 49% over CMP.

This was just an example for one pipe diameter, and actual savings will obviously vary depending on local costs and availability. Additionally, the service life assumptions and maintenance costs are dependent upon installation conditions and the specific material types selected. For example, a polymer-coated or aluminized CMP pipe system may offer comparable service life to HDPE and RCP pipe systems in certain service conditions. However, the purpose of this example was to illustrate the potential for cost savings associated with Corrugated HDPE pipes manufactured both with and without recycled materials.

Chapter 6: Conclusions and Future Work

6.1 Research Summary and conclusions

The objective of this research project was to compare the performance of corrugated HDPE pipes manufactured with recycled materials to those manufactured with only virgin materials and to determine their suitability for culvert and storm sewer applications for MnDOT. Additionally, the research project provided an environmental and economic assessment of these materials for MnDOT applications.

Two 36-in. (900 mm) diameter corrugated HDPE test pipes – one manufactured with recycled content in accordance with AASHTO M 294R and one manufactured with only virgin materials in accordance with AASHTO M 294V – were installed underneath Minnesota State TH2 near Fosston, MN. Test sections from the pipes were instrumented with strain gages and string potentiometers to collect live load data, but unfortunately the sensors were not able to withstand harsh winter conditions, and full-flowing pipes made entry and installation of new sensors unsafe throughout the test period. However, physical measurements and inspections of the pipes showed no significant performance differences between the virgin and recycled test pipes. It was noted that both pipes appear to have exceeded MnDOT's 5% deflection limit, and the cause of this excessive deflection is likely related to installation errors regarding the selection and compaction of backfill materials around the pipes, as well as measurement errors due to sediment in the invert of the pipes and difficulty accessing the pipes due to high water levels. The recycled HDPE pipes have slightly lower deflections than the virgin HDPE pipes, but they are comparable within measurement error. The pipes do not appear to have changed in diameter or performance between the June 12, 2023, to April 28, 2024, inspection dates.

A modified life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) was conducted to compare the pipes manufactured with virgin materials (AASHTO M 294V) to those manufactured with recycled content (AASHTO M 294R). The LCA showed that corrugated HDPE pipes manufactured with recycled materials may offer environmental benefits in most impact categories relative to traditional pipe materials based on standard life-cycle assessment methodologies. The LCCA showed potential cost savings associated with the specification of corrugated HDPE pipes manufactured with recycled content. An example LCCA was conducted based on established ASTM methodologies. The example analysis showed that HDPE pipe manufactured with virgin materials offers life-cycle cost savings of 34% over RCP and 45% over CMP, while corrugated HDPE pipe manufactured with recycled materials offers life-cycle cost savings of 39% over RCP and 49% over CMP.

Based on this research project, it is recommended that MnDOT consider the allowance of corrugated HDPE pipes manufactured with recycled content in accordance with AASHTO M 294R for their culvert and storm drainage applications. The AASHTO M 294R pipes performed comparably to the AASHTO M 294V pipes, and the pipes are still performing well in the 3rd year of service. While both the M 294V and M 294R pipes appear to have slightly exceeded MnDOT deflection requirements, it is deemed that this was likely due to a failure to follow MnDOT installation guidelines as well as measurement errors due to sediment and water in the pipes. Additionally, since the water levels in the pipes made it difficult to accurately measure deflections and monitor the pipes over time, it is recommended to identify an additional test site for further analysis. An LCA showed significant environmental benefits to using corrugated HDPE pipes manufactured with recycled content, and an LCCA showed some potential economic savings.

6.2 Suggestions for Future Work

Since we were unable to collect any live load data on the pipes, we would like to complete this work in the summer of 2025. We have acquired some new string potentiometers, but we would need to dewater the pipes to safely enter them and install the sensors. It is unlikely that we will be able to re-install strain gages in the in-situ pipes, as it will be too challenging to do so in the field conditions. However, the live load data from string potentiometers could be useful for comparing the performance of the virgin and recycled pipes.

Additionally, it should be noted that there is a published AASHTO standard method to assess the service life of corrugated HDPE pipes manufactured with recycled content. This method is published as AASHTO R 93, *Standard Practice for Service Life Determination of Corrugated HDPE Pipes Manufactured with Recycled Content (*AASHTO, 2023b). The method is based on assessing the service conditions of the installed pipe (i.e., temperature, wall strains, etc.) and conducting a materials test for stress crack resistance (the un-notched constant ligament stress test, or UCLS test, in accordance with ASTM F3181) to determine how long the material will last in that condition. UCLS testing is currently underway in accordance with ASTM F3181 (ASTM, 2024), and the research team would like to conduct this analysis upon completion of the testing. This will provide an estimate as to how long this installed pipe will last in the given conditions.

Finally, due to the issues in installing and monitoring these test pipes, it is our recommendation to identify an additional test site where new test pipes could be installed. Ideally, this test site would not be as wet as the Fosston site, and the pipes could be more easily monitored over time. It is also recommended that the pipes are installed properly and in accordance with MnDOT installation standards. While the current pipes appear to be performing satisfactorily and do not show any difference in performance between the virgin and recycled pipes, we were unable to obtain the live load data that was desired for this project, and we feel that could be better obtained at a more suitable test site.

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