

# Development of a Process to Lower Global Warming Potential of Construction Materials

**Michelle A. Cooper, Principal Investigator**

Department of Civil Engineering, Environmental, and Geospatial Engineering  
Michigan Technological University

**May 2025**

Research Project  
Final Report 2025-24

To get this document in an alternative format or language, please call 651-366-4720 (711 or 1-800-627-3529 for MN Relay). You can also email your request to [ADArequest.dot@state.mn.us](mailto:ADArequest.dot@state.mn.us). Please make your request at least two weeks before you need the document.

## Technical Report Documentation Page

1. Report No. <b>MN 2025-24</b>	2.	3. Recipients Accession No.	
4. Title and Subtitle <b>Development of a Process to Lower Global Warming Potential of Construction Materials</b>		5. Report Date <b>June 2025</b>	
		6.	
7. Author(s) <b>Michelle A. Cooper and Amlan Mukherjee</b>		8. Performing Organization Report No.	
9. Performing Organization Name and Address <b>Civil, Environmental, and Geospatial Engineering Michigan Technological University 870 Dow Environmental Sciences 1400 Townsend Drive Houghton MI 49931</b>		10. Project/Task/Work Unit No. <b>Need Statement Number 643</b>	
		11. Contract (C) or Grant (G) No. <b>1036337</b>	
12. Sponsoring Organization Name and Address <b>Minnesota Department of Transportation Office of Research &amp; Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899</b>		13. Type of Report and Period Covered <b>Final Report</b>	
		14. Sponsoring Agency Code	
15. Supplementary Notes <b><a href="http://mdl.mndot.gov/">http://mdl.mndot.gov/</a></b>			
16. Abstract (Limit: 250 words)  <p>The objective of this research was to support sustainable procurement of concrete pavements by linking materials-level global warming potential (GWP) to the project level. Infrastructure owners require reliable environmental product declarations (EPDs) and methodologies for integrating GWP into the procurement process to ensure equitable decision-making. This work provided insights into high-level GWP estimation tools and EPD development tools. A benchmarking methodology was developed and implemented to establish reference values for procuring sustainable products within Minnesota. A data collection protocol and life-cycle information model (LCIM) for concrete pavement construction were developed to facilitate GWP integration into current project procurement practices. The LCIM methodology was developed and implemented to estimate the production and construction environmental impacts of five real-world concrete pavement construction projects and a joint repair project. Applying the LCIM methodology allowed this work to map GWP to pay items and incentives in specifications and provide a pathway to extend a LCIM across the life cycle. Ultimately, this research provided a framework for integrating environmental impacts into the procurement process to facilitate sustainable project procurement for infrastructure owners.</p>			
17. Document Analysis/Descriptors <b>GWP, LCA, construction, concrete, pavement, environmental impacts, embodied carbon emissions</b>		18. Availability Statement <b>No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312</b>	
19. Security Class (this report) <b>Unclassified</b>	20. Security Class (this page) <b>Unclassified</b>	21. No. of Pages <b>135</b>	22. Price

# Development of a Process to Lower Global Warming Potential of Construction Materials

## Final Report

*Prepared by:*

Michelle A. Cooper  
Department of Civil, Environmental, and Geospatial Engineering  
Michigan Technological University

Amlan Mukherjee  
WAP Sustainability Consulting

## May 2025

*Published by:*

Minnesota Department of Transportation  
Office of Research & Innovation  
395 John Ireland Boulevard, MS 330  
St. Paul, Minnesota 55155-1899

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation, Michigan Technological University, or WAP Sustainability. This report does not contain a standard or specified technique.

The authors, the Minnesota Department of Transportation, Michigan Technological University, and WAP Sustainability, do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

# Acknowledgements

- Thank you to the members of this project's Technical Advisory Panel:
- Curt Turgeon
- Jackie Jiran
- Alex Olin
- Brandon Brever
- Dan Labo
- Emil Bautista
- Jacob Gave
- John Cunningham
- Joseph Clendenen
- Mike Collins
- Nicolas Marks
- Peter Eakman
- Siri Simons
- Thomas Calhoon

# Table of Contents

<b>Chapter 1: Introduction.....</b>	<b>1</b>
<b>Chapter 2: Resources for Producing EPDs and LCAs .....</b>	<b>3</b>
2.1 Understanding EPDs and LCAs.....	3
2.2 Differentiating Tools from Datasets .....	6
2.3 High-Level GWP Estimating Tools.....	6
2.4 Tools for Producing EPDs.....	9
2.5 Other Educational Tools and Resources .....	10
<b>Chapter 3: Workshop Summary .....</b>	<b>11</b>
<b>Chapter 4: Survey of Specifications Adopted in Other Jurisdictions .....</b>	<b>14</b>
<b>Chapter 5: Concrete EPD Data Collection.....</b>	<b>17</b>
<b>Chapter 6: Recommendations for Formal Data Collection and Archival Protocol .....</b>	<b>18</b>
6.1 Recommendations.....	18
6.2 Why to Include Carbon Credits Information in the EPD Submittal Package .....	18
<b>Chapter 7: Characterization and Benchmarking of Ready-Mix Concrete EPDs.....</b>	<b>21</b>
7.1 Benchmarking Methodology and Results.....	21
7.2 Recommended GWP Intervals for Acceptance .....	28
<b>Chapter 8: Life-Cycle Information Model (LCIM) for the Construction Phase.....</b>	<b>30</b>
8.1 LCA Data Collected at Bid .....	30
8.2 LCA Data Collected After Successful Bid.....	31
8.3 LCA Data Collected During Construction .....	32
8.3.1 Concrete Pavement Reconstruction - Hampton .....	33
8.3.2 Concrete Pavement Reconstruction – Lake Elmo .....	36
8.3.3 Concrete Pavement Reconstruction – Sacred Heart.....	39
8.3.4 Concrete Pavement Reconstruction – Courtland.....	41

8.3.5 Joint Repair – Mendota Heights.....	43
8.4 Background on A4, A5, and LCIMs.....	45
8.5 LCIM Methodology .....	46
8.6 Estimated Concrete Mixture (A1-A3) LCA Results.....	51
8.7 Estimated Construction Phase (A4-A5) LCA Results.....	54
8.8 Estimated Construction Phase (A1-A5) LCA Results.....	58
8.9 Mapping of A1-A5 LCA Results .....	62
8.10 QA/QC Metrics.....	70
<b>Chapter 9: Recommendations for Integrating EPDs into the Procurement Process .....</b>	<b>71</b>
<b>Chapter 10: Summary and Conclusions .....</b>	<b>76</b>
<b>References.....</b>	<b>80</b>
<b>Appendix A EPDs Introduction</b>	
<b>Appendix B Data Collection Protocol for A1-A5</b>	
<b>Appendix C Specification for EPD Submittal Package</b>	
<b>Appendix D Minnesota Benchmarking</b>	
<b>Appendix E GWP Acceptance and Incentives Thresholds</b>	
<b>Appendix F Estimating A1-A3 GWP of Mobile Batch Plant Concrete</b>	
<b>Appendix G Estimating A1-A5 GWP of a Concrete Pavement</b>	
<b>Appendix H Integrating EPDs into the Procurement Process</b>	
<b>Appendix I Recommendations to Environmental Standards Procurement Task Force</b>	

# List of Figures

Figure 2.1 Life-cycle stages based on ISO 21930. Source: Michelle Cooper based on (ISO 2017). .....	3
Figure 2.2 Expressing sustainability terms in terms of strength. Source: Michelle Cooper. ....	4
Figure 7.1 Flow chart of benchmarking methodology (Cooper and Mukherjee 2025). ....	21
Figure 7.2 Variations in estimated GWP based on differences in concrete mixture designs used on Minnesotan projects. ....	22
Figure 7.3 A2 and A3 GWP distributions based on EPDs with (a) showing the distributions in this study and (b) showing the same in comparison with the 20 <sup>th</sup> and 40 <sup>th</sup> percentiles as well as average values from the NRMCA statistical addendum / FHWA LCTM thresholds (labeled as 20 <sup>th</sup> percentile, 40 <sup>th</sup> percentile, and average) and from this analysis (labeled as A2 percentiles and A3 percentiles) (Salazar et al. 2024, FHWA 2024b). ....	24
Figure 7.4 Illustration of how the A1 scenario GWPs combine with the A2 and A3 distribution percentile values of interest to develop benchmarks at the reference values of interest (Cooper and Mukherjee 2025). ....	25
Figure 7.5 A1-A3 GWP reference values by application based on the benchmarking process described in Figure 7.4 and compared to 4,000 psi concrete industry benchmarks for (a) paving applications, (b) high-early-strength (HES) applications, and (c) all other applications. ....	27
Figure 7.6 Empirical distribution of combined A1-A3 GWPs from Minnesotan EPDs and corresponding reference values compared with industry benchmarks. ....	28
Figure 8.1 Construction equipment fuel consumption summary illustration. ....	33
Figure 8.2 Mapping of input and output parameters for concrete production (Cooper 2025) .....	46
Figure 8.3 Mapping of input and output parameters for concrete pavement reconstruction (Cooper 2025) .....	47
Figure 8.4 Illustration of inputs to develop the A1-A5 LCIM (Cooper 2025) .....	48
Figure 8.5 A1-A3 environmental impacts. ....	51
Figure 8.6 A1-A3 GWP for mobile batch plant concretes. ....	52
Figure 8.7 A1-A3 GWP for the concrete mixtures produced by ready-mix versus mobile batch plant in (a) and (b) showing the same with the thresholds identified in section 7.0. ....	53
Figure 8.8 A3 GWPs of the project concretes produced by mobile batch plants. ....	54
Figure 8.9 A4 environmental impacts for each project .....	55

Figure 8.10 A5 environmental impacts for each project .....	56
Figure 8.11 A4 and A5 GWP for each project .....	56
Figure 8.12 A4 and A5 GWP for each project separated into concrete transportation, steel transportation, equipment transportation, and equipment operation .....	57
Figure 8.13 A4 and A5 empirical probability density curves for the scenarios analyzed .....	58
Figure 8.14 A1-A5 environmental impacts for each project.....	59
Figure 8.15 A1-A5 GWP based on the paving application, including turn lane, intersection handwork, and mainline paving.....	60
Figure 8.16 Percentage contribution of each life-cycle stage to the A1-A5 GWP across all assessed scenarios. ....	61
Figure 8.17 Project A1-A5 GWPs and production rates.....	62
Figure 8.18 A1-A5 concrete GWP per concrete pavement pay item in square yards.....	63
Figure 8.19 A4-A5 concrete GWP per concrete pavement pay item in square yards.....	64
Figure 8.20 A1-A5 concrete GWP per cubic yard, as required by the concrete PCR.....	65
Figure 8.21 GWP by life-cycle stage when dividing that GWP by pavement thickness.....	66
Figure 8.22 A1-A3 concrete GWP per concrete material pay item in cubic yards. ....	66
Figure 8.23 A1-A5 steel GWP per dowel pay item.....	67
Figure 8.24 A1--A5 steel GWP per reinforcement pay item in lbs of steel.....	67
Figure 8.25 How parameters affect environmental impacts and therefore will affect material versus project benchmark.....	69
Figure 8.26 w/cm compared to GWP per pay item for both A1-A5 per yd <sup>2</sup> and A1-A3 per yd <sup>3</sup> .....	70
Figure 9.1 Flow chart summarizing the recommendations for integrating EPDs into the procurement process.....	75
Figure 9.2 Interaction diagram for stakeholders' requests and actions.....	75

# List of Tables

- Table 2.1 Comparison between verified EPD and estimating tools..... 9
- Table 4.1 Low-carbon thresholds for 4000 psi concrete GWP in other jurisdictions. .... 16
- Table 7.1 Benchmark GWPs for paving, HES, and all applications of concrete mixtures ..... 25
- Table 8.1 Project information. .... 33
- Table 8.2 Concrete materials quantities for Hampton project. .... 34
- Table 8.3 Reported fuel consumption for equipment used during the Hampton project. .... 35
- Table 8.4 Production rates for the Hampton project. .... 36
- Table 8.5 Overlay thickness materials quantities for Lake Elmo project. .... 37
- Table 8.6 Reported fuel consumption for equipment used during the Lake Elmo I-94 project. .... 38
- Table 8.7 Production rates for the Lake Elmo I-94 project. .... 39
- Table 8.8 Reported fuel consumption for equipment used during the Sacred Heart project. .... 41
- Table 8.9 Production rates for the Sacred Heart project. .... 41
- Table 8.10 Reported fuel consumption for equipment used during the Courtland project. .... 43
- Table 8.11 Production rates for the Courtland project. .... 43
- Table 8.12 Reported fuel consumption for each piece of equipment used during the joint repair project. .... 45
- Table 8.13 Data and flow sources used in environmental impact estimations. .... 49
- Table 8.14 Data sources for the concrete mixture framework used in the LCAs Sample table ..... 50
- Table 8.15 MnDOT pay items for concrete paving ..... 63
- Table 9.1 Summary of recommended acceptance and incentives thresholds for concrete. .... 73

## List of Abbreviations

CO <sub>2</sub>	carbon dioxide
CO <sub>2</sub> -eq	carbon dioxide equivalents
DOT	department of transportation
EPD	environmental product declaration
GHG	greenhouse gas
GWP	global warming potential
ID	identifier
in	inches
ISO	International Organization for Standardization
kg	kilogram
LCA	life-cycle assessment
LCIM	life-cycle information model
m <sup>3</sup>	cubic meters
max.	maximum
min.	minimum
NRMCA	National Ready-Mixed Concrete Association
NYS	New York State
PCA	Portland Cement Association
PCR	product category rule
PEM	performance-engineered mixture
psi	pounds per square inch
SCA	Slag Cement Association
SCM	supplementary cementitious material
SD	standard deviation
t·km	metric ton-kilometers
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
US	United States
w/cm	water-to-cementitious materials ratio
yd <sup>2</sup>	square yards

## Executive Summary

The purpose of this work is to facilitate the implementation of sustainable project procurement for concrete pavements. This work introduces the concepts of life cycle assessments (LCAs), environmental product declarations (EPDs), and product category rules (PCRs). EPDs are documents that report the results of an LCA that was performed in a standardized manner specified in the relevant PCR. Global warming potential (GWP) is the leading environmental impact indicator for construction materials, and therefore, it is often the focus of high-level environmental impact assessments. High-level concrete GWP estimating tools use industry-average constituent emissions factors, regional-average transportation distances from the National Ready-Mix Concrete Association (NRMCA) benchmarking report, and regional-average ready-mix concrete production plant emissions from the NRMCA benchmarking report. High-level concrete GWP estimating tools should be used with the understanding that GWPs reported in verified EPDs are likely to be different than those indicated when using the tool, but they can provide valuable, preliminary insights.

Minnesota's concrete stakeholders shared during a workshop their concerns about: (a) the amount of data that will need to be collected, tracked, and shared to develop and appropriately use EPDs; (b) how EPDs will be incorporated into specifications, quality assurance, and incentives programs; (c) how mobile batch plants will be incorporated into the LCA process; (d) how to account for changes in mixture design that are made in real time to modify field constructability; and (e) whether a minimum project size will be instituted for requiring EPDs. The workshop also discussed how performance-engineered mixture design strategies that help improve durability performance of concrete mixtures can be used to lower environmental impacts.

This study includes a synthesis of requirements that other districts and states have instituted for concrete mixtures to decrease their environmental impacts. A variety of strategies are being pursued by various entities related to maximum cement contents and maximum GWP requirements and by providing incentives at multiple levels for using concrete mixtures with GWPs below certain thresholds.

This project reviews more than 850 published concrete EPDs that claim to pertain to Minnesota to develop A2 (transportation of constituent to the concrete production facility) and A3 (concrete production energy) GWP distributions. A1 GWPs for paving and high-early-strength concrete scenarios were estimated based on 32 Minnesota concrete mixtures designs. These distributions were used to develop GWP reference values that can be used as incentive thresholds for reducing GWP of Minnesota concretes. The developed GWP reference values for slipform paving concretes were lower than those identified in the NRMCA benchmarking report and more recent statistical addendum because of the performance-engineered mixture design concepts already often employed by Minnesota concrete producers. The GWP reference values for high-early-strength concretes and other applications were similar to those published in the NRMCA benchmarking report and statistical addendum.

The EPDs used to develop the A3 distribution informing the GWP reference values were specific to stationary or ready-mix concrete plants. While A3 GWPs for portable concrete plants can be similar to those for stationary plants, portable plants often use diesel-powered generators to operate, resulting in

much higher A3 GWP. The A1-A3 GWPs of concrete produced by mobile batch plants were estimated to range from 8% to 39% higher than the average A1-A3 GWPs for the same concrete mixes produced at ready-mix plants. Therefore, the GWP reference values developed herein may be used for thresholds and incentives for ready-mix concrete, but they may only be suitable for incentives for mobile batch plant-produced concrete until more mobile batch plant-produced concrete EPDs are available.

This work developed recommendations for integrating EPDs into the procurement process and a specification or special provision for an EPD Submittal Package that MnDOT can apply to projects to assist in achieving sustainable project procurement. The requirements set forth within the specification provide MnDOT with the information necessary to perform a high-level estimation of the GWP presented in an EPD to assist with EPD verification. The recommendations highlight the importance for program operators to develop an audit program for EPDs that allows for LCA input verification and EPD secure digital transmission from program operators to infrastructure owners.

Data for estimating A1-A5 (production, transport, and installation) were collected at five concrete pavement reconstruction projects and one joint repair project. This work created a data collection spreadsheet and protocol to facilitate future data collection efforts by MnDOT. An LCIM was developed and published to estimate the environmental impacts across life-cycle stages A1-A5. An analysis that identified the benefits and risks associated with collecting EPDs at various times in the project timeline revealed that the optimal time for collecting EPDs was two weeks prior to construction initiation so that the data collected was most accurate for project expectations. Data collection should occur additionally at the end of construction to determine the as-built environmental impacts. Mobile batch plant generators, pavers, and boom trucks demonstrated the highest fuel consumption per day and highest variability in fuel consumption from project to project. Mobile batch plant fuel consumption varied by project depending on the concrete production rate of the plant as well as the ages of the generator and mobile batch plant equipment. Newer equipment was reported to be typically twice as efficient as older generators.

A4 and A5 environmental impacts were estimated and added to the A1-A3 estimations for their corresponding mobile batch plant-produced concrete using the LCIM developed as part of this project. A4 and A5 contributed 16.5% of the project A1-A5 GWP on average. Contributions from steel and dowel bars were minimal compared to those of concrete because of the relative quantities used in Minnesota, given that most are jointed plain concrete pavements. For mainline paving construction, the environmental impact of categories besides GWP follow the same trends identified for GWP across the projects. For the joint repair, the GWP was not as clearly a leading indicator for the other environmental impact categories. The A1-A5 GWP was assessed for turn-lane paving, intersection handwork, mainline paving, and joint repair scenarios. Due to the lower production rates associated with starting and stopping operations as well as less paving output for a full day of active mobile batch plant operation, the turn lane and intersection productions resulted in much higher GWPs than mainline paving. For most scenarios, particularly those for mainline paving and having typical production rates, a majority of the environmental impacts arose from the A1 life-cycle stage due to the cement's impacts.

The GWP results were mapped against the MnDOT pay items to develop guidance on the range of GWP per pay item. The MnDOT pay items include dowel bars, concrete pavement and placement, structural concrete, and supplemental pavement reinforcement, for which the GWP average and standard deviations were, respectively,  $58.4 \pm 13.2$  kg of CO<sub>2</sub>-eq/yd<sup>2</sup> of concrete pavement and placement for A1-A5,  $10.4 \pm 6.95$  kg of CO<sub>2</sub>-eq/yd<sup>2</sup> of concrete pavement and placement for A4-A5,  $6.32 \pm 1.39$  kg of CO<sub>2</sub>-eq/yd<sup>2</sup>/in of concrete pavement and placement for A1-A5,  $1.12 \pm 0.78$  kg of CO<sub>2</sub>-eq/yd<sup>2</sup>/in of concrete pavement and placement for A4-A5,  $185 \pm 20$  kg of CO<sub>2</sub>-eq/yd<sup>3</sup>,  $2.0 \pm 0.9$  kg of CO<sub>2</sub>-eq/each dowel, and  $0.42 \pm 0.04$  kg of CO<sub>2</sub>-eq/lb. In addition to mapping against pay items, the environmental impact results were mapped against the concrete PCR declared unit of cubic yards, with the projects herein having A1-A3 ranges of 168 to 214 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>, and A1-A5 ranges of 191 to 351 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>. When factoring in pavement thickness such that GWP ranged for all 5 projects from 5 to 9 kg of CO<sub>2</sub>-eq/yd<sup>2</sup>/in. The w/cm for the mixtures used on the projects in this study poorly correlated with the A1-A5 GWP/yd<sup>2</sup> and the A1-A3 concrete GWP/yd<sup>3</sup>.

This work provides recommendations for using GWP intervals for acceptance and incentives, integrating EPDs into the procurement process, and estimating environmental impacts of life-cycle stages and modules from A1-A5. The appendices in this report provide two-pagers on: EPDs introduction, Minnesota benchmarking, GWP acceptance and incentives thresholds, estimating A1-A3 GWP of a mobile batch plant, estimating A1-A5 GWP of a concrete pavement, and integrating EPDs into the procurement process.

# Chapter 1: Introduction

This report discusses the results of work that develops a process for lowering the environmental impacts, namely GWP, of construction materials, focusing on concrete. The purpose of this work was to provide a framework incorporating environmental impact metrics into agency project procurement such that infrastructure projects can support and incentivize the use of low-carbon construction materials. Activities for this work included:

- Providing and identifying resources and educational tools for producing EPDs and LCAs and compiling those resources online.
- Identifying conformance of available EPD tools with their PCR.
- Conducting a workshop to seek input on EPD availability and provide guidance to industry and contractor personnel on EPDs.
- Recommending a formal data collection and archival protocol supporting the estimation of cradle-to-gate and cradle-to-constructed GWP estimates.
- Surveying current specifications adopted.
- Developing an initial online database on concrete mixture EPDs.
- Collecting EPD data.
- Characterizing and benchmarking ready-mixed EPD data.
- Identifying projects for which data typically needed for developing a concrete EPD and construction phase data were collected.
- Collecting quality metrics associated with each pay item.
- Generating a full life-cycle information model (LCIM) for construction phase operations.
- Mapping concrete production and construction LCA data to metrics of GWP per unit of pay item.
- Conducting statistical analyses on cradle-to-gate and cradle-to-construction LCA data.
- Developing GWP intervals for acceptance.
- Providing recommendations for integrating EPDs into the procurement process.

In other words, the results of this project will help MnDOT and the Minnesota pavement industry to quantify the environmental impacts associated with pavement projects. To help us achieve our goals, we collected and analyzed EPDs associated with concrete mixtures used in Minnesota. We worked with industry members to quantify the environmental impacts related to construction operations and the transportation of materials and equipment to the job site. This information was then used to connect global warming potential of project components and aspects with pay items.

This work addresses strategic priorities of the MnDOT for climate change and environment through development of a system that allows for continual decrease in GWP of construction materials, particularly cement and concrete, using the traditional competitive bidding system and without negatively impacting desired engineering properties. In addition, this work supports the strategic priority of asset management by establishing web-based resources for ready-mixed concrete EPD support.

This work will benefit MnDOT by facilitating the development and piloting of a regionalized framework for using LCAs in the highway construction procurement process. The framework addressed technical and organizational challenges in collecting, analyzing, benchmarking, and integrating EPDs into the procurement process. A collaborative relationship with industry partners allowed for peer exchange, data collection, and framework development of a LCIM for construction phase activities. Web-based resources were compiled and developed to support the concrete ready-mixed industry and contractors in understanding and producing LCAs and EPDs that conform with agency needs.

In 2024, Minnesota launched a buy clean pilot program in response to legislation passed in 2023 that will analyze environmental impacts of asphalt, concrete, rebar, structural steel, and other construction materials (Minnesota Department of Administration 2024). The program will be geared toward understanding materials supply chains, availability of EPDs, and potential impacts from setting GWP thresholds for materials. The pilot project will incorporate eight buildings as well as roughly one quarter of MnDOT paving projects. Minnesota has also committed to a federal-state buy clean partnership that has aims aligned with this work (Office of the Federal Chief Sustainability Officer 2024). The goals of this pilot program and legislation parallel the work performed within this project, and the work presented herein can directly support Minnesota's initiatives.

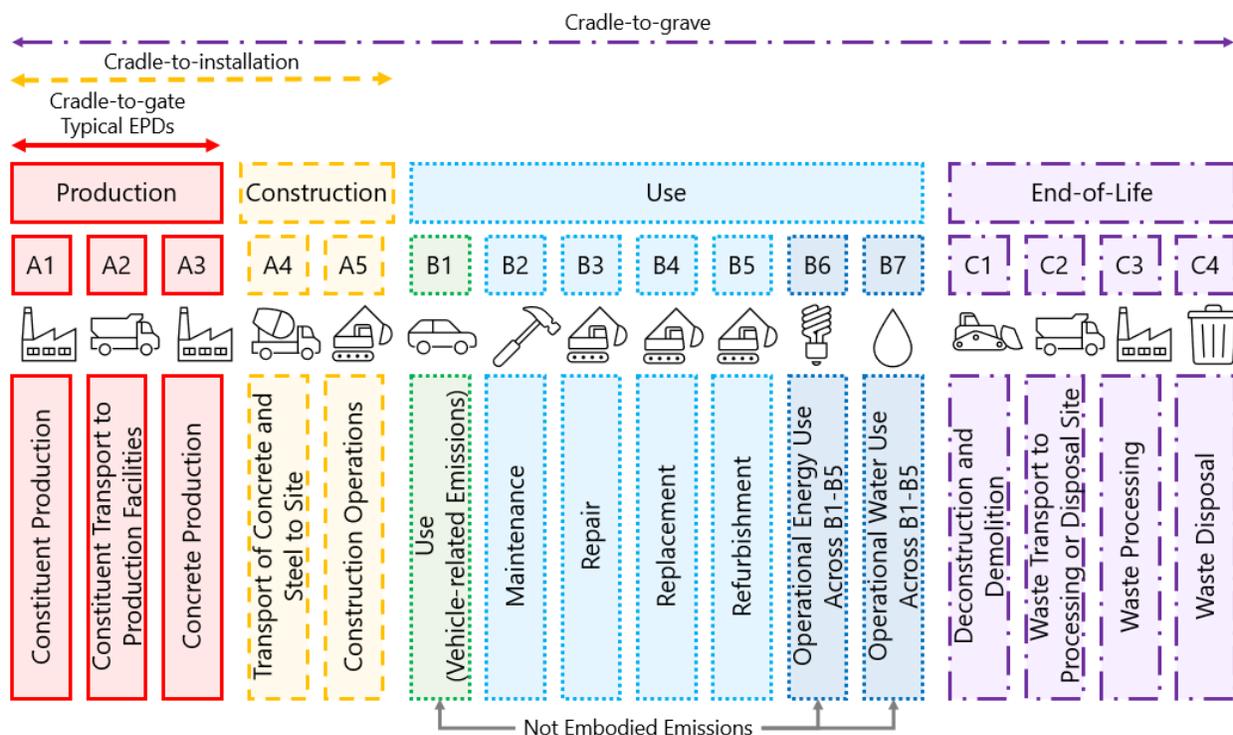
# Chapter 2: Resources for Producing EPDs and LCAs

Much of the information provided in this section of this report is also provided at: <https://sites.google.com/mtu.edu/mndotworkshop/tools> (Cooper and Mukherjee 2024a).

## 2.1 Understanding EPDs and LCAs

Already in this report, EPDs, LCAs, and GWP have been mentioned. This section will define and demystify these terms and a few others.

Figure 2.1 displays the life-cycle stages of construction products according to International Organization for Standardization (ISO) 21930 (ISO 2017).



**Figure 2.1** Life-cycle stages based on ISO 21930. Source: Michelle Cooper based on (ISO 2017).

ISO 21930 is the primary set of rules by which environmental impacts should be estimated using an LCA and reported in an EPD. However, specific groups of products have an additional set of rules, called a sub-category product category rule (PCR), to provide deeper insight for that group of products. In other words, an EPD reports environmental impacts, such as GWP, which are estimated by performing an LCA, which is performed in accordance with ISO 21930 and the applicable PCR (ISO 2017, NSF International 2024). Figure 2.2 further expresses the relationship between PCRs, LCAs, and EPDs using an analogy for compressive strength testing of a concrete cylinder.

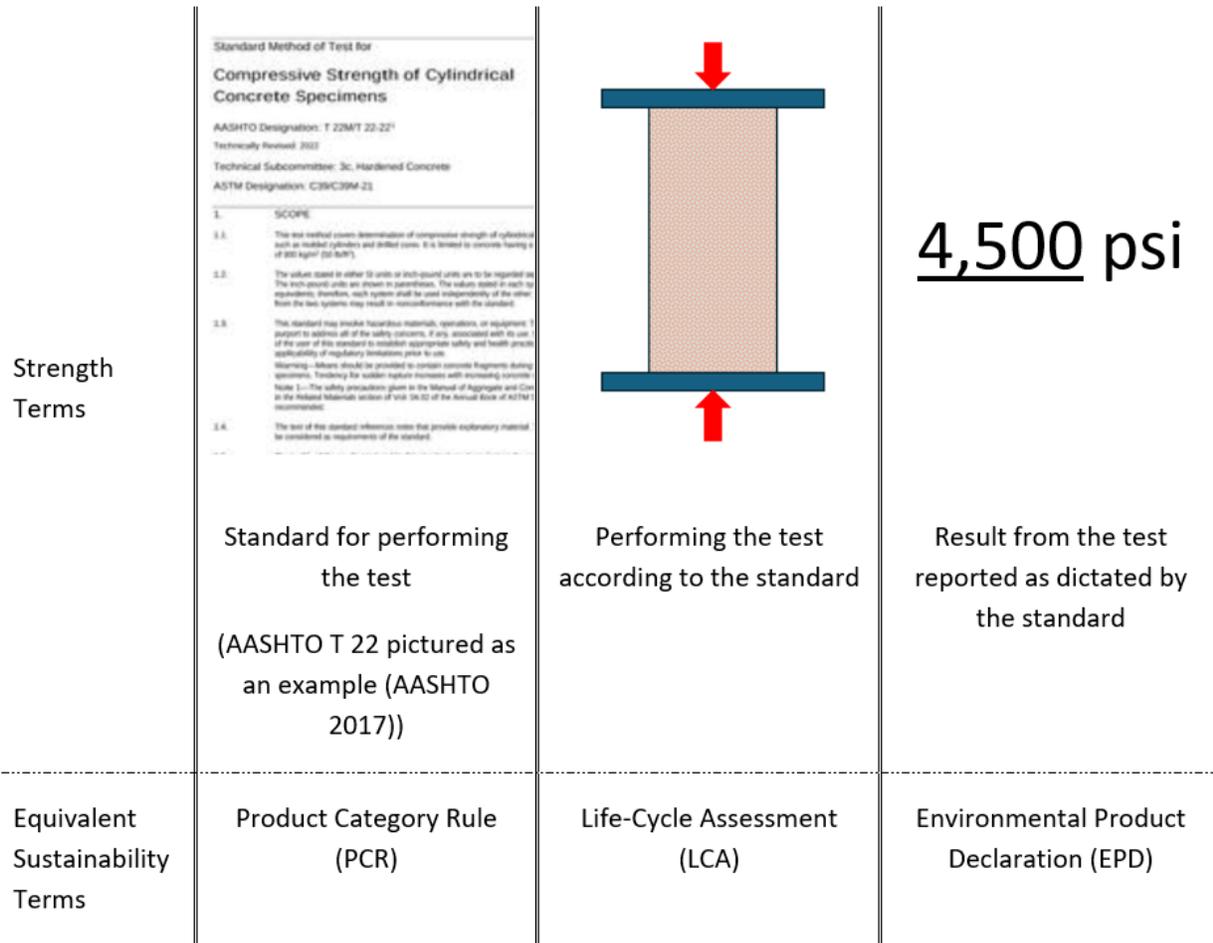


Figure 2.2 Expressing sustainability terms in terms of strength. Source: Michelle Cooper.

The PCR is the standardized method for performing an LCA for a sub-category of products that:

- Identifies which life-cycle inventory modules (refer to Figure 2.1) are required, optional, or out of scope to be reported.
- Provides guidance additional to and at time overruling ISO 21930 to be more specific for evaluating environmental impacts associated with the specific group of applicable products. For example, a PCR may require environmental impact indicators to be reported that are additional to those required within ISO 21930.
- Identifies the units by which the environmental impacts shall be reported (e.g., per m<sup>3</sup>, per yd<sup>3</sup>, etc.).
- Is developed using a consensus-based approach that has representative memberships from stakeholders across the product’s supply chain.
- Ensures the LCA is performed in the same manner across multiple facilities, tools, and operators.
- Ensures comparability between test results.

The LCA can be thought of as the performing of the standardized test method using the background datasets identified in the PCR and the methodology described in the PCR. The LCA shall incorporate the life-cycle stages and modules allowed by the PCR. For most construction materials, the PCRs allow

inclusion of A1, A2, and A3 (refer to Figure 2.1). The current concrete PCR optionally allows for A4 and A5. ISO 14040 provides the required methodology for performing an LCA (ISO 2006).

The EPD reports the environmental impacts that were estimated in the LCA. EPDs for construction materials shall be ISO 21930 conformant (ISO 2016), ISO 14040 conformant (ISO 2006), sub-category PCR conformant, and include the environmental impacts associated with at least production (life-cycle stages A1-A3 (refer to Figure 2.1)). EPDs must be third-party reviewed and verified by the program operator for the sub-category PCR. In accordance with the Concrete PCR (NSF International 2024), the following environmental impacts shall be reported on all concrete EPDs:

- Global warming potential,
- Ozone depletion potential,
- Eutrophication potential,
- Acidification potential,
- Photochemical smog creation potential,
- Abiotic depletion potential for nonfossil mineral resources,
- Abiotic depletion potential for fossil resources,
- Total waste disposed, and
- Consumption of freshwater.

GWP is most often the focus of legislation and emissions reductions efforts because it is a leading environmental indicator for construction materials. GWP is presented in units of kilograms of carbon dioxide equivalents (kg CO<sub>2</sub>-eq), meaning that carbon dioxide and other gases released into the atmosphere are converted into units of CO<sub>2</sub>, such as methane which has 36 kg of CO<sub>2</sub>-eq for 1 kg of methane, are aggregated. Processes such as the calcination of clinker to make cement release high amounts of CO<sub>2</sub> into the atmosphere because of the dissociation of limestone (calcium carbonate (CaCO<sub>3</sub>)) into lime (calcium oxide (CaO)) and CO<sub>2</sub>.

EPDs can report LCA results or use data with a variety of different specificity levels, including:

- Product-specific.
- Facility-specific.
- Product-average.
- Facility-average.
- Manufacturer-average.
- Industry-average.

EPDs can even use combinations of these specificity levels for different constituents to develop its reported environmental impact estimates. For example, a product- and facility-specific cement EPD or an industry-average cement EPD may be used to inform a concrete mixture EPD, and therefore may change the results for two EPDs performed using the same foreground data (mixture proportions, constituent sourcing, constituent transportation, mixture production).

Construction materials PCRs indicate a preference for using product- and facility-specific constituent EPDs to inform downstream product EPDs. However, when those are not available, industry-average data is often used. In addition to constituent production information, developing concrete EPDs and/or estimating concrete GWP requires knowledge of the constituent materials, mixture design/constituent proportioning, transportation modes and corresponding distances for each constituent to move from its constituent production facility to the concrete production facility, and energy needs for concrete production.

## 2.2 Differentiating Tools from Datasets

Construction materials PCRs often prescribe specific datasets that must be used during the LCA to produce a conformant EPD. Those specific datasets, however, can be used by multiple different tools. Therefore, multiple different tools can be used to develop ISO 21930- and sub-category PCR-conformant EPDs. Using the same datasets within different tools allows for increased comparability from EPD to another for the same product class and functionality.

Datasets for LCAs store the environmental impacts associated with a unit of an activity or product, such as the amount of CO<sub>2</sub> associated with one ton×km of train transportation. Federal LCA Commons (Federal LCA Commons 2022) is one example of a dataset, whose database additionally includes datasets from the Environmental Protection Agency (EPA), the National Renewable Energy Laboratory (NREL) (NREL 2012), the National Energy Technology Laboratory (NETL) (NETL 2019), and Federal Highway Administration (FHWA) (Federal LCA Commons 2022). EcoInvent is another example of a dataset (EcoInvent 2024). The datasets from Federal LCA Commons are free and publicly available, while other datasets are often proprietary and are not free.

Tools for performing LCAs provide a method of identifying inputs, using the appropriate datasets, choosing an impact assessment method (typically the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 within the United States which was developed by the EPA (EPA 2022a)) to estimate the output environmental impacts associated with an activity or product. The tools help users perform an LCA and estimate the output results found in an EPD. Examples of tools include openLCA (GreenDelta 2024), FHWA's LCA Pave (FHWA 2022), SimaPro (SimaPro 2024), Theta (WAP Sustainability Consulting 2024), and Climate Earth's tool (Climate Earth 2024). Some of these tools are described in greater detail in later sections.

## 2.3 High-Level GWP Estimating Tools

A plethora of tools exist for estimating initial indications of GWP for a concrete mixture. Ease of use for these tools range significantly, but each can serve its purpose of providing an initial indication of GWP for a concrete mixture while waiting for an ISO-conformant EPD to be developed, reviewed, and verified. The tools identified in this section do NOT produce EPDs because the estimations will not be reviewed or verified. However, these tools can provide a starting point for identifying mixture designs that may reduce environmental impacts. When using any of these tools, pay extra attention to the units that should be entered and the units in which the results will be output. These tools include:

- ***NRMCA Concrete Carbon Calculator*** (NRMCA 2024). This tool is free, web-based, sponsored by the National Ready-Mixed Concrete Association (NRMCA), is based on the Climate Earth tool (Climate Earth 2024), and is conformant with the background datasets in the Concrete PCR (NSF International 2024). The user creates a free account, inputs the location of their concrete’s production, inputs the concrete’s 28-day compressive strength, and inputs their concrete mixture design. The tool uses the input location to determine the average transportation distances and modes that apply to each constituent within the concrete mixture design, and uses the average A3 production emissions estimated in the input location’s region based on the NRMCA industry-average LCA benchmarking report (Athena Sustainable Materials Institute 2021). The tool uses the industry-average EPDs for each constituent, where available, and datasets conformant with the current PCR to estimate the GWP of the concrete mixture. The tool also provides the relevant comparison GWP, such as the national or north central industry-average concrete GWP from the NRMCA industry-average LCA benchmarking report (Athena Sustainable Materials Institute 2021). The user should use the output estimates as only an initial indication of how the mixture design compares with the average concrete mixture because the average GWP from constituents’ productions, transportation, and concrete production are used. Note that when using this tool, there is an option to include sinks for carbonation of the concrete. The methodology for estimating the emissions offsets from carbonation has not been peer-reviewed and therefore should not be included in the emissions estimations.
- ***Slag Cement Association (SCA) LCA Calculator*** (SCA 2022). The SCA LCA calculator is an excel spreadsheet that can be downloaded for free from the SCA’s website. The excel spreadsheet, contains macros, which can trigger safety warnings from Microsoft Office that may be difficult to remove and allow for its use. However, the SCA website also provides instructions on how to disable the safety precautions to allow use of the spreadsheet if the user trusts the spreadsheet. The user of the spreadsheet inputs the concrete mixture(s) of interest, and the spreadsheet calculates the environmental impacts, with GWP reported as “Climate Change,” associated with each concrete mixture and its equivalent if 35% slag were used to replace cement. The spreadsheet appears to use average emissions intensity values from available industry-average constituent EPDs. The spreadsheet does not, however, provide the emissions intensities being used in the calculations and therefore it is unknown whether the calculations are consistent with the Concrete PCR (NSF International 2024). The tool was created based on data provided in the NRMCA industry-average benchmarking report (Athena Sustainable Materials Institute 2021).
- ***Guide for Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete*** (National Concrete Pavement Technology Center (CP Tech) 2024). This guide document is free and was published in the Spring of 2024 through a partnership between FHWA and CP Tech. The document is currently undergoing ballot to be turned into an AASHTO guide. The document includes a quantification section and methodology that guides the user through performing initial GWP estimates of a concrete mixture design. At the time of its publication and currently, the estimations produced using this guide are conformant with the Concrete PCR’s background datasets and methodology (NSF International 2024). However, this guide document is static and

therefore may experience periods of time between document updates where updated PCR and EPD publications may not be reflected. The guide document provides default emissions intensity factors (such as 919 kg of CO<sub>2</sub>-eq / metric ton of cement (Portland Cement Association (PCA) 2023a)) and the sources for those emissions intensity factors are provided. The emissions intensity factors for a constituent material can be input and used instead of the default values provided, allowing for use of product- and facility-specific cement EPDs, for example, to be used in the estimation instead of an industry-average. Additionally, the transportation distances for each constituent should be input and used. Therefore, the use of product- and facility-specific constituent production data and actual transportation distances of constituents may provide more context-specific estimations for concrete GWP than the NRMCA Concrete Carbon Calculator (NRMCA 2024).

- **FHWA LCAPave** (FHWA 2022). FHWA LCAPave is an experimental effort by FHWA to illustrate how a pavement LCA tool could be developed using common background datasets. At its time of development, it conformed with the subcategory PCRs for asphalt and concrete. It set the mark for tool development. LCA Pave is currently undergoing updates. While useful the tool can be difficult to access due to multiple levels of permissions needed to allow macros to run.
- **OpenLCA** (GreenDelta 2024). OpenLCA is an open source, free-to-use tool that can be loaded with Federal LCA Commons datasets (Federal LCA Commons 2022) to perform LCAs of any kind and develop life-cycle information models (LCIMs). The FHWA dataset from Federal LCA Commons (Federal LCA Commons 2022) has already built an LCIM for ready-mixed concrete environmental impacts estimations that can be used by any user. The background datasets in the existing LCIM for concrete entitled “concrete mixture framework” are conformant with the background datasets in the Concrete PCR (NSF International 2024). However, the default background datasets refer to industry-average EPD values for the constituents. Product- and facility-specific constituent production data can be used instead of industry-averages, but performing this action within openLCA is not intuitive to many users and may present a challenge. In general, openLCA is not an easy-to-use software for those with an elementary understanding of performing LCAs. There are, however, video tutorials for using openLCA (FHWA 2023a). The user will input the mixture design, transportation distances, and can change the power generation inputs (such as electricity, natural gas, waste, etc.) associated with A3 concrete production or can use the default values already listed in the “concrete mixture framework” LCIM. Therefore, the estimates from openLCA may provide more context-specific results than the other tools identified thus far.

Given that these tools do not produce ISO-conformant EPDs, users may question whether the results of these tools can be trusted. It is typically difficult to compare the accuracy of these tools with those from EPDs because mixture design and sourcing data of a ready-mixed concrete company are considered proprietary, making it difficult to know the mixture design that corresponds with an EPD. However, two control concrete mixtures from MNROADs paved in 2022 received EPDs and their mixture design information was provided as part of the research study. Therefore, the EPD results provided for the two mixtures could be compared with the estimations of some of the identified tools. All tools will present

differences between the verified EPD values and the estimated values from the free tools. There is not one estimating tool that will be better for every situation.

**Table 2.1 Comparison between verified EPD and estimating tools.**

Tool	Mixture 1		Mixture 2	
	GWP (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Difference with EPD (%)	GWP (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Difference with EPD (%)
Verified EPD	226.0		220.0	
openLCA (GreenDelta 2024)	187.9	-16.9%	208.6	-5.2%
SCA LCA Calculator (SCA 2022)	223.7	-1.0%	246.7	+12.1%
Guide for Reducing Cradle-to-Gate Embodied Carbon Emissions (CP Tech 2024)	202.1	-10.6%	227.2	+3.3%
NRMCA Concrete Carbon Calculator Tool (NRMCA 2024)	235.4	+4.2%	261.3	+18.8%

There is no substitute for developing an ISO-conformant, verified EPD. However, these free estimating tools can provide an initial indication of concrete mixture GWP while working towards developing an ISO-conformant, verified EPD for that concrete mixture. EPDs that are product-, facility-, and supply-chain specific will provide more precise estimations of your concrete mixture's environmental impacts.

There is not one estimating tool that is more appropriate than another for all concrete mixtures or all scenarios. Both the OpenLCA tool and the NRMCA tool can provide indicators of the GWP associated with a concrete mixture (GreenDelta 2024, NRMCA 2024). NRMCA - who is the program operator for the Concrete PCR - specifically identifies that the Theta and Climate Earth tools for developing an ISO-conformant EPD have been verified (NRMCA 2023).

We recommend that the user utilize the tool that allows them to input the most project-specific data available to them. For example, if only the concrete mixture proportions are known, the NRMCA tool may be a better choice for an initial indication of the concrete mixture's GWP. However, if transportation distances of the constituents, mixture proportions, and some production data is known, OpenLCA may be a more appropriate choice of tools for estimating the concrete mixture's GWP.

## 2.4 Tools for Producing EPDs

There are multiple different tools that can produce EPDs that can be third-party reviewed and verified. Two of those tools are used frequently to develop construction materials EPDs, and a third is emerging. All three tools are considered proprietary and are available to use through a license.

- **Theta** (WAP Sustainability Consulting 2024). The Theta tool was developed in partnership between WAP Sustainability Consulting and the Global Cement and Concrete Association (GCCA).
- **Climate Earth** (Climate Earth 2024). Climate Earth claims to have produced a majority of the existing concrete EPDs.
- **Labeling Sustainability** (Labeling Sustainability 2022). This tool provides EPDs that are ISO-conformant, third-party reviewed, and verified. However, some concrete EPDs resulting from this tool have been observed to use background datasets not conformant with the PCR (using EcolInvent for all background data (EcolInvent 2024)) and did not provide all of the information required by the Concrete PCR (NSF International 2024).

The developers of the Theta and Climate Earth tools underwent a harmonization process a few years ago that ensured concrete environmental impact results are within two percent of each other given the same inputs to both tools.

## 2.5 Other Educational Tools and Resources

Other educational tools and resources exist.

**EPDs Two-Pager** (Cooper and Mukherjee 2024b). In Appendix A of this report, a two-pager on EPDs is provided. The two-pager is a quick read that can be provided to anyone involved on a project, and it answers the following four questions:

- What is an EPD?
- How are EPDs developed?
- How do you use an EPD?
- How not to use an EPD?

**FHWA Every-Day Counts Program: EPDs for Sustainable Project Delivery** (FHWA 2024a).

[https://www.fhwa.dot.gov/innovation/everydaycounts/edc\\_7/sustainable\\_epds.cfm](https://www.fhwa.dot.gov/innovation/everydaycounts/edc_7/sustainable_epds.cfm). This website provides information about the state of practice for EPDs, what they are, and how they can be used. The site additionally includes a fact sheet on EPD and a link to a website all about EPDs (<https://www.fhwa.dot.gov/pavement/sustainability/epds/>).

**FHWA Community of Scholars** (FHWA 2023a). <https://sites.google.com/mtu.edu/community-of-scholars/home>. The FHWA Community of Scholars platform is a website that provides guidance to infrastructure owners including state departments of transportation (DOTs) and other public agencies regarding EPDs and LCAs. The Modules tab of the site provides videos educating the viewer on basic LCA guidance, information about different data types (such as foreground versus background data), and how to use openLCA to perform environmental impact estimations. The website provides a generic data collection framework for construction materials LCAs, specifically for those collecting construction data for life-cycle stages A4, A5, and B2-B5.

## Chapter 3: Workshop Summary

A workshop was held on November 30, 2022, from 1pm to 5pm in the Marriott West Minneapolis. The workshop received an impressive turnout of 40 people, including suppliers, producers, contractors, consultants, state engineers, and representatives from national industry organizations. The goal of the workshop was to provide producers with an overview of EPDs and how they are prepared. The workshop provided guidance on what EPDs are, how they are produced, and how a company might obtain them. It is important to note that EPDs are specific to each mix, at each plant, for a given project. A change in mixture constituents, constituent sourcing, or location of the plant may change the environmental impacts of a concrete mixture and therefore require a new EPD.

The workshop began with Dr. Amlan Mukherjee from WAP Sustainability Consulting welcoming the attendees to the workshop and providing purpose for the importance of the workshop. Workshop participants were seated in breakout teams. The breakout teams were divided with the intent of distributing at least one agency member, consultant, industry association member, and producer / supplier to each team. Dr. Mukherjee informed the participants about federal and local regulations appearing around the United States regarding sustainability of construction materials, federal initiatives that are working towards improving construction materials' sustainability, and possible upcoming opportunities for demonstration projects. These initiatives and opportunities include the Climate Challenge and Inflation Reduction Act.

Lianna Miller from WAP Sustainability Consulting then provided background detail on sustainability-related terms that industry members will need to be familiar with, including LCAs, EPDs, and PCRs. Miller explained how PCRs are used to standardize the method and data used for performing an EPD. An EPD summarizes a product's potential to impact the environment communicating the outcomes of a life-cycle assessment conducted in conformance with a PCR. An EPD has, on occasion, been compared to a nutritional facts label in how it communicates potential environmental impact information. Global warming potential (GWP) and energy use estimations are currently the environmental impact indicators being used from an EPD. All the other midpoint indicators also contain valuable information for considering localized impacts.

Discussion then ensued about the process of developing PCRs, the standardization of background datasets, and how an EPD may be used by project owners. Representatives of program operators for asphalt and concrete mixtures for North America were present in the room and they informed of their verified software that improves EPD reliability and helps with harmonizing data and methods.

Dr. Tom van Dam from NCE Consulting (at the time of the workshop) provided additional context into how EPD requirements are developing in other regions, the typical timeline for specifying EPDs, and how this may affect the industry.

Workshop participants performed an interactive activity in their breakout teams looking at a variety of different industry EPDs and answering the following questions for each EPD:

- Does the EPD use a functional or declared unit? Where is that information?
- Where is the scope of the EPD identified?
- Where is the system boundary of the EPD identified?
- Where is the information of background datasets provided?
- Where can you find the material's GWP?
- How long is the EPD valid for?

The workshop EPDs are publicly available, and belonged to cement suppliers, concrete ready-mix producers, asphalt producers, and aggregate suppliers.

During the activity, Dr. Mukherjee additionally presented general rules of thumb for industry members regarding construction materials sustainability, such as:

- Concrete GWP is typically between 200 and 400 kg of CO<sub>2</sub>-eq/m<sup>3</sup>, depending highly on the cement content.
- Ordinary portland cement production generally emits 0.92 kg of CO<sub>2</sub>-eq per kg of cement.
- Portland limestone cement production generally emits 0.84 kg of CO<sub>2</sub>-eq per kg of cement.
- Asphalt mixture production generally has a GWP in the range of 55 – 65 kg of CO<sub>2</sub>-eq/short ton.

After the EPD interactive activity, Michelle Cooper from Michigan Technological University presented on the synergy between concrete sustainability and performance. Additionally, she provided data from field and laboratory mixture designs comparing mechanical performance and durability performance with GWP. No correlation was identified between compressive strength and GWP, while durability performance tended to improve with lower GWP mixture designs (Helsel et al. 2023).

Following this presentation, attendees returned to their breakout teams for a second interactive activity. This activity modeled a procurement scenario and asked each team member to consider and discuss their roles in the EPD process while answering the following questions:

- Where do I see myself fitting into the LCA information flow?
- What information will I need from other stakeholders to conduct my duties?
- What information will I need to provide to other stakeholders to conduct my duties?
- What is my current level of preparedness and what support do I need to be fully prepared?

At the end of this activity, each team was given the opportunity to share main takeaways and discussion points from within their group. These concepts included:

- Concerns:
  - That designers on the front end of a project not knowing a lot of the construction stage information that may change the GWP.
  - The extent to which incentives and pay factors should be involved.

- The burden of reporting and compliance.
- Impact on mobile batch plants.
- How industry can utilize funding from the Inflation Reduction Act.
- Need for clarity on how the construction phase aspects work for an EPD. What needs to be included? To how much detail? What about when construction scheduling and staging changes?
- EPD utilization: materials and plans for construction that change between procurement and installation phases of a project.
- Need for harmony in EPD requirements across regions and states to facilitate transport of materials across state lines. For example, there are no cement producers in Minnesota or Wisconsin, so they get material shipped from other states. How might this impact the industry if EPD requirements vary by state, particularly in scope?
- Need to consider flexibility of the requirements and tasks to the end user.
- Mixture designs are tweaked on the fly. At what point in changes to the mixture design is an EPD out of tolerance or out of conformance?
- Lessons / Realizations:
  - That until we have GWP values from many industry EPDs in the region, we will have more questions than answers. We may need several years of data to get a baseline number and understanding of project GWPs.
  - That there will be a lot of values to track that must be input to EPDs. This generated discussion about possibly using an e-ticketing system to simplify the data collection and tracking process.
  - Recognition that all members of the industry need to be on board for EPDs to be successfully developed and utilized.
  - Many aspects of the EPD will need to be provided by the general contractor, and many aspects of the EPD will also need to be provided to the general contractor.
  - Understanding the exact scope of an EPD is essential.
  - How to evaluate products that are reused on site.
- Possibilities / Ideas:
  - Specification relief.
  - It may be beneficial to institute a minimum project size that is affected by EPD requirements. The amount of effort and cost associated with developing an EPD may not be worthwhile for small projects such as a 20 ft sidewalk.

Dr. Van Dam identified clinker reduction as the main lever to pull in reducing GWP. Dr. Van Dam then presented a short discussion on the industry's concrete mixture overdesign and the inconsistencies in cement content requirements throughout the United States, even between regions with similar climates.

## Chapter 4: Survey of Specifications Adopted in Other Jurisdictions

With low-carbon materials becoming increasingly identified as a decarbonization strategy, specifications and thresholds have been developed to target construction materials' environmental impacts reductions. Overall, the specifications typically identify a minimum amount of concrete on the project to which the low-carbon requirements apply and identify GWP limits to the concrete mixtures as calculated using a provided methodology or stated on an EPD. Most of the GWP limits are classified by concrete strength, likely because the NRMCA benchmarking report provides that classification (Athena Sustainable Materials Institute 2021). Table 4.1 provides a summary of the GWP benchmarks identified by other jurisdictions for concrete with 4,000 psi compressive strength.

The United States' Inflation Reduction Act, which was passed in 2022, tasked the General Services Administration (GSA) and FHWA with procuring low-carbon transportation materials (Inflation Reduction Act 2022). FHWA was appropriated funding for the Low-Carbon Transportation Materials (LCTM) Grant Program which allows for the incentivization or incremental cost reimbursement of steel, concrete, glass, asphalt, and assemblies with substantially lower levels of embodied carbon emissions (FHWA 2023b). The EPA determined the definition of substantially lower levels of embodied carbon emissions for the LCTM within an interim determination (EPA 2022b). A material with substantially lower levels of embodied carbon emissions has a GWP in the lowest 20<sup>th</sup> percentile or, if not available within the region, in the lowest 40<sup>th</sup> percentile or, if not available within the region, better than average (EPA 2022b, FHWA 2024b). Therefore, the distributions for materials' GWPs must be determined, and the development of those distributions are currently in progress by their respective industries.

The GSA approach for low-carbon concrete provided GWP limits to all concrete mixtures depending on strength class of the concrete, and the type of concrete (standard, high early strength, or lightweight) (GSA 2023). The GSA allows exemptions if the only concrete suppliers in the maximum transportation range for the project are small businesses currently without EPDs and do not offer concrete mixtures meeting the limits. GSA's GWP limits apply to all concrete mixtures where at least 10 yd<sup>3</sup> of concrete are used on a project.

The NRMCA previously published a benchmarking report and industry-average EPD which classified different average GWPs by 28-day compressive strengths (Athena Sustainable Materials Institute 2021, NRMCA 2021). The same benchmarking report also provided average GWPs by strength class for eight different regions of the United States (Athena Sustainable Materials Institute 2021). The NRMCA benchmarking report has recently been updated to incorporate a statistical addendum that includes 20<sup>th</sup>, 40<sup>th</sup>, and 50<sup>th</sup> percentile GWP values for each compressive strength class of concrete. The NRMCA national industry average GWP values were adopted by the Federal Emergency Management Agency (FEMA) as the thresholds for sustainable concrete mixture procurement (FEMA 2024). Minnesota falls within the North Central region identified in the NRMCA benchmarking report. Next year, NRMCA will be gathering more recent data for concrete EPDs to update the benchmarking report.

In 2023, the American Concrete Institute (ACI) created committee 323 to develop a Low-Carbon Concrete Code (ACI Committee 323, 2024). The code suggested a project-wide GWP threshold for low-carbon concrete of  $\alpha$  multiplied by the industry-average GWP. The default value for  $\alpha$  was identified as 0.85 but can be changed by an infrastructure owner implementing the code if a localized analysis is performed.

Marin County in California additionally has implemented a low-carbon concrete specification that institutes a maximum ordinary portland cement content and maximum embodied carbon emissions (GWP) per EPD depending on the minimum specified 28-day compressive strength (Marin County 2019). The specification allows for a 30% increase in these limits if a building official requires the concrete to be high early strength. The specification also allows increases in maximum cement content if a blended cement is used instead of ordinary portland cement and a “plant-specific” EPD demonstrating the GWP is less than 1,040 kg of CO<sub>2</sub>-eq/metric ton is provided for the blended cement. The specification incorporates limitations to individual concrete mixture GWPs as well as project limits. Exemptions are allowed if a project applicant proves hardship or infeasibility to meet the requirements, such as lack of commercially available material to comply with the requirements, disproportionate cost, and historic integrity.

New York State (NYS) has a low-carbon concrete specification (NYS 2022a) that will be updated in late 2024 to reflect the requirements of the NYS Buy Clean Concrete Guidelines (NYS 2022b). At this time, the NYS low-carbon concrete specification (NYS 2022a) requires EPDs to be provided when they exist and GWP to be estimated (a methodology is provided) when an EPD does not exist. Mix designs have a limiting portland cement content depending on the concrete’s application, and supplementary cementitious materials (SCMs) must replace cement content by at least 30%. In addition, blended aggregates must be used when available to reduce paste content. Buy clean guidelines (NYS 2022b) will require all concrete mixtures used on state construction projects to have an EPD. This requirement will apply to state agency contracts over \$1 million with at least 50 yd<sup>3</sup> of concrete and NYSDOT contracts over \$3 million with at least 200 yd<sup>3</sup> of concrete. Exemptions are similar to those required by Marin County. However, the guideline limits emissions to 150% of the NRMCA’s eastern region average (Athena Sustainable Materials Institute 2021).

Colorado buy clean efforts have also required that EPDs be collected for construction materials, including concrete, and GWP thresholds be developed for sustainable project procurement (Colorado 2023, Colorado 2024). Colorado’s requirements require that the thresholds be reviewed and revised periodically, but do not allow the thresholds to be decreased at any time. Colorado is currently using the NRMCA rocky mountain regional average GWP for concrete while EPDs specific to Colorado’s concrete industry are collected.

The City of Portland Oregon allows GWP limits to be applied on a per mix or project average basis (City of Portland 2022). The limits for concrete were determined based on the NRMCA’s pacific northwest regional GWP averages. For the project average basis calculations, the volume of each concrete mixture is multiplied by each concrete’s GWP.

**Table 4.1 Low-carbon thresholds for 4000 psi concrete GWP in other jurisdictions.**

Jurisdiction	Threshold Type	Region	Low-Carbon Concrete GWP Threshold (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Reference
EPA	≤ 20 <sup>th</sup> percentile	National	Varies	(EPA 2022)
EPA	≤ 40 <sup>th</sup> percentile	National	Varies	(EPA 2022)
EPA	< Average	National	Varies	(EPA 2022)
GSA	≤ 20 <sup>th</sup> percentile	National	284	(GSA 2023)
GSA	≤ 40 <sup>th</sup> percentile	National	326	(GSA 2023)
GSA	< Average	National	352	(GSA 2023)
FHWA	≤ 20 <sup>th</sup> percentile	North Central	284	(FHWA 2024b)
FHWA	≤ 40 <sup>th</sup> percentile	North Central	326	(FHWA 2024b)
FHWA	< Average	North Central	352	(FHWA 2024b)
FEMA	NRMCA industry average	National	308	(FEMA 2024)
ACI	0.85×NRMCA industry-average	National	262	(ACI Committee 323 2024)
ACI	0.85×NRMCA industry-average	North Central	259	(ACI Committee 323 2024)
Marin County, California	Maximum cement content or GWP threshold	Marin County	< 1,040 kg CO <sub>2</sub> -eq/metric ton	(Marin County 2019)
Marin County, California	For 4,500 psi	Marin County	313	(Marin County 2019)
New York State	< 150% of NRMCA’s regional average	Eastern Region	434	(NYS 2022b)
Colorado	Based on NRMCA regional average	Rocky Mountain Region	301	(Colorado 2024)
City of Portland, Oregon	Per mix or per project on a volume basis based on NRMCA regional average	Pacific Northwest Region	316	(City of Portland 2022)

## Chapter 5: Concrete EPD Data Collection

In order to begin reaching the objectives of this project, EPDs were collected from a variety of sources with the goal of identifying only those pertaining to concrete used in Minnesota. Therefore, EPDs were collected from:

- Collaborative and cooperative concrete ready-mix suppliers providing concrete in and around Minnesota (32 mix designs).
- Building Transparency's EC3 Tool (813 EPDs) (Building Transparency 2021).
- NRMCA (44 EPDs) (NRMCA 2023).

EPDs collected for concrete mixtures used in Minnesota are additionally posted here:

<https://sites.google.com/mtu.edu/mndotworkshop/epds> (Cooper and Mukherjee 2024c). The EPDs collected from the EC3 tool are not posted at that location due to the quantity of EPDs from Minnesotan ready-mix plants but can be found from the EC3 tool (Building Transparency 2021). Many of these EPDs can be identified as pertaining to a Minnesotan concrete mixture because they were developed for ready-mixed concrete plants located in Minnesota.

# Chapter 6: Recommendations for Formal Data Collection and Archival Protocol

## 6.1 Recommendations

LCA data for transportation infrastructure projects should be collected within a few weeks of construction initiation. This timeframe allows for the highest degree of data specificity while allowing enough time for the infrastructure owner to review and provide feedback to the contractor on the project's sustainability. LCA data for the project holistically can be collected using the Data Collection Protocol spreadsheet provided in Appendix B. The spreadsheet allows for data collection that facilitates the estimation of environmental impacts from life-cycle stages A1-A5. EPDs should be collected during this same timeframe along with the mixture designs, and if collected can negate the need to collect certain materials-related LCA data within the data collection protocol spreadsheet. An EPD Submittal Package Specification is provided in Appendix C describing additional information that should be submitted along with EPDs.

The EPD Submittal Package should include production quantities for each material used on the project, as well as the associated mix design for each asphalt and concrete mixture EPD. The package should have all documents provided labeled with the infrastructure owners' identification for each material. The submittal package specification includes an attestation of whether any carbon credits have been sold or transferred in relation to the relevant products. The submittal package additionally includes an attestation that the EPDs provided are for the materials placed on the project site.

## 6.2 Why to Include Carbon Credits Information in the EPD Submittal Package

Carbon credits are becoming more commonly used within the construction industry to create a business case for decarbonization efforts. However, carbon credits are distributed via the voluntary carbon market, which requires that the decarbonization occurring must be performed voluntarily. Additionally, the distributors of carbon credits typically develop their own methodology for calculating the baseline and carbon credits applied for any given scenario, thus the methodologies also differ from distributor to distributor. Carbon credits within the construction industry are often being applied for perceived improvements in cement GWP. However, the baseline from which those carbon credits are calculated may not be realistic. For example, providing carbon credits to cement manufacturers for producing Type IL cement instead of Type I/II cement, despite that Type IL is the current norm for the industry. The industry is currently under discussions, as well, as to whether the carbon credits should be owned by the infrastructure owner, because they effectively are purchasing the product that the decarbonized material creates, or by the material producer.

The inclusion of attestations regarding carbon credits, therefore, are provided so that infrastructure owners can make decisions about whether the transfer of carbon credits affects the eligibility of low-

carbon incentivization for a material. Infrastructure owners may consider the following scenarios during their determination of whether carbon credits effect incentivization eligibility:

- A project receives grant money to implement low-carbon materials on projects. The infrastructure owner therefore specifies low-carbon materials to be placed on the project to meet the criteria for grant eligibility. While applying for the grant was voluntary for the infrastructure owner, once that grant money is received, the use of low-carbon materials is not voluntary. The contractor's and supplier's use of low-carbon materials is also no longer voluntary and is a requirement of the project. Therefore, carbon credits should not be received for their use on this project. However, the distributors of carbon credits on the voluntary carbon market may not know that the use of these materials was mandated.
- An infrastructure owner specifies the use of low-carbon materials on a project, whether as a requirement from legislation, grant funds, or a special provision for piloting. The contractor's and supplier's use of low-carbon materials is not voluntary and is a requirement of the project.
  - Carbon credits should not be received for their use on this project because the use of low-carbon materials was not voluntary.
  - Carbon credits should also not be sold for their use on this project because that allows another entity to claim the differential environmental impact potentials for another product. The product placed on the project was therefore not low-carbon. Using EPDs for establishing sustainable project procurement would not safeguard against this concern because EPDs report environmental impact potentials of the material without influence of carbon credits. Therefore, there is potential for a supplier to submit EPDs indicating that low-carbon materials were used and thus receive incentives AND sell carbon credits that negate project decarbonization efforts. The EPD Submittal Package's inclusion of attestation of carbon credit transfer is intended to assist in safeguarding against this scenario.
  - Carbon credits should not be bought and applied to the materials used on site to meet the low-carbon requirements because low-carbon claim would not be representative of the materials placed on site. EPDs do not currently allow influence of carbon credits on the reported environmental impact potentials. Therefore, the use of EPDs for establishing sustainable project procurement mitigates this concern.
- An infrastructure owner incentivizes the use of low-carbon materials on a project, whether as a requirement from legislation, grant funds, or a special provision for piloting. The incentive is not a mandatory requirement to use low-carbon materials on the project. The contractor's and supplier's use of low-carbon materials is voluntary.
  - The infrastructure owner may determine that selling carbon credits on this project removes the eligibility for incentives. Selling carbon credits allows another entity to claim the differential environmental impact potentials for another product. The product placed on the project was therefore not low carbon. Using EPDs for establishing sustainable project procurement would not safeguard against this concern because EPDs report environmental impact potentials of the material without influence of carbon credits. Therefore, there is potential for a supplier to submit EPDs indicating that

low-carbon materials were used and thus receive incentives AND sell carbon credits that negate project decarbonization efforts. The EPD Submittal Package's inclusion of attestation of carbon credit transfer is intended to assist in safeguarding against this scenario.

- Carbon credits should not be bought and applied to the materials used on site to meet the low-carbon requirements because low carbon claim would not be representative of the materials placed on site. EPDs do not currently allow influence of carbon credits on the reported environmental impact potentials. Therefore, the use of EPDs for establishing sustainable project procurement mitigates this concern.

# Chapter 7: Characterization and Benchmarking of Ready-Mix Concrete EPDs

## 7.1 Benchmarking Methodology and Results

Benchmarking is defined in ISO 21678 as the “process of collecting, analyzing, and relating performance data of comparable...construction products” and results in “values indicating the relative performance required for a particular attribute [environment impacts and sustainability, in this case] on a relative scale” (ISO 2020). In the context of transportation materials’ sustainability, benchmarking ensures that the environmental performance of a materials is being assessed within the constraints of its market, discounting for factors outside a contractor’s control.

The EPDs collected in section 5.0, including those from collaborative ready-mix producers, EC3, and NRMCA, were used to develop benchmarks for Minnesotan concrete. The benchmarks created herein can serve to provide thresholds for procurement, if desired, as more project-specific EPDs are collected based on product- and facility-specific data. Using the EPD Submittal Package specification that is previously described in section 6.0 and included in Appendix C, production quantities of each mixture design will also be collected along with each mixture’s EPD. With production quantities and project-specific EPDs for the concrete mixtures being placed on MnDOT project, the methodology described in this section can be performed again to develop production-weighted benchmarks.

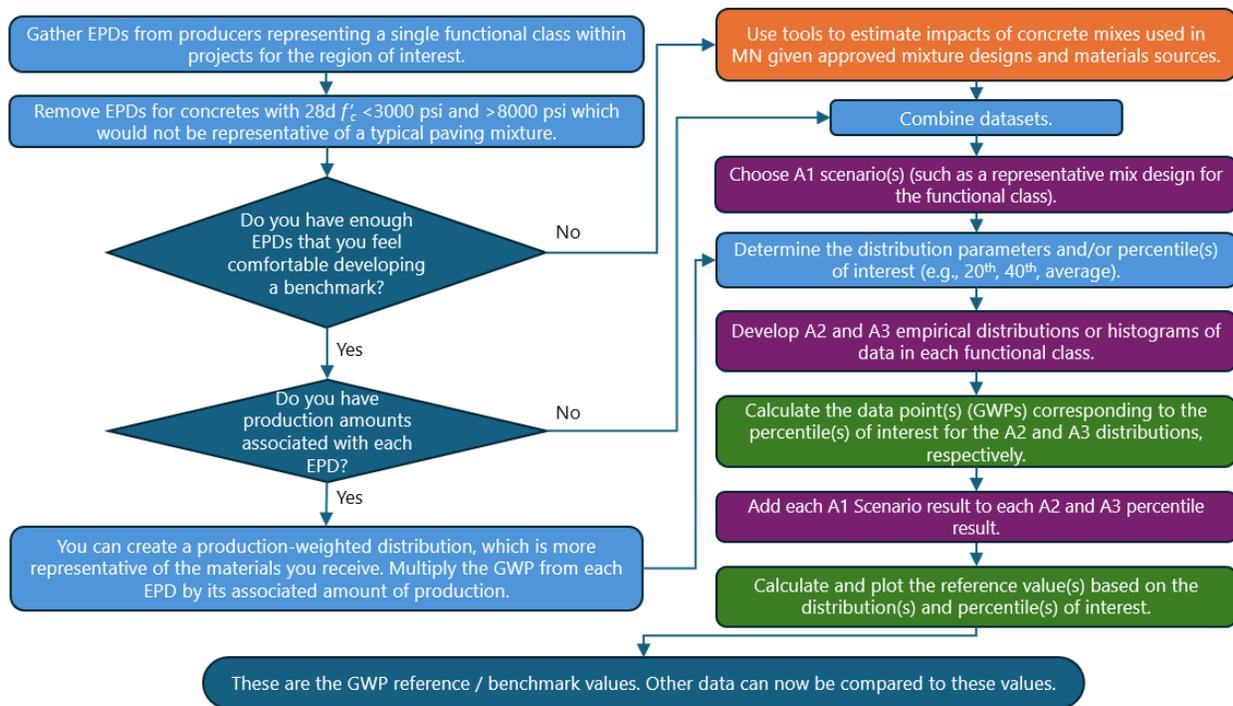


Figure 7.1 Flow chart of benchmarking methodology (Cooper and Mukherjee 2025).

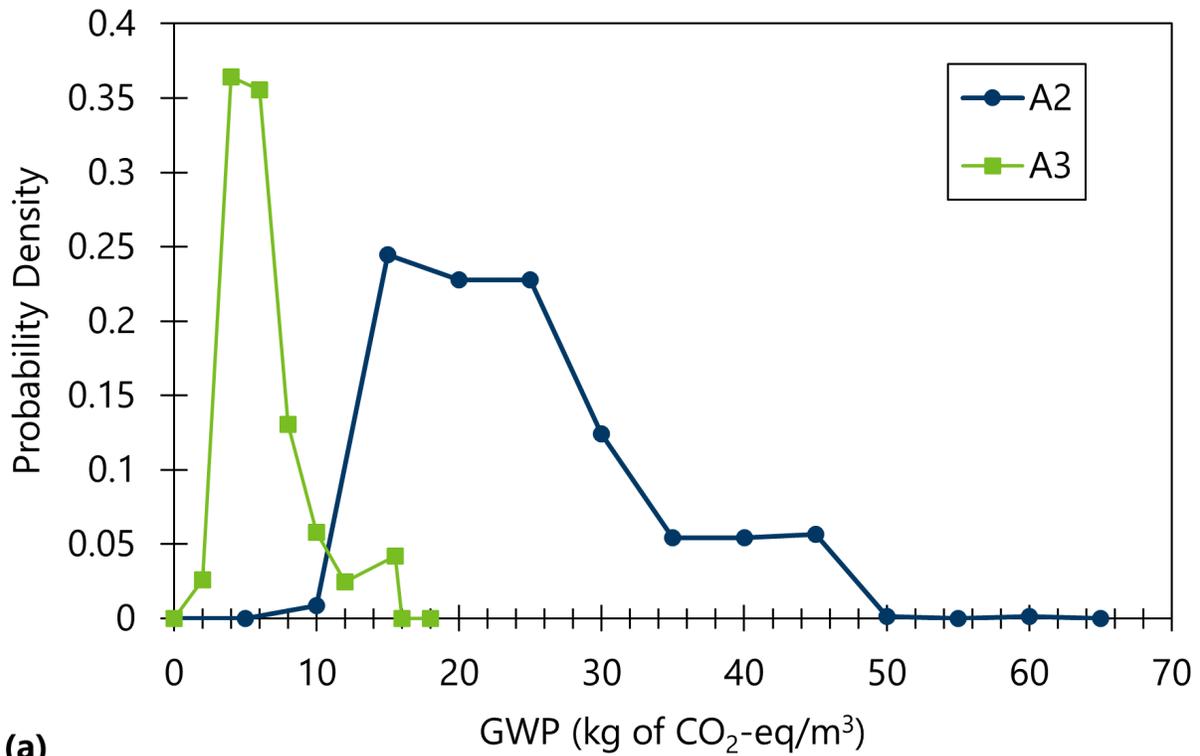
As described in Figure 7.1, A1 scenarios were chosen for benchmarking environmental performance. Three scenarios were identified based on the approved project mixture designs from MnDOT: paving, high-early-strength (HES), and all applications. The A1 GWPs were estimated using the Guide document (CP Tech 2024) for each mixture design provided from MnDOT for the typical paving and HES mixtures. The variations in GWP from mixture proportioning are demonstrated in Figure 7.2.

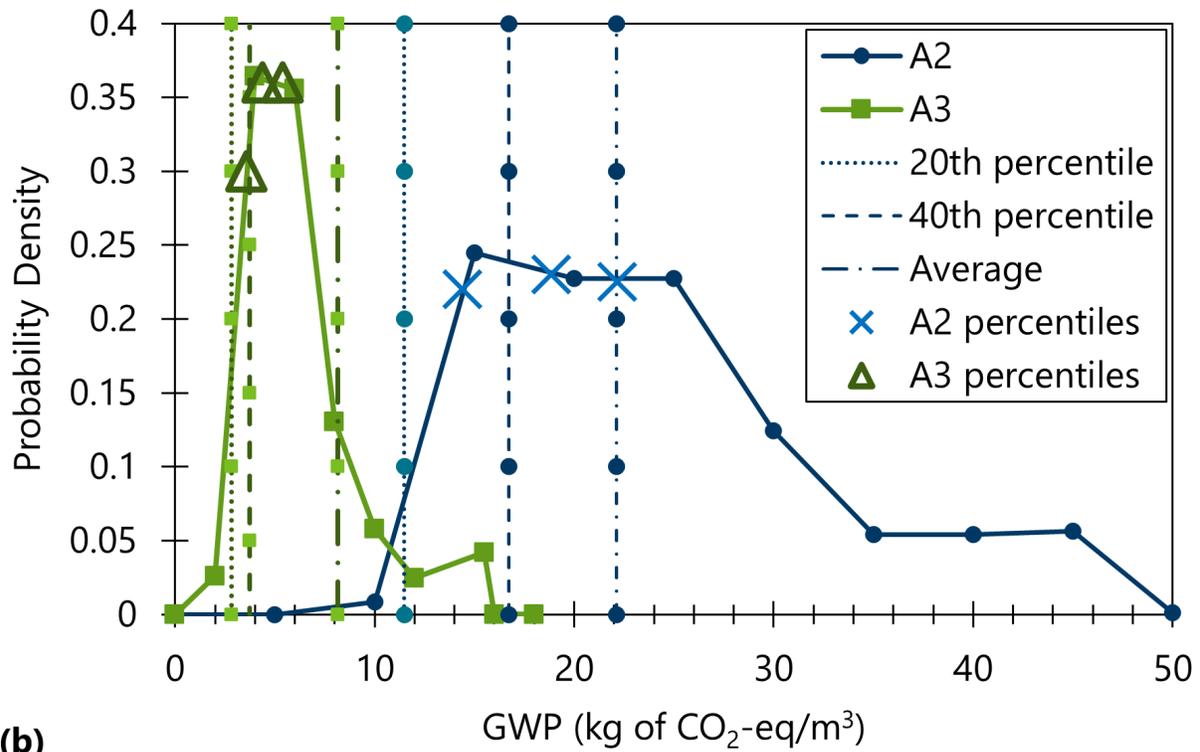


**Figure 7.2 Variations in estimated GWP based on differences in concrete mixture designs used on Minnesotan projects.**

Using the EPDs collected from EC3 (Building Transparency 2021) and NRMCA (NRMCA 2023) which originated from Minnesotan ready-mix plants, separate A2 and A3 distributions were developed. Those

A2 and A3 distributions were used to determine the 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, 50<sup>th</sup> percentile, and average values. Figure 7.3 displays the A2 and A3 distributions based on the values reported in EPDs. In addition, Figure 7.3 shows the distributions in comparison to the 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, and average values for A2 and A3 from this study's analysis and the NRMCA north central regional benchmark. The A2 values suggested in the NRMCA benchmarks (Salazar et al. 2024) are lower than those for the same values determined in this study. The A3 values are comparable for this study and the NRMCA benchmark. The A3 distribution shown is based on ready-mixed concrete. Limited EPDs have been developed and published for mobile batch plant produced concrete.



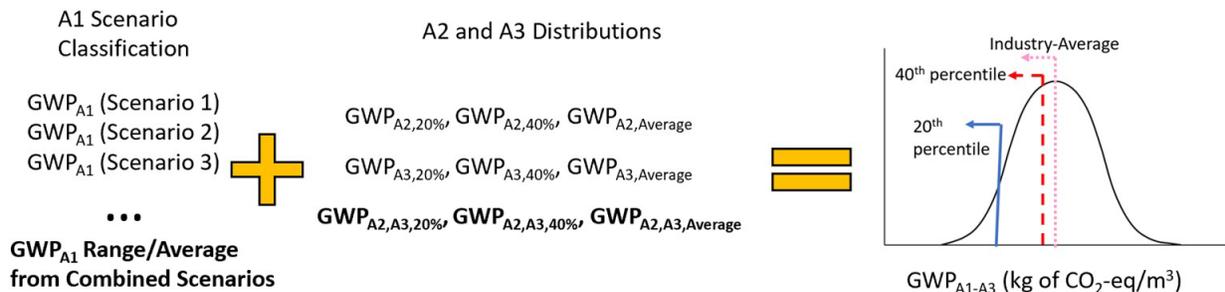


**(b)** Figure 7.3 A2 and A3 GWP distributions based on EPDs with (a) showing the distributions in this study and (b) showing the same in comparison with the 20<sup>th</sup> and 40<sup>th</sup> percentiles as well as average values from the NRMCA statistical addendum / FHWA LCTM thresholds (labeled as 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, and average) and from this analysis (labeled as A2 percentiles and A3 percentiles) (Salazar et al. 2024, FHWA 2024b).

Table 7.1 describes the A1 GWPs for the typical paving and HES mixture designs, as well as the percentile values of interest for the A2 and A3 distributions, and the combinations. The range of A1 GWPs for both scenarios are additionally provided in Table 7.1 to demonstrate the similarity between mixtures of the same scenario used in this analysis. Figure 7.4 describes how the A1 scenario GWP values are added to the percentile GWP values for the A2 and A3 distributions, which are the A1-A3 combinations presented in Table 7.1.

**Table 7.1 Benchmark GWP for paving, HES, and all applications of concrete mixtures**

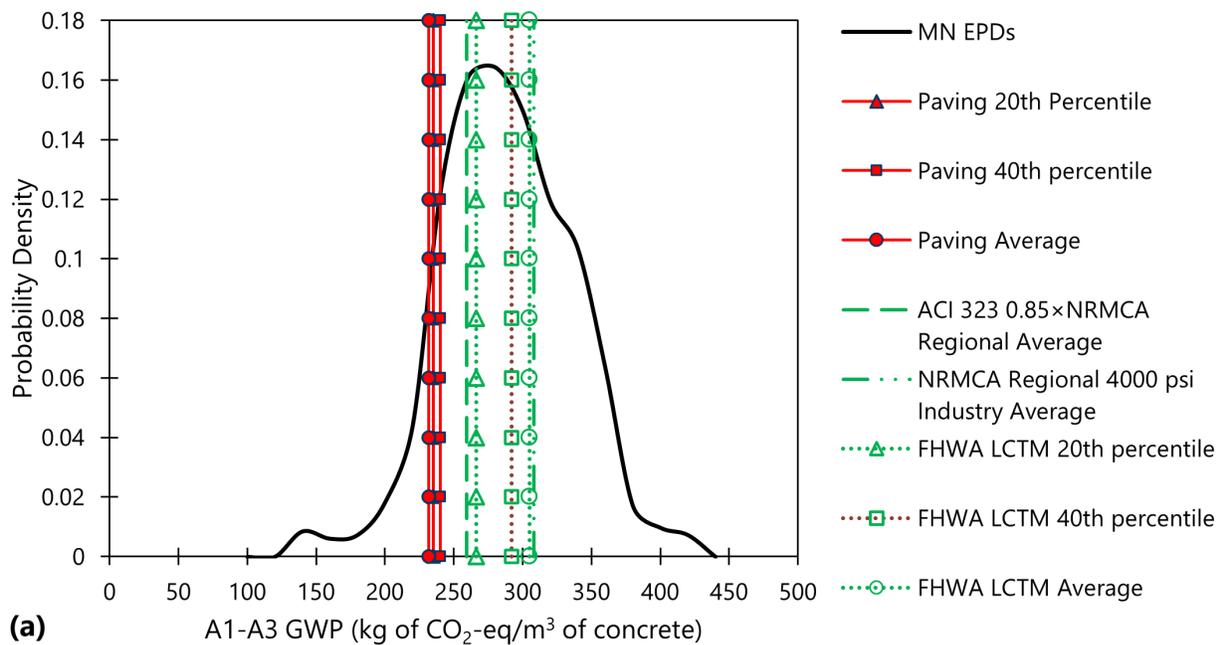
Life-Cycle Stage	Parameter	Paving Concrete	HES Concrete	All Other Applications
A1 GWP used to describe the scenario	Average	217.49	252.80	251.64
	Median	216.78	265.24	253
	Minimum	209.15	227.87	114
	Maximum	231.91	265.26	680
A2 GWP	20 <sup>th</sup> percentile	14.40	14.40	14.40
	40 <sup>th</sup> percentile	18.86	18.86	18.86
	50 <sup>th</sup> percentile	20.30	20.30	20.30
	Average	22.16	22.16	22.16
A3 GWP	20 <sup>th</sup> percentile	3.57	3.57	3.57
	40 <sup>th</sup> percentile	4.38	4.38	4.38
	50 <sup>th</sup> percentile	4.89	4.89	4.89
	Average	5.40	5.40	5.40
A1-A3 GWP	20 <sup>th</sup> percentile	234.75	270.77	269.61
	40 <sup>th</sup> percentile	240.02	276.04	274.88
	50 <sup>th</sup> percentile	241.97	277.99	276.83
	Average	245.05	280.36	279.20

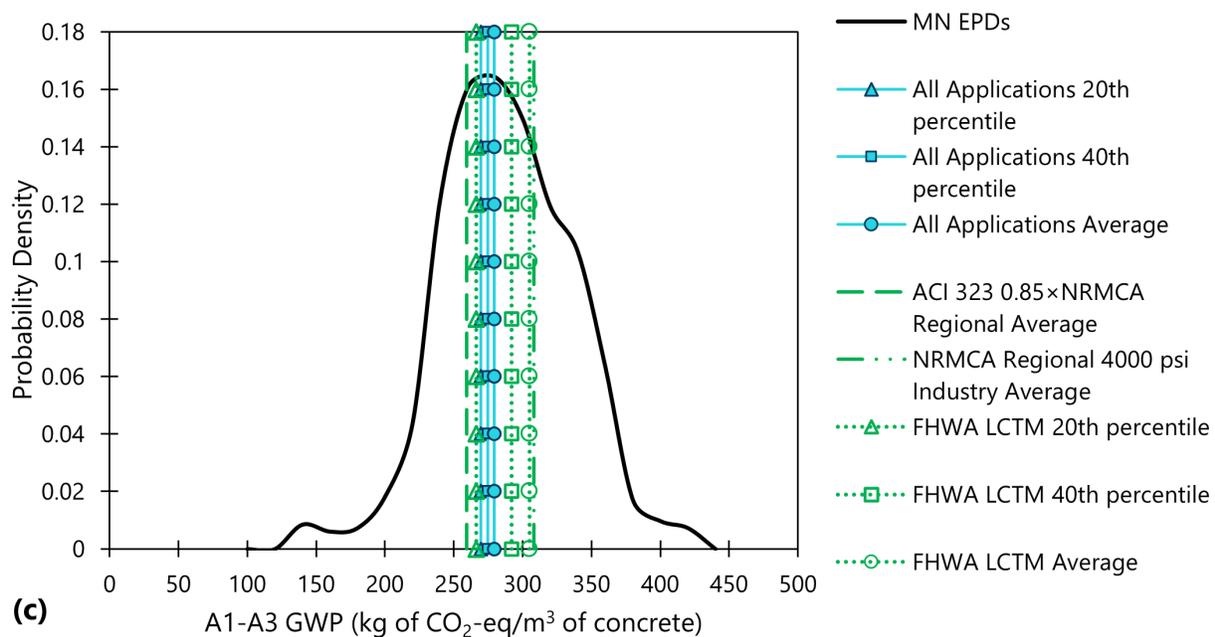
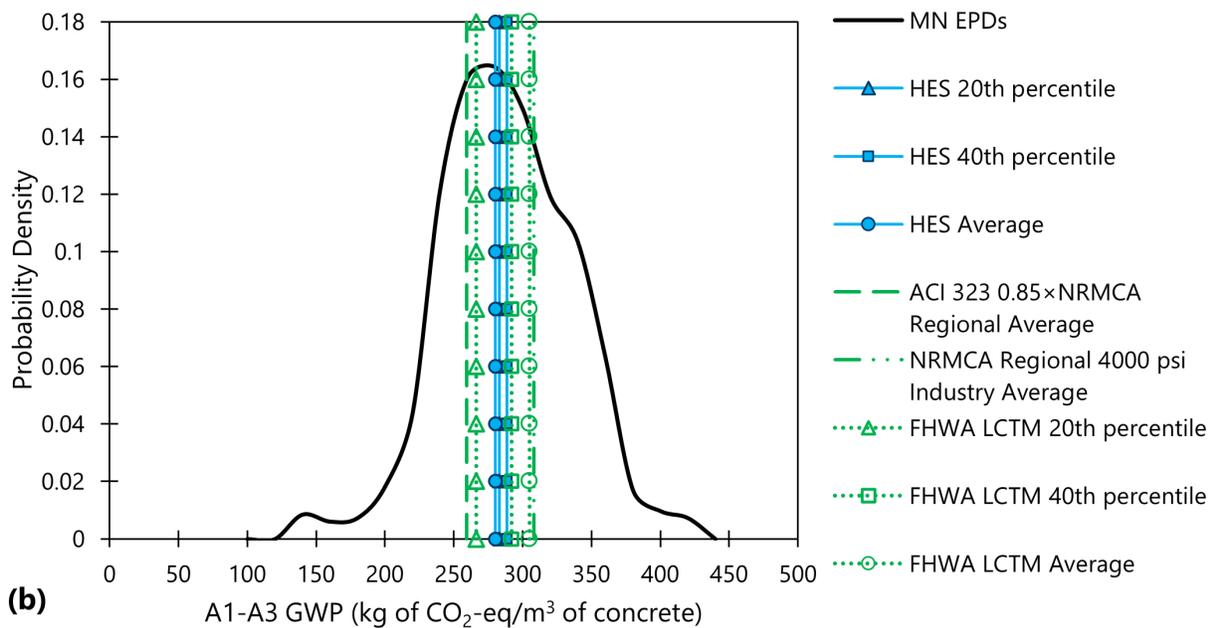


**Figure 7.4 Illustration of how the A1 scenario GWP values combine with the A2 and A3 distribution percentile values of interest to develop benchmarks at the reference values of interest (Cooper and Mukherjee 2025).**

Figure 7.5 describes the A1-A3 GWP reference values for Minnesotan concrete paving, HES mixtures, and all application mixtures. The benchmarks presented in Figure 7.5 are those determined using the methodology described in Figure 7.4, and the values presented in Table 7.1. The 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, and average values show tight distributions for each of the three scenarios. The tight distributions are related to the limited range of the A2 and A3 distributions, as shown in Figure 7.3, demonstrating that the transportation distances of materials for the concrete mixtures in Minnesota and the production efficiencies of plants in Minnesota are similar from one concrete supplier to another.

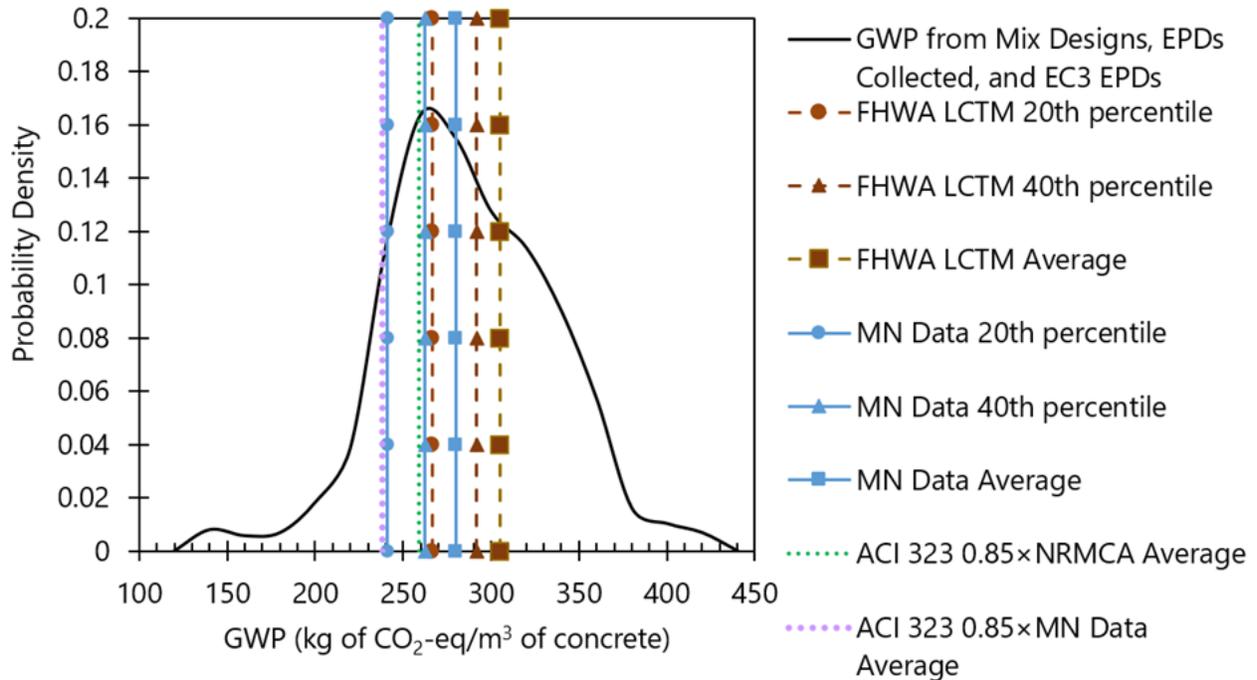
Figure 7.5 compares the 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, and average values for each application's distribution with other industry benchmarks. The ACI 323 Low-Carbon Concrete Code (ACI Committee 323 2024) previously mentioned recommends a benchmark of 0.85 multiplied by the NRMCA national or regional industry average from the most recent benchmarking report (Athena Sustainable Materials Institute 2021). The NRMCA national industry average for 4,000 psi concrete, which was the strength class observed for most EPDs, is 308.17 kg of CO<sub>2</sub>-eq/m<sup>3</sup> (Athena Sustainable Materials Institute 2021) and therefore the ACI 323 suggested value is 261.94 kg of CO<sub>2</sub>-eq/m<sup>3</sup>. The NRMCA north central regional industry average for 4,000 psi concrete is 305 kg of CO<sub>2</sub>-eq/m<sup>3</sup> (Salazar et al. 2024). The ACI 323 benchmark of 0.85 times the industry average was also applied for comparison purposes with the average determined for the Minnesota-specific mixtures during this analysis and has a value of 208.29 kg of CO<sub>2</sub>-eq/m<sup>3</sup> of concrete (ACI Committee 323 2024).





**Figure 7.5 A1-A3 GWP reference values by application based on the benchmarking process described in Figure 7.4 and compared to 4,000 psi concrete industry benchmarks for (a) paving applications, (b) high-early-strength (HES) applications, and (c) all other applications.**

For comparison, Figure 7.6 displays the empirical probability distribution of GWPs reported in the gathered Minnesotan EPDs based on the combined A1-A3 GWPs instead of developing the benchmarks based on A1 scenarios with A2 and A3 distributions. The A1-A3 GWP values are compared with other reference values created by industry.



**Figure 7.6 Empirical distribution of combined A1-A3 GWPs from Minnesotan EPDs and corresponding reference values compared with industry benchmarks.**

## 7.2 Recommended GWP Intervals for Acceptance

When accepting EPDs to be archived, the agency should check that the EPD is representative of materials used on the project. The EPDs should include a unique identifier that can be used to trace the EPD to the mix design information known by the agency. This connection could allow the agency to map A2 transportation distances between sources and batch plants, view mix design proportions, and verify data sources. Agencies can perform an automated estimation of environmental impacts to provide a preliminary assessment that the EPD results align with engineering judgement. An audit program should be developed to ensure quality of EPDs. To help achieve these goals and tie environmental performance with mechanical and durability performance, a software program or integration with platforms such as e-ticketing could be used.

When developing GWP intervals for acceptance, it is first important to note that A3 environmental impacts are expected to differ significantly depending on whether a ready-mix plant or mobile batch plant produced the concrete. While mobile batch plant production can have impacts aligning with ready-mix plants, concrete mobile batch plant production in this study resulted in A1-A3 GWPs up to 39 percent higher than expected from a ready-mix plant. However, mobile batch plants may provide significant advantages to contractor means and methods, reduced construction timeframes, and potentially better consistency of concrete production that translates to improved concrete quality. For these reasons along with potential cost implications, the agency should not disincentivize or preclude using mobile batch plant production. Therefore, GWP intervals for acceptance should be different for ready-mix concrete versus mobile batch plant concrete while EPDs continue to be collected. After a

sufficient number of mobile batch plant-produced concrete EPDs have been collected, the GWP intervals may be revisited to determine whether the acceptance intervals can converge.

GWP intervals for acceptance should be developed such that there is a continuous cycle for system improvement. Acceptance thresholds may be higher than incentives thresholds to allow for inclusion of special scenarios that may require other-than-typical paving mixtures. Therefore, the GWP acceptance thresholds are recommended to be equal to the north central regional average identified by NRMCA in their most recent benchmarking study (Salazar et al. 2024). Setting the regional average as the GWP acceptance threshold provides flexibility on projects where circumstances warrant it, while also allowing for a continuous cycle of improvement by maintaining that the acceptance threshold is the NRMCA regional average, even after updates to that average.

## Chapter 8: Life-Cycle Information Model (LCIM) for the Construction Phase

Materials, transportation, production, and construction data were collected on four MnDOT concrete pavement reconstruction projects and one joint repair project. The data was collected using the protocol previously described in section 6.0 and located in Appendix B. Three timeframes for performing data collection were investigated during this study: at bid, after successful bid, and during construction. These data were used to inform the development of an LCIM and were input to the LCIM to develop A1-A5 environmental impacts estimations of concrete pavement projects. To estimate those environmental impacts, the LCIM additionally estimates the A1-A3 emissions of concrete produced at a mobile batch plant.

The data collection protocol previously described in section 6.0 and provided in Appendix B requires reporting of:

- Mixture designs to determine constituent materials quantities which can be confirmed within reason by agency personnel based on the submitted mixture designs and collected batch tickets.
- Materials transportation distances, for which agency personnel are aware of the materials sources, providing access and understanding of the distances and modes.
- Pavement geometry which is known by agency personnel.
- Production rates of the concrete production facility, which is data that can be collected from the mobile batch plant operator. Project production rates can also be used based on the amount of time the mobile batch plant was on site and the total paved area on the project, which is a pay item for MnDOT.
- Equipment fuel consumption and production rates, which can be gathered from contractors, though may be considered proprietary. With further data demonstrating consistency of fuel consumption and production rates for construction equipment, however, data collection may not be needed after a duration.
- Equipment transportation distances, for which project scheduling may provide sufficient information to estimate the transportation distances needed to move equipment from one site to another.

As evidenced in the descriptions of these needed data, agency personnel should have sufficient knowledge of the materials, materials transportation, pavement geometry, project production rates, pay items, and equipment onsite that many of the inputs for the LCIM can be verified.

### 8.1 LCA Data Collected at Bid

Much of the data needed to perform an LCA of life-cycle stages A1-A3 or A1-A5 is not known at the time of bid. Estimations and educated guesses of the needed materials and operations can be provided and are needed for a contractor to provide cost estimates of the work to be performed. Many of the

strategies that improve sustainability, however, are related to specific materials, production facilities, and scheduling means and methods. The details that would likely result in a sustainable project versus a business-as-usual project would not be known at bid, such as:

- The exact concrete mixture design,
- The specific materials suppliers and their facilities' production efficiencies,
- The specific concrete production plant,
- The precise schedule and equipment to be used during operations, and
- The transportation mode(s) and distances that will be used for materials and equipment movements.

Therefore, collecting LCA data at the time of bid would not necessarily provide information regarding whether the project will be sustainable. Despite not being able to determine if sustainable project procurement would be possible for the project of interest, performing LCA data collection at the time of bid could provide benefits such as:

- Indicating to the contractors that sustainable project procurement is a priority to the infrastructure owner,
- Using the lca data to estimate the sustainability of a project's design, and
- Using the lca data for the purposes of investigating alternative, more sustainable designs.

## **8.2 LCA Data Collected After Successful Bid**

Similarly to collecting LCA data at bid, data collected after successful bid has varying usefulness. Collecting LCA data immediately after project award but well before construction initiation will likely result in similar benefits and challenges described in section 8.1.

The best timeframe for data collection is possibly after project award approximately two weeks prior to construction initiation. This timeframe provides advantages to the LCA data collected such that the contractor should know:

- The exact suppliers for each material,
- Where the suppliers are located,
- How the materials are being transported,
- Materials quantities,
- The means for materials production (e.g., mobile batch plant vs. Ready-mix),
- Construction schedule,
- The means and methods for construction,
- Equipment needs,
- Where the equipment will be transported from, and
- Typical fuel consumption needs for each piece of equipment.

In addition to the contractor having sufficiently accurate data and information about the materials and equipment needed to complete the project, receiving LCA data two weeks prior to construction initiation allows for the following advantages:

- Indicating to the contractors that sustainable project procurement is a priority to the infrastructure owner,
- Using the lca data to estimate the sustainability of a project's design,
- Using the lca data for the purposes of investigating alternative, more sustainable designs,
- Allowing the infrastructure owner time to investigate and provide feedback on the sustainability of the project, and
- Allowing the contractor to make changes prior to construction that facilitate sustainability improvements.

Therefore, LCA data could be collected after project award and prior to construction beginning. As changes occur during construction, those modifications concerning LCA-related data could be resubmitted to the infrastructure owner to better reflect the placed infrastructure.

### **8.3 LCA Data Collected During Construction**

LCA data collected during construction provides many of the same advantages described in section 8.2, including:

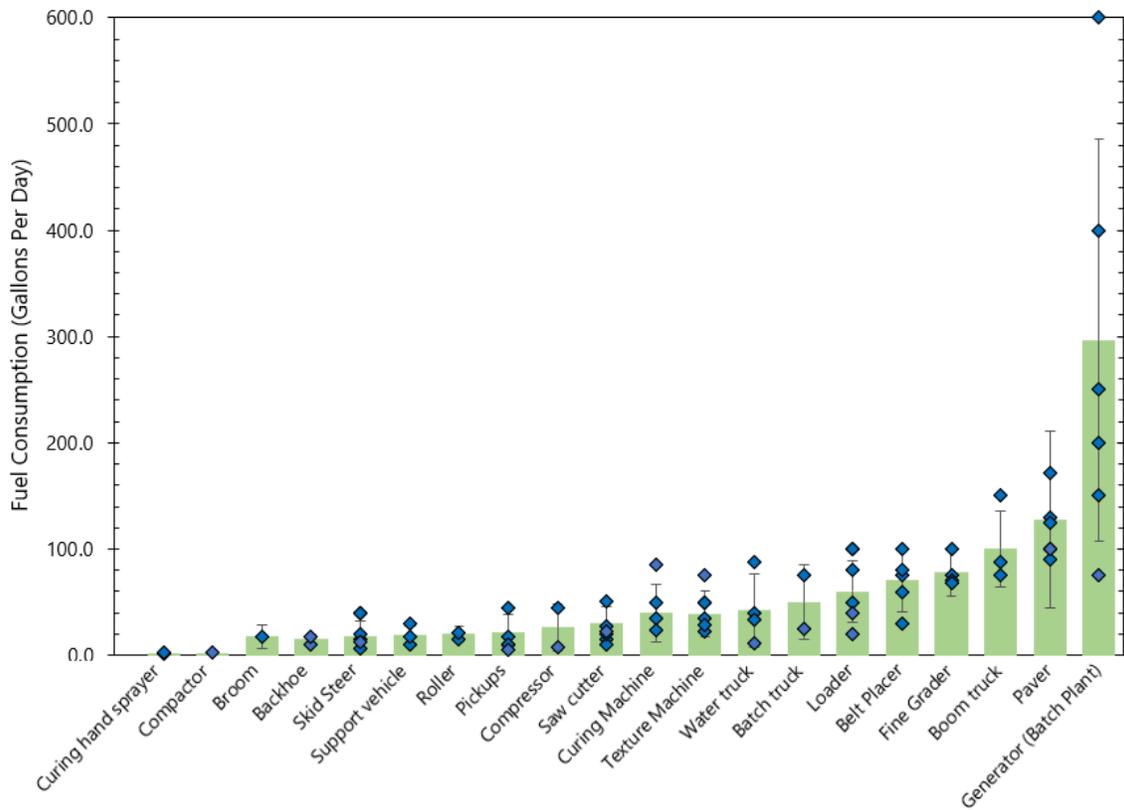
- The contractor knows:
  - The exact suppliers for each material,
  - Where the suppliers are located,
  - How the materials are being transported,
  - Materials quantities,
  - The means for materials production (e.g., mobile batch plant vs. Ready-mix),
  - Construction schedule,
  - The means and methods for construction,
  - Equipment needs,
  - Where the equipment will be transported from, and
  - Typical fuel consumption needs for each piece of equipment.
- The infrastructure owner indicates to the contractors that sustainable project procurement is a priority to the infrastructure owner.
- The LCA data can be used to estimate the project sustainability.

The data collected during this investigation was gathered during construction on the project and concrete mobile batch plant sites. As previously mentioned, data was collected on four concrete pavement reconstruction projects and one joint repair project. Further details about the sizes of those projects are stated in Table 8.1 with their project identifiers for this report.

**Table 8.1 Project information.**

Project ID	Quantity (yd <sup>2</sup> )	Quantity (yd <sup>3</sup> )	Thickness (in)	Length (mi.)	Length (lane miles)
Hampton	673,854	172,015	7-9	15.81	63.6
Lake Elmo	880,262	189,362	7.5-10	10.47	77.5
Sacred Heart	207,000	40,250	7	10.90	21.8
Courtland	420,281	87,558.5	7.5	12.08	48.3
Mendota Heights	N/A	N/A	N/A	0.72	1.4

Figure 8.1 summarizes the fuel consumption rates of the construction equipment as collected from the projects.



**Figure 8.1 Construction equipment fuel consumption summary illustration.**

### 8.3.1 Concrete Pavement Reconstruction - Hampton

The TH 52 Hampton project was 15 miles long in total, with 10 miles in both directions paved during 2023 and 5 miles to be paved in 2024. This project included pavement removal and reconstruction of two lanes in each of two directions. For project water needs, a well was drilled and a generator was used to run the well. The generator for pumping well water required about 20 to 30 gallons of diesel per

day. For peak water needs, well water was supplemented with city water. Table 8.2 provides the concrete materials quantities expected for this project.

**Table 8.2 Concrete materials quantities for Hampton project.**

Quantity (yd <sup>2</sup> )	Overlay Thickness (inches)	Notes
7,000	7	Low Volume Ramp
22,000	8.5	Mainline suburb
45,000	9	Mainline suburb

The batch plant utilized 25 to 28 trucks for delivering the concrete to the job site on typical mainline days and used approximately 22 trucks on light days. It took approximately 1.5 minutes to dump material into each truck at the batch plant. Each truck typically required on average 45 minutes to travel from the batch plant to the jobsite, pour the concrete, and return to the jobsite, though this timeframe highly depended upon the location currently in production on the jobsite. In total, all of the batch trucks required about 750 gallons of diesel per day. Each truck carried approximately 1.5 loads of concrete per hour. Each concrete truck carried 8.5 cubic yards of concrete. The batch plant was transported from one jobsite to another using 12 flatbed-type trucks and 1 truck per loader. The batch plant onsite could accommodate 3 different aggregates, and therefore 3 hoppers and conveyors. The batch plant could be prepared for mobilization within 3 hours. The batch plant used at the Hampton location was moved to another site 15 miles away for a few weeks before being returned to the Hampton site. The batch plant equipment included a tilt drum of 54 metric tons, silo of 48 metric tons, and a horizontal drum of 55 metric tons.

On the project site, one truck circulated and delivered water every 2 hours for dust control. Another truck was available onsite for water as needed. The greatest amount of water consumption occurred when paving the shoulders due to increased needs for dust control. The curing machine typically travelled 50 feet behind the paver. The jobsite was active 6 days per week for 12 to 13 hours per day during mainline paving, and 10 hours per day during shoulder paving. Brooming was performed after milling, after should preparation, and before pavement opening. Table 8.3 provides the reported fuel consumption for the equipment used during this project, while Table 8.4 shows the production rates.

**Table 8.3 Reported fuel consumption for equipment used during the Hampton project.**

<b>Equipment</b>	<b>Quantity</b>	<b>Reported Fuel Consumption</b>	<b>Unit</b>
Front end loaders	2	80	Gallons of diesel per day each
Generator – New	1	200	Gallons of diesel per day
Generator – Old	0	500	Gallons of diesel per day
Air compressor	1	30	Gallons of diesel per day
Paver – New	1	80	Gallons of diesel per day
	1	6.3	Gallons of diesel per hour
Paver – Old	0	30	Gallons of diesel per hour
Belt placer	1	40	Gallons of diesel per day
	1	80	Gallons of diesel per 12 hours
Fine grader / trimmer	1	60	Gallons of diesel per day
	1	85	Gallons of diesel per 2 days
	1	100	Gallons of diesel per 12 hours
Blade	1	85	Gallons of diesel per 2 days
Brooms	2	30	Gallons of diesel per 3 days
	2	25	Gallons of diesel per 10 hours
Roller	1	15-20	Gallons of diesel per day
	1	60	Gallons of diesel per 20 hours
Curing hand sprayer	1	3	Gallons of diesel per 2 ramps
Curing machine	1	50	Gallons of diesel per day
	1	1	Gallons of diesel per ramp
	1	10-12	Gallons of diesel per day during mainline
Texturing machine	1	50	Gallons of diesel per day
	1	1	Gallons of diesel per ramp
	1	8	Gallons of diesel per day
Skid steer	3	1.7	Gallons of diesel per hour
Saw cutter – centerline	1	60	Gallons of diesel per 5000 linear feet
Saw cutter – transverse	1	50-60	Gallons of diesel per 5000 feet
Boom truck	1	75	Gallons of diesel per day
Pickup truck	8	1	Tank per 2 days per truck
Water truck	1	65	Gallons of diesel per day per truck
	1	65	Gallons of diesel per week per truck
	2	25	Gallons of diesel per day per truck

**Table 8.4 Production rates for the Hampton project.**

Item	Quantity	Unit	Notes
Water consumed for dust control	5000	Gallons of water per day	For one truck
	4500	Gallons of water per day	For the second truck
Water consumed during saw cutting	3500	Gallons of water per water tank	2 water trucks for saw cutting water
	2	Tanks of water per day per truck	
Concrete production	4000	Cubic yards per day	
Paver	9-11	Feet per minute	Mainline
	7-8	Feet per minute	Ramp
	5-6	Feet per minute	Average
Pavement reconstruction	10	Miles per 8 weeks of work	
Placement rate	500	Cubic yards per hour	Maximum during mainline paving
	350-400	Cubic yards per hour	Average during mainline paving
Saw cutting	333	Panels per 10 hours	
	1	Mile per day per machine	
Grinding	1	Mile per day	
	40	Lane-miles per 2 weeks	
Fine grader / trimmer	1	Mile per 20 hours	
Roller	1	Mile per 20 hours	

The fine and coarse aggregate for the concrete was from Laguna Aggregates approximately 50 miles from the site. The geopolymer was 18 inches wide and placed along the lane width plus 3 feet per side along each shoulder. The geopolymer was spaced 15 feet apart, in line with each panel.

The concrete pavement in each direction was designed with 15 feet panel lengths, two 12 feet driving lanes, a 1-foot shoulder, and a 3-foot shoulder. In some places, there were also turning lanes. Eight steel dowel bars 1 ¼ inches in diameter were placed along the 12 feet width of each lane. The ties were located every 3 feet along the edge of each lane.

### **8.3.2 Concrete Pavement Reconstruction – Lake Elmo**

The concrete pavement of I-94 near Lake Elmo was under reconstruction for an unbonded overlay. During the first season of construction in Summer of 2023, 4.5 miles of the east lanes of I-94 were reconstructed over a 3-week period. A different contractor, whom we were not in contact with, paved the western lanes of these 4.5 miles. During the second construction season on this project in Summer of 2024, 5 miles in each direction will be paved in 7 weeks. Each direction includes 4 lanes plus shoulder.

The mobile batch plant near site was able to produce 5,200 to 5,500 cubic yards of concrete per day. A well was drilled specifically for concrete batching water. At this site, previous water contamination in

that area disallowed the well water from being used for watering on the site. The mobile batch plant could be mobilized using one semitruck for each piece of equipment, with 12-13 pieces of equipment. The batch plant was typically transported within a 30-minute range.

The cement was produced approximately a 10-minute drive from the site, while the fly ash was from a distance approximately 1 hour and 45 minutes from the site in St. Joseph Minnesota. The aggregates used in the concrete were from very near the batch plant. Each of the 34 concrete trucks carrying concrete from the batch plant to the pouring location transported 9 cubic yards of concrete per cycle, with a 40-minute cycle time from the mobile batch plant to the pouring location and back to the mobile batch plant. Loaders were located on the batch plant site to transport aggregates.

The majority of the project used the approved concrete mixture design identified as 3A21-21. The concrete trucks were scraped at the end of each day – no washout water was used. Work was performed onsite 12 hours per day and 6 days per week. The fine grader was typically only used 10-12 hours per week.

The concrete panels on this site were 15 feet by 12 feet, with 11 dowels across the 12 feet wide lanes. A number 4 tie bar was placed every 3 feet such that there were 5 per panel. The average overlay thickness was reported as 8 inches, though the overlay thickness was also reported to range from 9.5 inches to 12 inches. Thicker overlays were considered typical for urban areas with higher traffic volumes and the less thick overlays were considered typical for lower traffic volumes. The ramp had a shoulder that began at 3-feet and continued to gain width up to 16-feet as the ramp continued along its 315 feet length. Brooms were used to clean debris off the ramp(s) multiple times during the project. For the ramp shoulders, the joint was tooled in and then saw cut at a later time. Table 8.5 displays the materials quantities used on the project.

**Table 8.5 Overlay thickness materials quantities for Lake Elmo project.**

Quantity (yd <sup>2</sup> )	Overlay Thickness (inches)	Notes
65,000	7.5	Low Volume Ramp
86,000	8.5	Urban Ramp
2,000	9	
558,700	9.5	Mainline
13,300	10	Near supers

Two large pavers and one smaller paver were used on the site, though all were 12-32 feet-sized pavers. The pavers typically ran at a speed of 11-12 feet per minute. The curing machine typically operated approximately 50 yards behind the paver. The texture machine typically operated approximately 30 yards behind the paver. The skid steers were located at the paving site to move extra concrete from one place to another as needed. The water truck transported 3,000 gallons of water per tank, and typically refilled its water 15-20 times per day. Saw cutting occurred at varying time intervals. While we were onsite, saw cutting was still being performed on the concrete paved the previous day.

Table 8.6 reports the fuel consumption of the equipment and Table 8.7 reports the production rates associated with I-94 near Lake Elmo.

**Table 8.6 Reported fuel consumption for equipment used during the Lake Elmo I-94 project.**

<b>Equipment</b>	<b>Quantity</b>	<b>Reported Fuel Consumption</b>	<b>Unit</b>
Batch plant generator	1	200	Gallons of diesel per day
Air compressor	3	50	Gallons of diesel per day
Pavers	3	100	Gallons of diesel per day
		35-40	Gallons of diesel per day
Curing Machine	3	50	Gallons of diesel per day
	3	20	Gallons of diesel per day
Fine grader	1	100	Gallons of diesel per day
Belt placer	2	100	Gallons of diesel per day
	2	35-40	Gallons of diesel per day
Skid steer	3	40	Gallons of diesel per day each
Loader	2	100	Gallons of diesel per day each
Boom truck	2	75-100	Gallons of diesel per day each
Water truck	1	75-100	Gallons of diesel per day
Saw cutters	3	25-30	Gallons of diesel per day each
Support vehicle	1	30	Gallons of diesel per day
Batch truck	34	75	Gallons of diesel per day each
Gator smoothness measuring system	1	1	Gallons of diesel per day

**Table 8.7 Production rates for the Lake Elmo I-94 project.**

Item	Quantity	Unit	Notes
Placement rate	5,000	Square yards per day	Average
	5,100	Square yards per day	Day prior to site visit
	4,500	Cubic yards per day	Using big paver
	7,500	Linear feet	
	11-13	Linear feet per minute	Mainline
	10-20	Linear feet per minute	
Shoulder paving rate	3,500	Square yards per day	
	7,500-8,000	Linear feet	
Ramp paving rate	1,200	Cubic yards per 6 hours	
Ramp shoulder paving rate	15	Feet per minute	
Curing compound application	1	Gallon of curing compound per 150 square feet	
Curing machine speed	30-35	Feet per minute	
Texture machine speed	10	Feet per minute	
Saw cutting	15	Feet per 2-3 minutes	

After pavement reconstruction, the smoothness of the pavement was measured. The measurements were typically taken using a gator with lasers. The contractor was targeting, for this project and typically, 15-20 inches of vertical change per mile. A smoothness of 68 inches per mile is required at construction per specifications.

### **8.3.3 Concrete Pavement Reconstruction – Sacred Heart**

An unbonded overlay was performed on TH-212 in Sacred Heart. The milling was performed before paving by a different company. The concrete was paved in a single lift of 7 inches. This project, and those typically in this area, use more local rock than sand. Sand comes from farther distances. The coarse aggregate came from Granite Falls, the sand came from Chaska which is a 3-hour distance, fly ash came from St. Joseph, and cement from St. Paul.

The mobile batch plant had a double drum. Two loaders were used to move aggregates as needed. Local well water was used for all project water needs. To transport the mobile batch plant, 14 or 15 tractor trailers were needed, one to move each piece of equipment. The batch plant was typically mobilized within a 100-mile radius.

The hand work performed during the project used the approved concrete mixture design identified as 3A41-9, while the slipform work performed during the project used approved concrete mixture designs of 3A41-1 and 3A41-4.

Two grinders were, atypically, used along 1,600 feet of concrete pavement in order to remove hail damage that occurred during a storm shortly after the concrete was placed along that stretch. Those two grinders removing hail damage in total used less fuel than the paver used over the course of a typical day. The grinders required 3 tankers of water and then 3 tankers of slurry were transported away from the project site to a waste disposal site. The grinder was typically used when tying the pavement in with other projects, correcting smoothness, or for other corrective actions as needed, and therefore was not typically used on a regular basis.

Some hand work was performed during this project, which made for some days of slower operations. When performing hand work, only three concrete trucks were needed. Curing compound was sprayed using a hand pump with a small generator. A boom truck with a roller and screed attachment was used to place and finish the concrete. Curing compound was applied until visually determined to be white as a sheet of paper. The curing compound was sprayed out from the pump at 200 psi. The generator for dispensing the curing compound used 6-8 ounces of diesel per day.

For mainline slipform paving, 25 to 35 concrete trucks were needed to deliver concrete to site continuously. It took 5 to 20 minutes, depending on the location along the pavement being paved at that time, for the concrete trucks to receive material, deliver the material to site, and return to the batch plant to receive more material. The cement and fly ash were delivered to the concrete batch plant in 39 and 18 trucks, respectively, with over 16 metric tons of material.

The concrete pavement had joints spaced every 15 feet. The number of saw cutters depended upon the number of lanes and therefore centerlines. The saws cut along the lane edges and transverse joints. Approximately 57,000 linear feet of saw cutting was performed for each mile paved when there were five centerlines. One dowel was used per linear foot such that 11 dowels were needed per lane for mainline paving. For overlays, one dowel was used for every 1.5 feet such that 8 dowels were needed per lane.

Tables 8.8 and 8.9 display the fuel consumption and production rates, respectively, for the Sacred Heart project.

**Table 8.8 Reported fuel consumption for equipment used during the Sacred Heart project.**

Equipment	Quantity	Reported Fuel Consumption	Unit
Paver	1	100-150	Gallons of diesel per day
Belt placer	1	100	Gallons of diesel per day
Texturing machine	1	50	Gallons of diesel per day
Curing machine	1	50	Gallons of diesel per day
Saw cutters	3	20	Gallons of diesel per day each
Skid steers	3	40	Gallons of diesel per day each
Line truck	-	15-20	Gallons of diesel per day
Air truck	-	15-20	Gallons of diesel per day
Setup foreman truck	-	15-20	Gallons of diesel per day
Steel truck	1	15-20	Gallons of diesel per day
Basket truck	1	15-20	Gallons of diesel per day
Hot pour kettle truck*	1	15-20	Gallons of diesel per day
Loll truck to pull fabric*	1	20-25	Gallons of diesel per day
Boom truck	2	150	Gallons of diesel per day
Loader	2	100	Gallons of diesel per day
Generator	1	250	Gallons of diesel per day
Air compressor	1	40-50	Gallons of diesel per day

\* = when using fabric; - = data not reported

**Table 8.9 Production rates for the Sacred Heart project.**

Item	Quantity	Unit
Hand work concrete placement	200	Square yards per day
	1	Intersection per hour
	7	Truckloads of concrete per intersection

### 8.3.4 Concrete Pavement Reconstruction – Courtland

A pavement reconstruction was performed on TH 14 in Courtland Minnesota. This project had Class 6 base with 8 inches thick concrete paving. Two different reports of 30,000 to 50,000 gallons of water, and 5,000 to 10,000 gallons of water were used for dust control each day. City water was piped in for this project.

Thirteen semitrucks were needed to haul the mobile concrete batch plant from one location to another, with one truck for each piece of equipment. The mobile batch plant used on this project had been previously used on projects in Branson Missouri, North Dakota, and Montana. The drum weighed 45 to 55 metric tons. The main section weighed about 40 metric tons. In total, the batch plant weighed about 200 to 250 metric tons. The contractor had 4 mobile batch plants servicing all of their active projects

during Summer 2023. Each batch plant typically travelled to 1 to 2 projects per year, but could, if needed, service up to five sites. It was typical to have four trailers on each batch plant site.

The cement was from Lehigh. The quartzite ¾-inch intermediate aggregate was from a nearby quarry. The coarse aggregate was from Sioux Rock near Jeffers Minnesota. The fine aggregate originated 1 mile away from the project site (in Yuland Minnesota). Fly ash class F was from Prairie State in Wisconsin.

The hand work performed during the project used the approved concrete mixture design identified as 3A41-18, while the shoulders and mainline paved during the project used approved concrete mixture designs of 3A21-16.

The panel joints were spaced every 15 feet. The lanes were 10 feet wide. Twelve hours of work were performed each day. On the mainline paving, the dowels were located 18 inches apart.

Fourteen trucks were delivering concrete when paving shoulders. A light day of paving shoulder typically included 200 loads of concrete being delivered from the batch plant to the site each day. In these instances, the cycle time of the concrete truck to load, deliver, and return to the batch plant was about 45 minutes.

The trucks were washed out between mixes and at the end of each day. It was estimated that 200 gallons of water were used per load per day.

This project incorporated paving a turn lane. The turn lane had 9 dowels across the lane width with the dowels 1-foot apart center-to-center. The turn lane had epoxy-coated reinforcement mats 2 feet by 14 feet by 10 feet with 2 feet between the bars creating the mat. One mat was located every 8 joints. The wheel pad baskets contained number 8 bars.

On busy days of mainline paving, 38 concrete trucks delivered approximately 500-600 loads of concrete to site. The typical cycle time was 20 to 45 minutes for the concrete trucks to travel from the batch plant, deliver concrete onsite, and return to the batch plant.

The curing compound was hand sprayed in certain places as the turn lane tapered. For the mainline paving, the curing machine was typically 12 to 15 feet behind the paver.

The skid steers were used to dig during grading and clean overruns of concrete off the slabs. One skid steer was active in front of the paver and the other behind the paver. Graders, rollers, excavators, trucks, and diggers were used onsite. Two to three dump trucks hauled waste materials as needed.

Tables 8.10 and 8.11 show the fuel consumed and production rates, respectively, of the equipment used during the Courtland project.

**Table 8.10 Reported fuel consumption for equipment used during the Courtland project.**

Equipment	Quantity	Reported Fuel Consumption	Unit
Concrete truck	12	40-50	Gallons of diesel per day
Curing compound hand sprayed	-	1	Gallons of diesel per day
Texture machine	-	20-25	Gallons of diesel per day
Saw cutter	-	10	Gallons of diesel per day each
Skid steer	2	16	Gallons of diesel per day each
Fine grader	-	140	Gallons of diesel per day
Loader	2	40-50	Gallons of diesel per day
	2	40-80	Gallons of diesel per day (hard day)
	2	50-70	Gallons of diesel per day
Paver (12 feet)	-	80	Gallons of diesel per day
Paver (16-32 feet)	-	180	Gallons of diesel per day
Belt placer	-	30	Gallons of diesel per day
Generator	-	300-500	Gallons of diesel per day

- = data not collected

**Table 8.11 Production rates for the Courtland project.**

Item	Quantity	Unit
Curing machine speed	18	Feet per minute
Curing compound	700	Square feet per barrel
Concrete placing	4000-5000	Cubic yards per day

### 8.3.5 Joint Repair – Mendota Heights

Joint repair was performed on a concrete pavement in Mendota Heights Minnesota. This project involved repairing every joint along 3,800 feet of roadway in two directions. The roadway was originally paved in the early 1990s. There were two lanes in each direction, with each lane being 12 feet wide. One side of the roadway had a 1-foot shoulder, and the other side had a 2 feet shoulder. Fifteen days of work were allocated for repairing the joints along each direction. Four weeks, or 30 days in total, were allocated to complete the work. The project goals targeted 75 repair sections completed per day, though only 54 and 49 repair sections were completed during the two days the project was underway prior to our visiting the jobsite.

The concrete removed and replaced was 7 to 8 inches thick. No dust control was needed on this project. Two saw cutters were used on the project, with each able to cut through 10 to 15 repair sections per hour. The concrete was removed in sections 4.5 feet wide by 13 feet long across each panel joint. The concrete was then broken into pieces using a small excavator with a drill head attachment. Two skid steers and a loader were used to remove the concrete and load the removed concrete onto a truck to

haul away. One repair section was removed for every 5 minutes of work and then taken to a staging area to await hauling away. The removed concrete was taken to a pit near the Hampton I-94 jobsite in Rosemount. Three 20-wheeler side dump tractor trailers hauled the removed concrete from the jobsite to the waste site.

The project schedule's greatest constraint was drilling in the dowels. One large machine drill, a reverse excavator, was able to drill 176 holes per hour, which equated to 8 repair sections per hour, with 11 holes on each side of the two sides of the section. A 2-man hand drill was additionally used to help speed up the drilling process, though this was not typically necessary. Using the 2-man hand drill resulted in drilling 66 holes per hour, or 3 repair sections per hour. The dowels, and therefore the drilled holes, were spaced 12 inches apart center-to-center.

A hand compactor was used to compact the soil where each repair section was removed prior to inserting the dowel bars. Three work trucks for tools, forms, and dowels, and 3 foreman trucks were onsite.

Dowel bars were inserted at a rate of 8 repair sections per hour, or 176 dowel bars per hour. The dowel bars were 1 ¼ inches in diameter and epoxy coated. Epoxy or grout were used to secure half of each dowel bar into the old pavement. Grease was applied to the other half of each dowel bar that remained exposed prior to placing concrete.

The concrete poured to repair the joint areas reached 1,500 psi within 24 hours after casting and met the 2,000-psi opening strength requirement at 36 hours. The concrete included portland limestone cement with fly ash. Approximately 70 to 80 cubic yards of concrete were poured each day.

Table 8.12 shows the fuel consumption reported for each piece of equipment. The equipment tanks were refilled every day. The water trucks contained 4,000 gallons of water per tank, with 1,500 to 2,000 gallons of water used per day.

**Table 8.12 Reported fuel consumption for each piece of equipment used during the joint repair project.**

Equipment	Quantity	Reported Fuel Consumption	Unit
Skid steer	2	10-15	Gallons of diesel per day each
Loader	1	20	Gallons of diesel per day
Compressor	1	10	Gallons of diesel per day
Backhoe	1	15-20	Gallons of diesel per day
Pickup truck	3	5	Gallons of diesel per day each
Box truck	3	5	Gallons of diesel per day each
Compactor	1	2-3	Gallons of diesel per day
Compressor in epoxy rig	1	5	Gallons of diesel per day
Hand drill compressor	1	10-15	Gallons of diesel per day
Saw cutter	2	20-25	Gallons of diesel per day each
Water trucks	1	10-12	Gallons of diesel per day
	-	1	Gallons of diesel per hour when idling

- = data not collected

## 8.4 Background on A4, A5, and LCIMs

The concrete PCR mandatorily requires inclusion of life-cycle stages A1 through A3, meaning A1 through A3 are reported in all concrete EPDs. The PCR also currently (as of December 2024) allows the inclusion of life-cycle stages A4 and A5 in EPDs (NSF International 2024). However, the authors know of no concrete EPDs that include A4 or A5 at this time.

An LCIM is an LCA building block that formalizes the system, underlying relationships, and upstream datasets (Bhat 2020). LCIMs provide a framework for performing an LCA in a consistent manner across multiple projects and multiple users/operators. An LCIM includes:

- Defining input parameters,
- Identifying default input parameters that represent typical values of the industry,
- Identifying the matter and energy sources that may create environmental impacts attributed to the system,
- Developing equations relating the input parameters to matter and energy quantities (i.e., dependent parameters),
- Quantifying the matter and energy that result in environmental impacts from the system,
- Identifying and justifying the emissions factors associated with each matter and energy source,
- Identifying and implementing a specific impact assessment methodology,
- Identifying the environmental impacts studied and reported in the lca, and
- Combining the input parameters, dependent parameters, and emissions factors to determine the environmental impacts of the system entirety.

Because no epds include a4 and a5, no formalized system has been developed for estimating the environmental impacts of those stages. This gap is addressed through this project.

## 8.5 LCIM Methodology

The development of an LCIM methodology began with the conceptual visualization of the input and output parameters, flows, and interactions from one step to another. Figures 8.2 and 8.3 provide mapping schematics of the input and output flows for an LCIM quantifying A1-A3 environmental impacts of concrete and A1-A5 environmental impacts of concrete pavement construction, respectively.

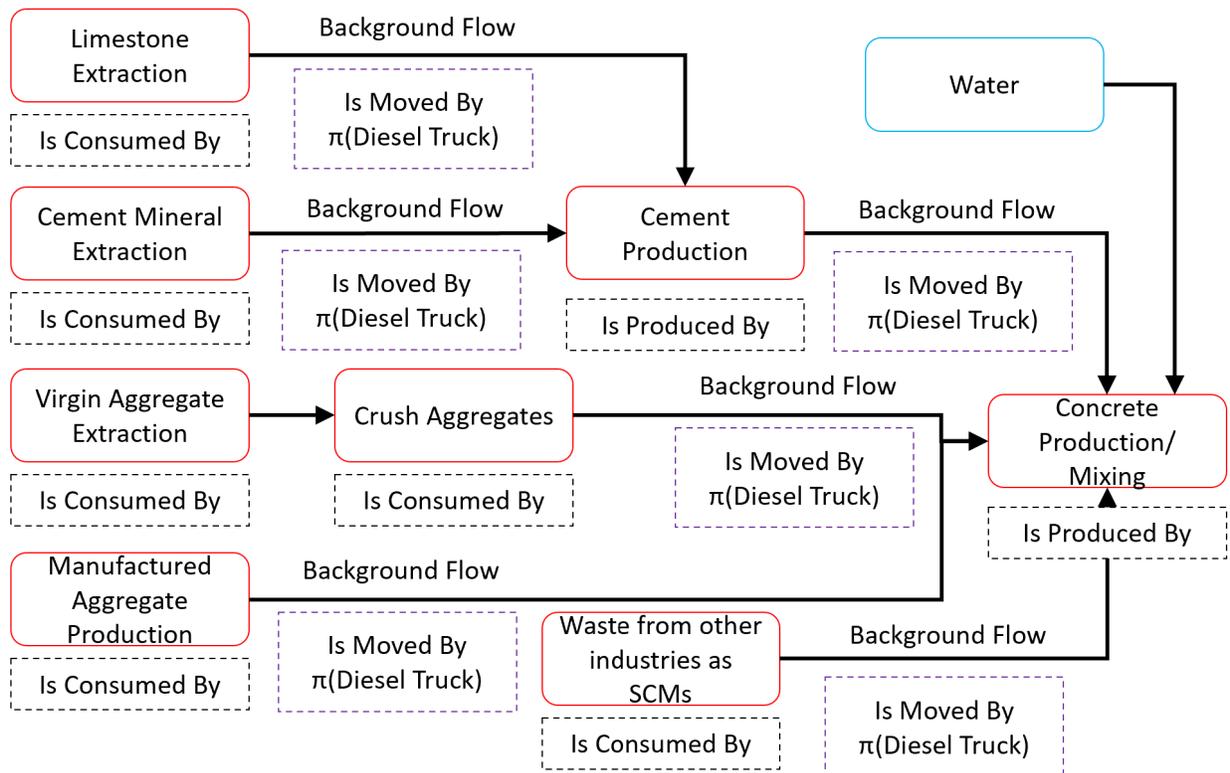
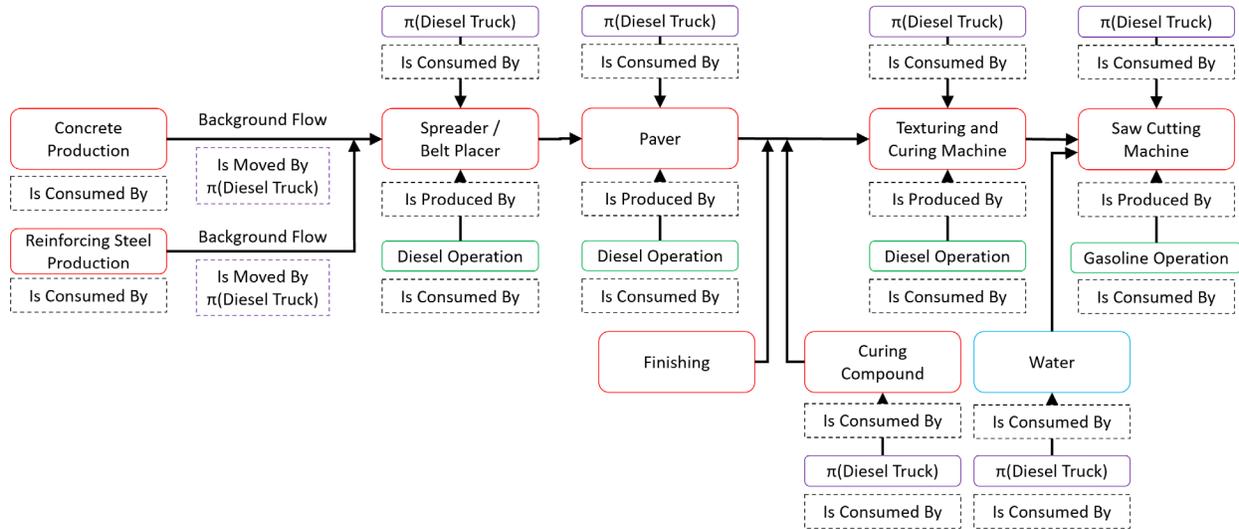


Figure 8.2 Mapping of input and output parameters for concrete production (Cooper 2025)

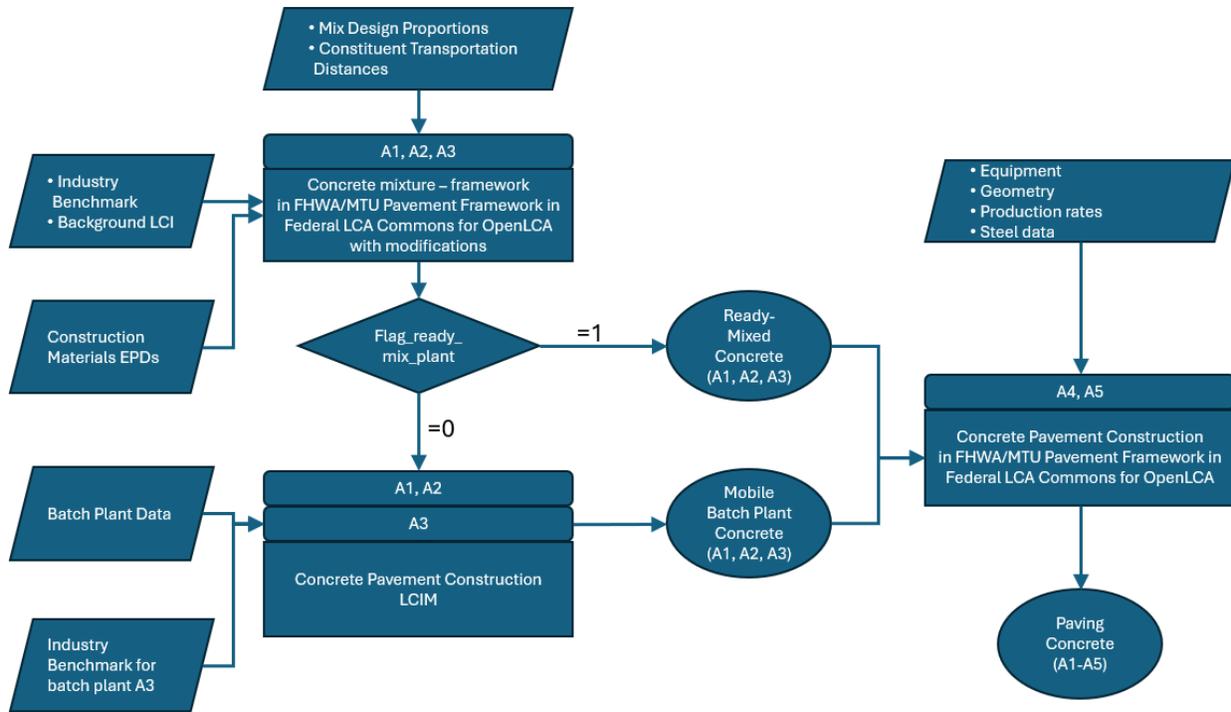


**Figure 8.3 Mapping of input and output parameters for concrete pavement reconstruction (Cooper 2025)**

The mapping of input and output parameters described in Figures 8.2 and 8.3 were then translated from the conceptual format in which they are presented, to a usable format that can receive user inputs, manipulate data, and provide environmental impact outputs. An LCIM compatible with openLCA was developed to estimate A1-A3 environmental impacts of ready-mixed and mobile batch plant concrete and A1-A5 environmental impacts of concrete pavement construction projects. An existing LCIM for ready-mixed concrete from Federal LCA Commons' Federal Highway Administration / Michigan Technological University (MTU) Asphalt Pavement Framework dataset (Federal LCA Commons 2022) was incorporated into the A1-A5 LCIM with a few modifications. Those modifications include:

- allowing A1, A2, and A3 environmental impacts to be estimated separately or combined,
- adding options for transportation mode, and
- separating aggregates into coarse, intermediate, and fine to allow for differentiated transportation distances and modes.

With these modifications, the A1-A3 framework can be an input to the A1-A5 LCIM by either providing A1-A3 of a ready-mixed concrete or providing A1-A2 of a mobile batch plant concrete. The A3 environmental impacts for producing concrete via mobile batch plants, if needed, can then be estimated along with the A4 and A5 impacts given the fuel consumption and production rates of the batch plant and construction operations. Figure 8.4 provides a schematic of the translation of LCIM flows from the conceptual to the model framework.



**Figure 8.4 Illustration of inputs to develop the A1-A5 LCIM (Cooper 2025)**

The LCIM was developed within open LCA 2.0.4 (GreenDelta 2024), which is a free, publicly-available software tool. Environmental datasets were imported from Federal LCA Commons (Federal LCA Commons 2022) and used United States Life-Cycle Inventory (USLCI) data as much as possible. The environmental impact flows and data sources are shown in Table 8.13. The TRACI 2.1 (EPA 2022a) impact assessment method is the most commonly used and PCR-prescribed method within the United States. The method estimates impacts for the potential midpoint environmental impact categories of acidification, eutrophication, freshwater ecotoxicity, global warming, human health-cancer, human health-noncancer, human health-particulate matter, ozone depletion, and smog formation potentials.

**Table 8.13 Data and flow sources used in environmental impact estimations.**

<b>Input</b>	<b>Units</b>	<b>Data/Flow Source</b>
Concrete consumed	m <sup>3</sup>	Concrete mixture - framework flow from FHWA Data Repository (Federal LCA Commons 2022)
Steel consumed	kg	(Commercial Metals Company 2016)
Equipment diesel fuel	gal (US liq)	(National Renewable Energy Laboratory (NREL) 2012)
Equipment gas fuel	gal (US liq)	(NREL 2012)
Combination truck transport	t·km	(National Energy Technology Laboratory (NETL) 2019)
Light commercial truck transport	t·km	(NETL 2019)
Single unit trucks transport	t·km	(NETL 2019)
Rail transport	t·km	(NETL 2019)
Titanium dioxide	kg	(Federal LCA Commons 2022)
Water	m <sup>3</sup>	(Federal LCA Commons 2022)

Industry-average EPD environmental impacts were used to inform the LCIM for constituent materials used for developing concrete pavements. With the formal data collection protocol described in section 6.0 in place, product- and facility-specific constituent EPDs can be used instead of these industry-average EPD results. Table 8.14 displays the data sources for the concrete mixture framework used to estimate the A1-A3 emissions of ready-mixed concrete and A1-A2 emissions of mobile batch plant concrete. The projects assessed used Portland limestone cement and natural aggregate are shown and therefore only those data sources are shown for cement and aggregate. Other inputs to the LCIM are possible.

When estimating the A1-A3 environmental impacts of ready-mixed concrete, the impact results for A3 are based on the industry-average EPD production inputs of electricity, natural gas, and wastes (Athena Sustainable Materials Institute 2021). The A3 environmental impacts for concrete produced at mobile batch plants estimated from this LCIM, however, are based on primary data for each project and therefore are representative of the mobile batch plant onsite during the project. The A3 emissions calculated for mobile batch plants are based on the fuel consumption of the mobile batch plant generator. On all project sites visited, the generator was observed to provide fuel for all of the equipment on the mobile batch plant site except loaders. One-way transportation of the mobile batch plants was included in the A3 environmental impacts estimations because the plant must arrive onsite to be used for the project. The inclusion of one-way mobile batch plant transportation aligns with the concrete PCR (NSF International 2024).

**Table 8.14 Data sources for the concrete mixture framework used in the LCAs Sample table**

Flow	Data Source
Portland limestone cement (PLC)	Portland Cement Association (PCA) PLC industry average (PCA 2023b)
Fly ash	Zero burden consistent with the supplementary cementitious materials product category rule (SmartEPD 2024)
Natural aggregate	(Marceau, Nisbet, and VanGeem 2006)
Electricity	(NETL 2019)
Fuels	(NREL 2012)
Transportation	(NREL 2012)

The A1-A5 LCIM was developed with a declared unit of square yards (for example: kg of CO<sub>2</sub>-eq/yd<sup>2</sup>) to align with the MnDOT pay item for concrete pavement. Using a declared unit of square yards reflects the agency’s interest in procuring infrastructure. MnDOT does not purchase materials from suppliers, but rather purchases a delivered asset via projects.

The LCIM was developed such that the pavement design (such as thickness) affects the materials quantities used on the project and the production rates. Differences in pavement depth may require the paver to move more slowly to achieve the project requirements such as smoothness, but this change would be reflected and accounted for in the paver’s fuel consumption and/or production rate. The project size will additionally be accounted for in the production rates for the mobile batch plant and construction.

The A1-A5 environmental impact results developed using this analysis can be translated from yd<sup>2</sup> to lane-mile if desired. The environmental impacts can be divided by the pavement thickness to represent a lane and the square yardage can be multiplied by pavement geometry to incorporate the mileage paved. The declared unit can be translated into a functional unit by MnDOT with sufficient usage information such as traffic loading. The pavement function is important for benchmarking purposes to differentiate, for example, urban mainline paving versus rural mainline paving versus intersection paving. Urban mainline paving, for example, is likely to have fewer turn lanes and intersections leading to fewer paving equipment resets and therefore a higher production rate. Higher production rates result in lower environmental impacts across the project because equipment usage is more efficiently managed. Due to these inherent project requirements which may intrinsically influence the environmental impacts, not accounting for functionality of the project infrastructure may inadvertently affect contractor competition and bidding.

Because the LCIM was designed with the declared units of yd<sup>2</sup>, the results for A1-A3 estimated using this LCIM are also presented in yd<sup>2</sup>, despite the declared unit for concrete being m<sup>3</sup> or yd<sup>3</sup> per the concrete PCR. The concrete A1-A3 environmental impacts are estimated in a manner consistent with the concrete PCR (NSF International 2024), and allow the user to input product-specific environmental impacts for constituents from EPDs. The A1-A3 environmental impacts from the LCIM can be translated to units per yd<sup>3</sup> by dividing the environmental impacts by the pavement thickness to obtain volume.

During data collection, a range of values was provided for certain input parameters. For example, ranges of fuel consumption for construction equipment and variation in production rates were acknowledged. The ranges were provided as typical quantities, minimums, and maximums. Therefore, at least three scenarios of the LCIM were analyzed for each project. Where data was additionally provided for specific aspect of the production, such as intersection hand work or turn lane paving, those scenarios were analyzed separately from the mainline paving to portray the change in production rate and how that affects the environmental impacts. Scenarios were also assessed to capture the production rate across the project entirety (e.g., 40,000 yd<sup>2</sup> of paving over 21 days of construction) versus production typically occurring on a single day (e.g., 4,500 yd<sup>2</sup> per day).

The implementation of the LCIM presented in this paper describes the data corresponding to four projects in Minnesota and one in Iowa, from which data was able to be collected in cooperation with the Iowa Climate Challenge project (Iowa DOT 2024).

## 8.6 Estimated Concrete Mixture (A1-A3) LCA Results

Figure 8.5 displays the estimated A1-A3 environmental impacts of the mobile batch plant-produced concrete mixtures used on the projects.

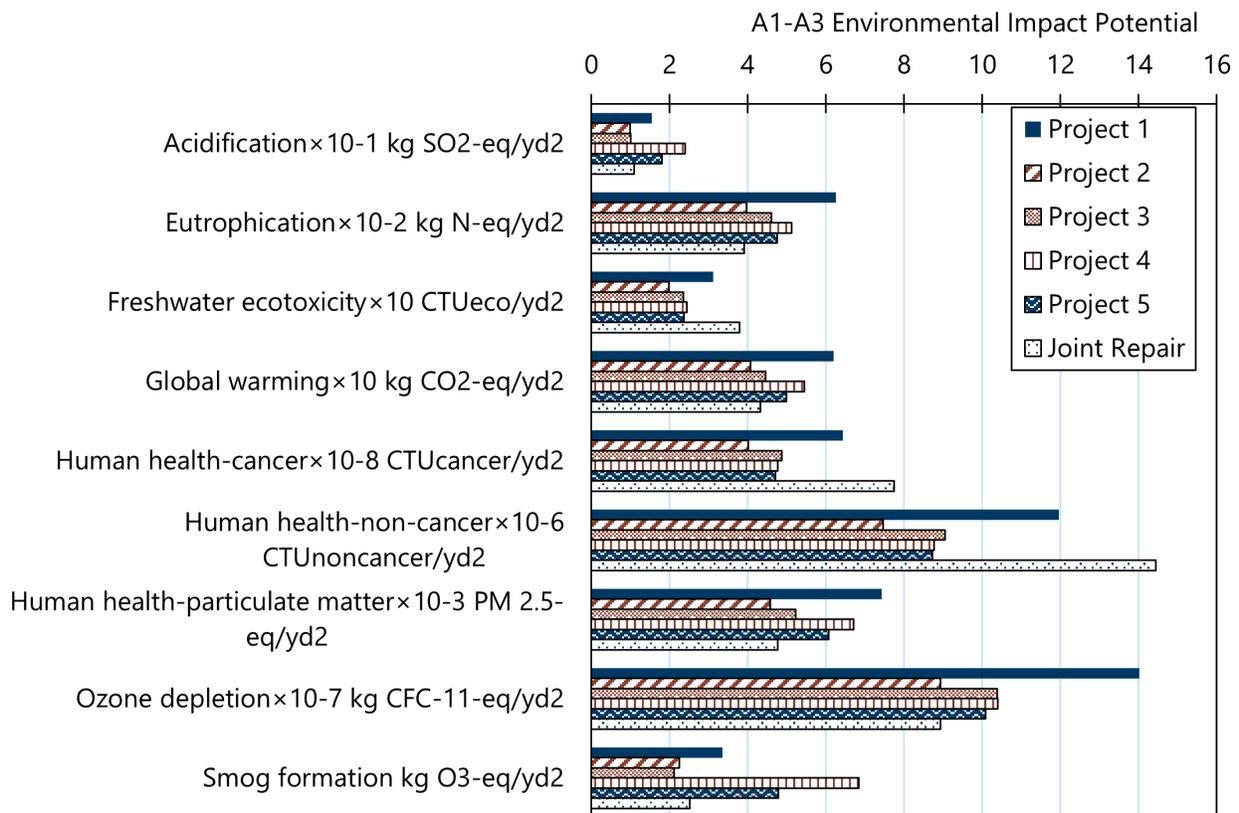
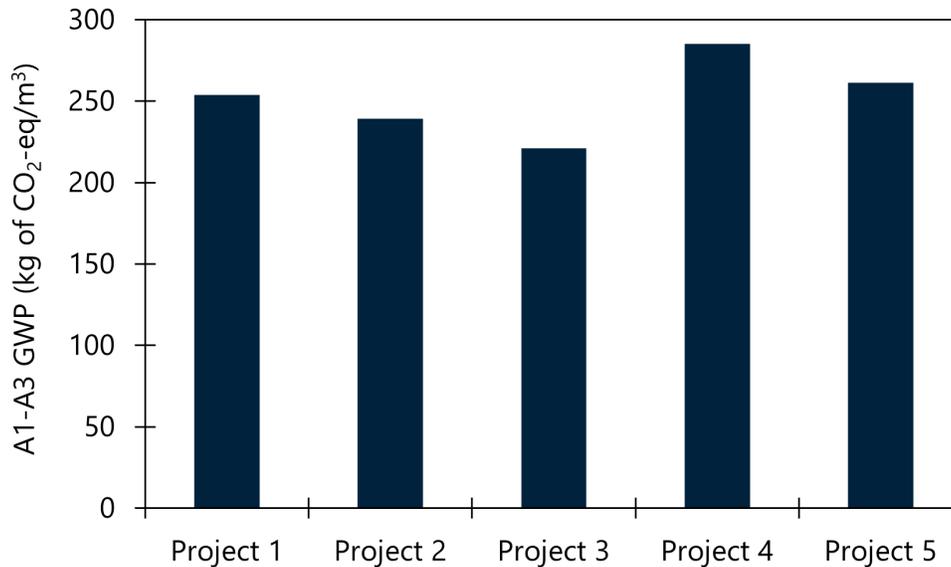


Figure 8.5 A1-A3 environmental impacts.

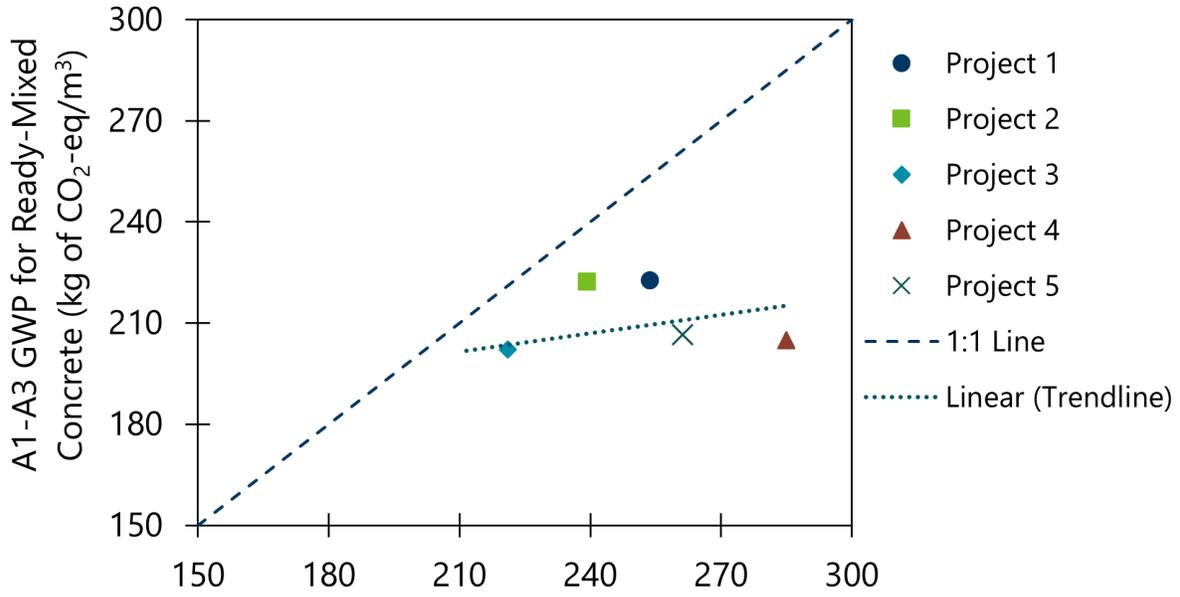


**Figure 8.6 A1-A3 GWP for mobile batch plant concretes.**

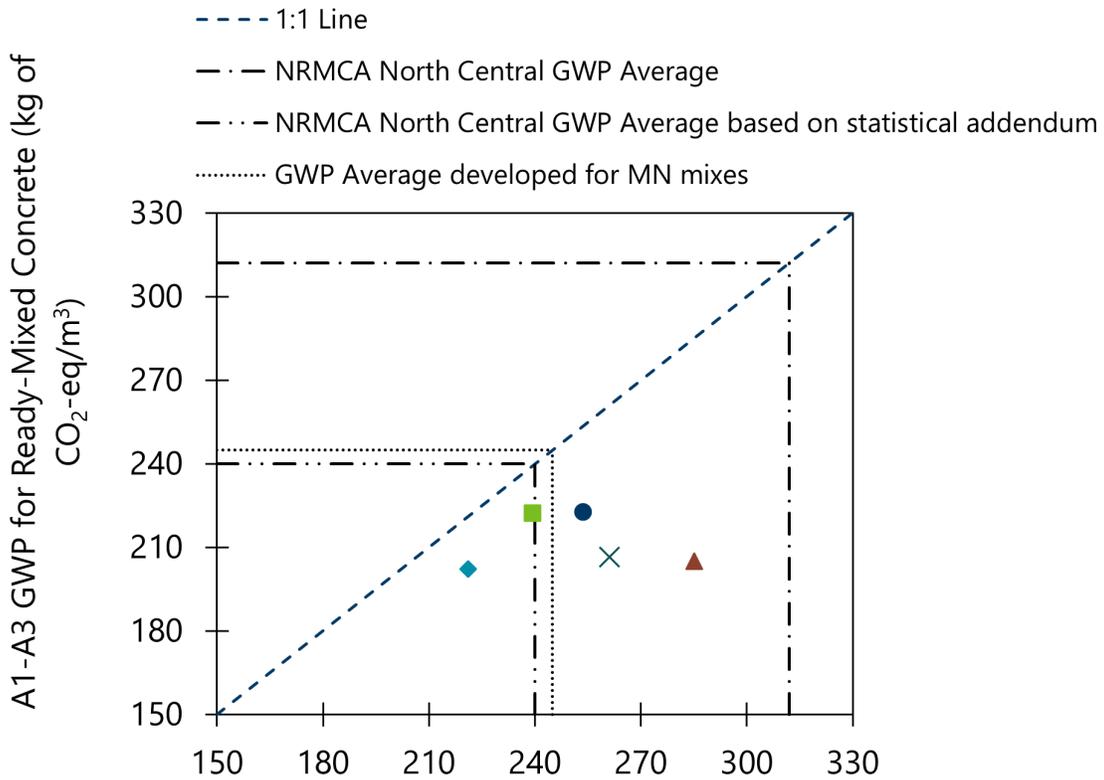
Figure 8.7 compares the A1-A3 GWP for the concrete mixtures used on the projects based on ready-mixed concrete production versus mobile batch plant production. The ready-mixed concrete A3 GWPs were estimated based on the national industry average A3 for ready-mixed concrete, while the mobile batch plant A3 GWPs were estimated using facility-specific, mobile batch plant fuel consumptions, transportation, and production rate data from each project.

The figure also shows, for comparison purposes, the A1-A3 GWPs for the projects compared to the benchmarks mentioned in Section 7.0. Two projects using mobile batch plant concrete would meet the thresholds while three projects would not. That three of the projects would not meet the benchmarks in Section 7.0 exemplifies that different benchmarks may be needed for concrete developed by mobile batch plant versus ready mix.

The A1-A3 GWPs shown in the figure from the mobile batch plant production are more accurate for the concrete mixtures used in these projects, since they were developed by mobile batch plant. The mobile batch plant production, however, resulted in higher GWPs than is typical for the same concrete mixture produced at a ready-mixed plant. This trend is further depicted in Figure 8.8, which shows an A3 GWP spread across the projects from 2 to 66 kg of CO<sub>2</sub>-eq/m<sup>3</sup>, which is related to the production rates of the plants. When analyzing these results, consider the limitations of the estimations, however, which are only utilizing the production rates of the mobile batch plants over the project duration rather than across a 12-month period as required by the concrete PCR (NSF International 2024). Therefore, when 12 months of production data are used in the A3 quantification process, the environmental impacts per m<sup>3</sup> of concrete may decrease; more data for concrete produced at mobile batch plants are needed.

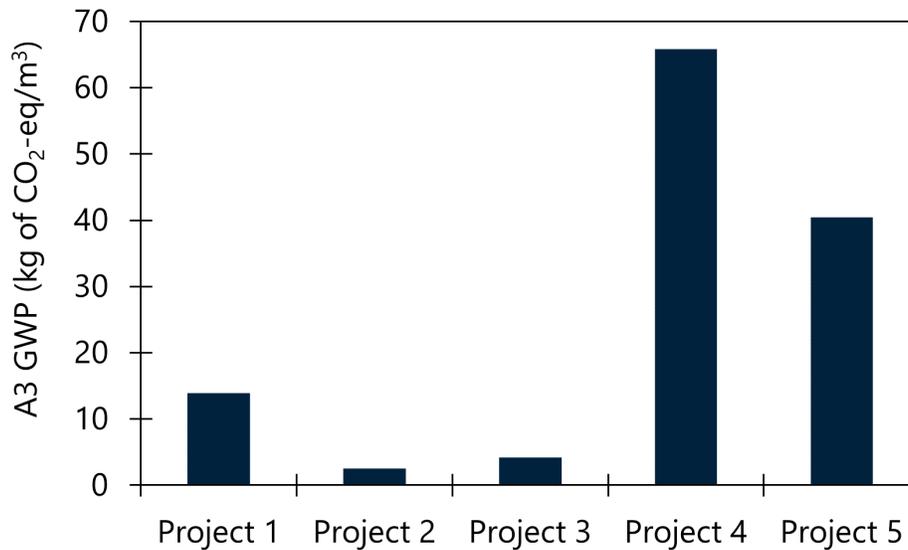


(a) A1-A3 GWP for Mobile Batch Plant Concrete (kg of CO<sub>2</sub>-eq/m<sup>3</sup>)



(b) A1-A3 GWP for Mobile Batch Plant Concrete (kg of CO<sub>2</sub>-eq/m<sup>3</sup>)

Figure 8.7 A1-A3 GWP for the concrete mixtures produced by ready-mix versus mobile batch plant in (a) and (b) showing the same with the thresholds identified in section 7.0.



**Figure 8.8 A3 GWPs of the project concretes produced by mobile batch plants.**

Due to the significant variability in A3 GWP that is demonstrated by mobile batch plants, more EPD and data collection for concrete produced by mobile batch plants is needed before concrete environmental impacts benchmarks can be considered inclusive of mobile batch plant concretes. Because the GWP is typically higher for concrete produced by mobile batch plant rather than ready-mixed concrete, different acceptance and incentive benchmarks and thresholds may need to be developed for mobile batch plant concretes. The higher environmental impacts for mobile batch plant concrete can be traced to lower production rates and/or higher generator fuel consumption. However, more EPDs and LCAs for mobile batch plant concrete are needed to confirm whether different benchmarks are needed.

The data provided in this section raises more questions than answers because of the small number of projects surveyed. Specifically, the questions that need further investigation are:

- Do mobile batch plants have a significantly different GWP than ready-mix concrete when analyzed across multiple projects for a 12-month period?
- How variable is A3 GWP for mobile batch plants from project to project?
- Does GWP vary significantly for mobile batch plants when powered by energy sources other than diesel fuel generators?

## 8.7 Estimated Construction Phase (A4-A5) LCA Results

Figures 8.9 and 8.10 display the A4 and A5 environmental impacts, respectively. The environmental impacts for A4 and A5 demonstrate that GWP is a leading indicator; the trends in environmental impacts follow those of the GWP such that the projects having higher GWP also showed higher environmental impacts in the categories other than GWP. The environmental impacts are tracking in the same direction. As analyses advance, it may be useful to track the rate at which the GWP increases compared to the other indicators.

Project 5 resulted in the highest estimated A4 environmental impacts compared to the other assessed projects, followed by Projects 4, 3, 1, and 2. Meanwhile, Project 4 had the highest estimated A5 environmental impacts compared to the other projects, followed by Projects 5, 1, 3, and 2. These results confirm that the factors influencing environmental impacts for life-cycle stage A4 are different than those for A5, considering that those project with higher A4 environmental impacts do not necessarily have higher A5 environmental impacts than the other projects shown. This result was expected because A4 transportation is related to the quantity of materials and distance between the mobile batch plant and the pouring site, whereas A5 is primarily a factor of the construction equipment fuel consumption.

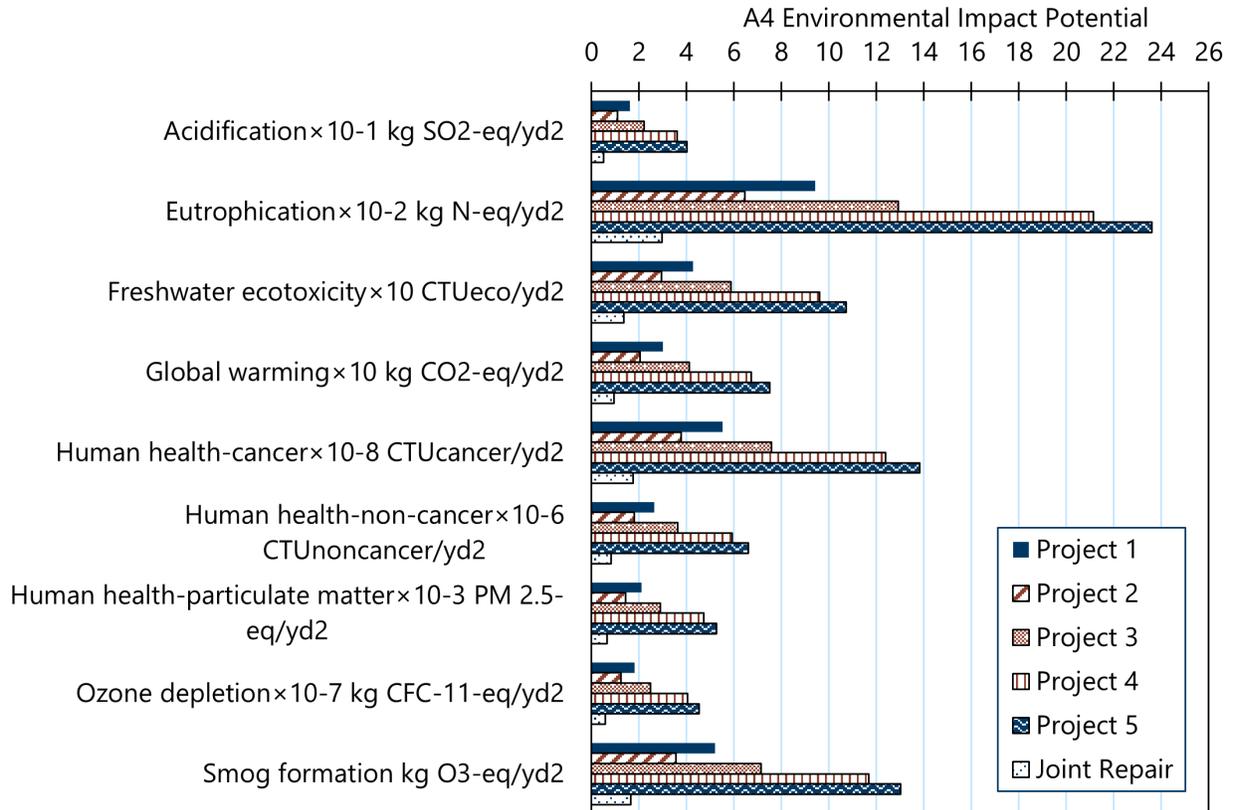


Figure 8.9 A4 environmental impacts for each project

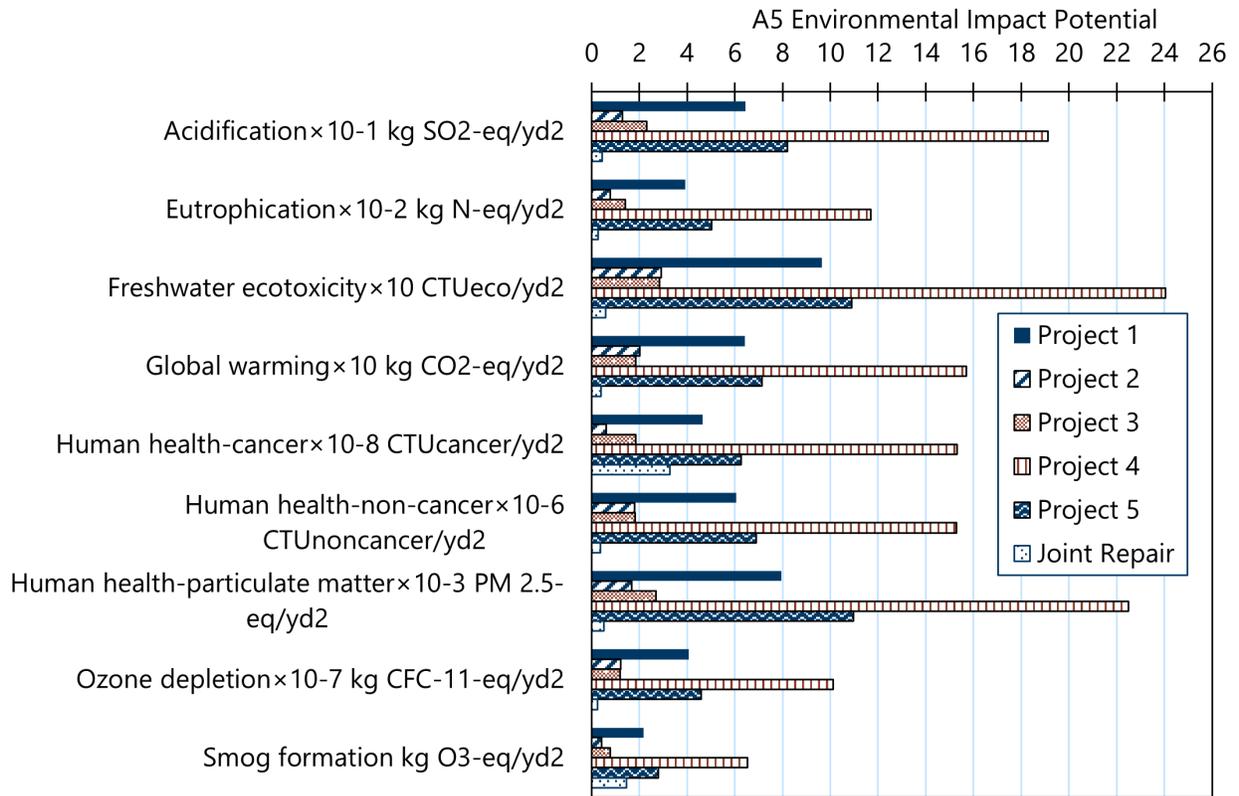


Figure 8.10 A5 environmental impacts for each project

Figure 8.11 emphasizes the A4 and A5 GWP by presenting side-by-side comparisons.

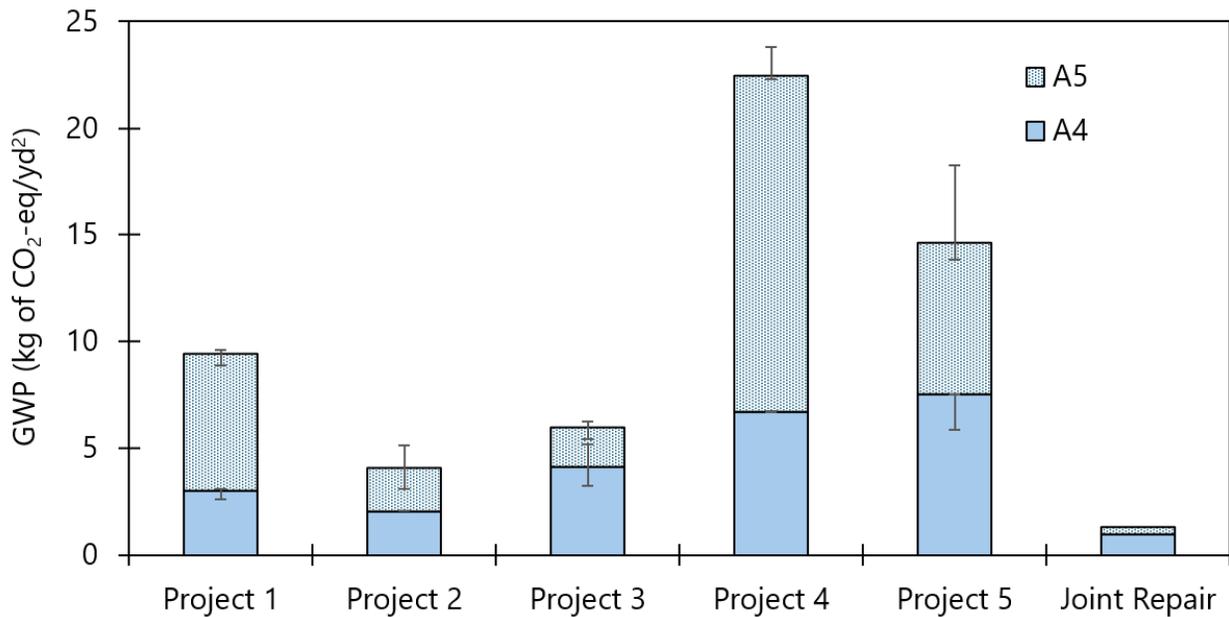
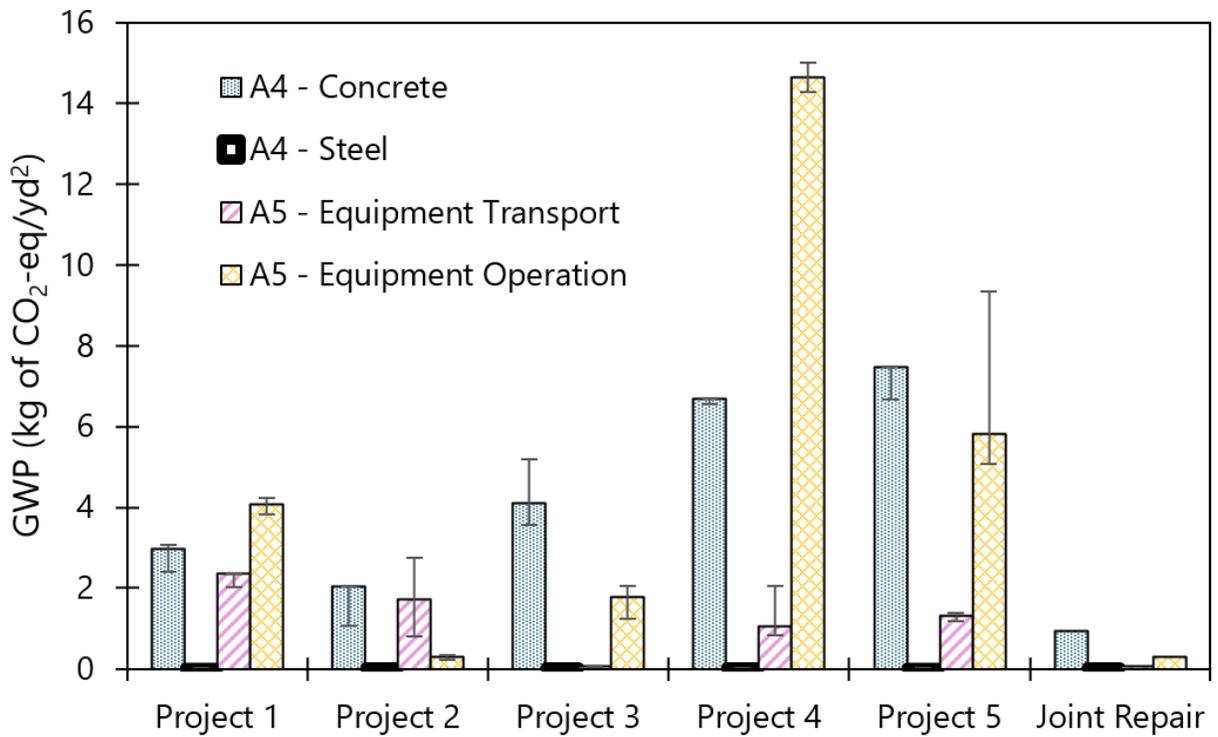
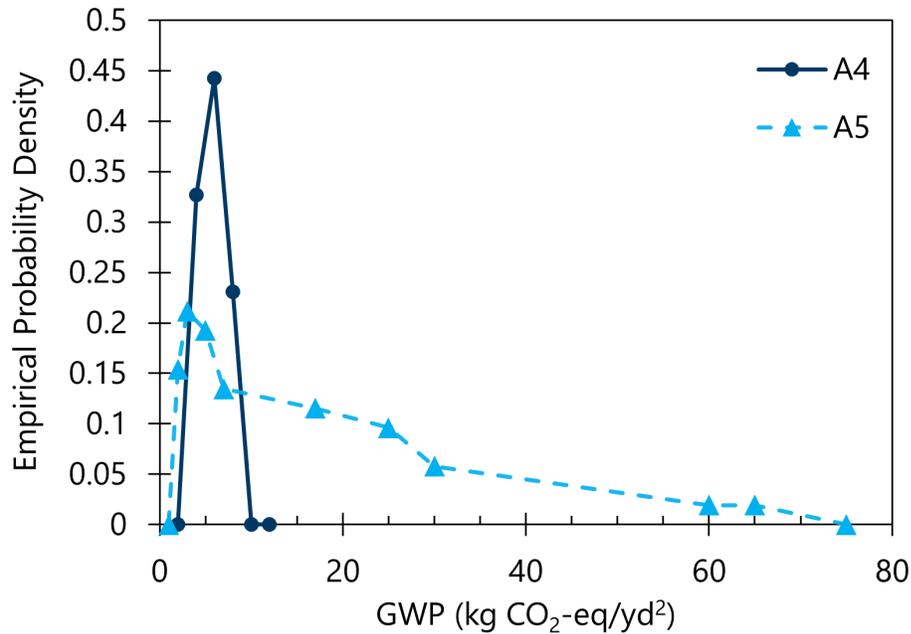


Figure 8.11 A4 and A5 GWP for each project



**Figure 8.12 A4 and A5 GWP for each project separated into concrete transportation, steel transportation, equipment transportation, and equipment operation**

Figure 8.13 represents the A4 and A5 distributions for all of the scenarios that have been analyzed. However, the distributions should not be used for benchmarking at this time due to the variability of the environmental impacts and the low number of projects that have been incorporated into the analysis.



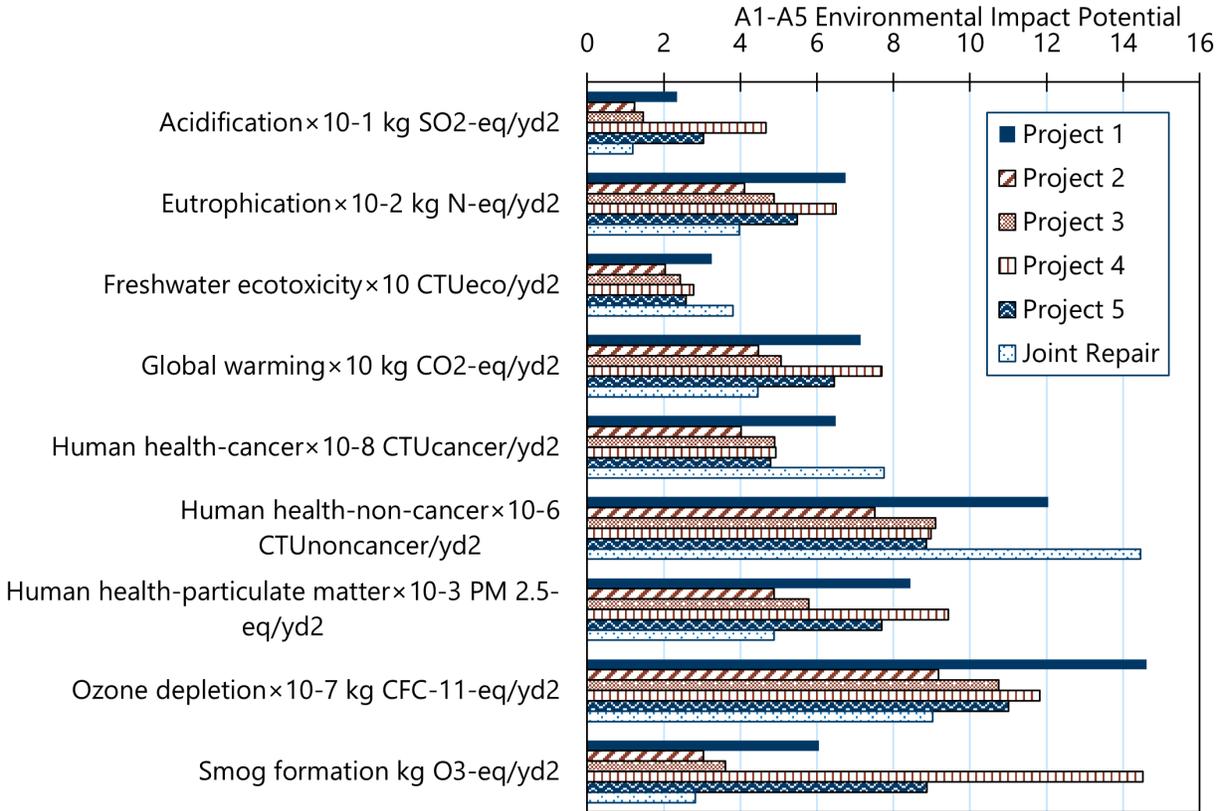
**Figure 8.13 A4 and A5 empirical probability density curves for the scenarios analyzed**

The data provided in this section raises more questions than answers because of the small number of projects surveyed. Specifically, the questions that need further investigation are:

- Does the A5 distribution become more normal when more projects are considered?
- Will further investigation with more projects demonstrate similar reliance on production rate for A5 environmental impact potentials?
- With more data, can we identify the key parameters contributing to A5 GWP such that the contributions can be scaled by project rather than require data collection efforts?

## 8.8 Estimated Construction Phase (A1-A5) LCA Results

Figure 8.14 shows the environmental impacts associated with A1-A5 for each project, demonstrating the sustainability at the project level with the culmination of the materials production and pavement construction.

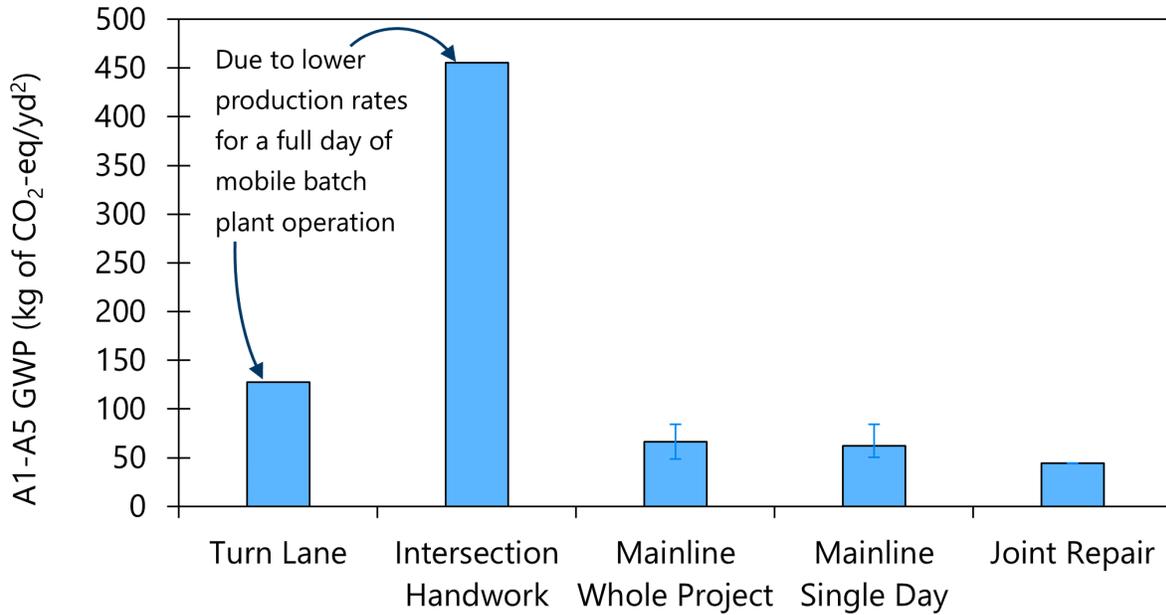


**Figure 8.14 A1-A5 environmental impacts for each project.**

On a few of the projects, multiple production types resulted in different production rates input to the LCIM. A typical production rate in terms of concrete placed per typical day of mainline paving and a production rate applying to the project entirety, such as 21 days of construction to pave 40,000 yd<sup>2</sup>, were collected for every project. In addition to mainline paving, turn lane paving and intersection handwork each occurred on a project. Data was separately collected related to those production activities, in addition to factoring into the whole project production. Figure 8.15 shows the differences in GWP that result for different paving production types due to the possibly high differences in production rates. The turn lane production results in higher A1-A5 GWP compared to mainline paving production. However, intersection handwork has much higher A1-A5 GWP than turn lane production due to the lower volume of concrete produced and placed compared to how much fuel is consumed for the mobile batch plant and roller used to finish the handwork. Both the turn lane and intersection handwork require multiple resets of materials, equipment, and workers to place the pavement in those more unique geometries. Paver resets, equipment resets, restarts, and stops reduce production rates and are more frequent in applications other than mainline paving.

The mainline paving on typical single days compared to mainline paving across whole projects resulted in A1-A5 GWPs with similar averages and ranges across projects. This similarity in A1-A5 GWP for whole project and single day production suggests that the specificity of production rates for the project are not critical as long as the number of days of construction and total area paved are reported. The most

important parameter to consider for comparing A1-A5 environmental impact is the application being considered (e.g., whether the input data represents mainline paving, turn lane paving, intersection handwork, or another scenario type).



**Figure 8.15 A1-A5 GWP based on the paving application, including turn lane, intersection handwork, and mainline paving.**

Figure 8.16 shows the percentage of contribution of each life-cycle stage for concrete and steel, separately, to the projects' A1-A5 GWP. The graph demonstrates the average contribution of A4 and A5 to A1-A5 GWP was 7.0 and 9.5%, respectively, or 16.5% together. A4 contributions ranged from 4.2 to 11.6%, while A5 contributions ranged from 9.1 to 29.2%. Previous figures allude to the multiple scenarios assessed for the projects of interest in this study. Multiple LCA scenarios were conducted for each project to account for the ranges in equipment fuel consumption and production rates. The average, maximum, and minimum equipment fuel consumptions and production rates were incorporated into the analysis as separate scenarios.

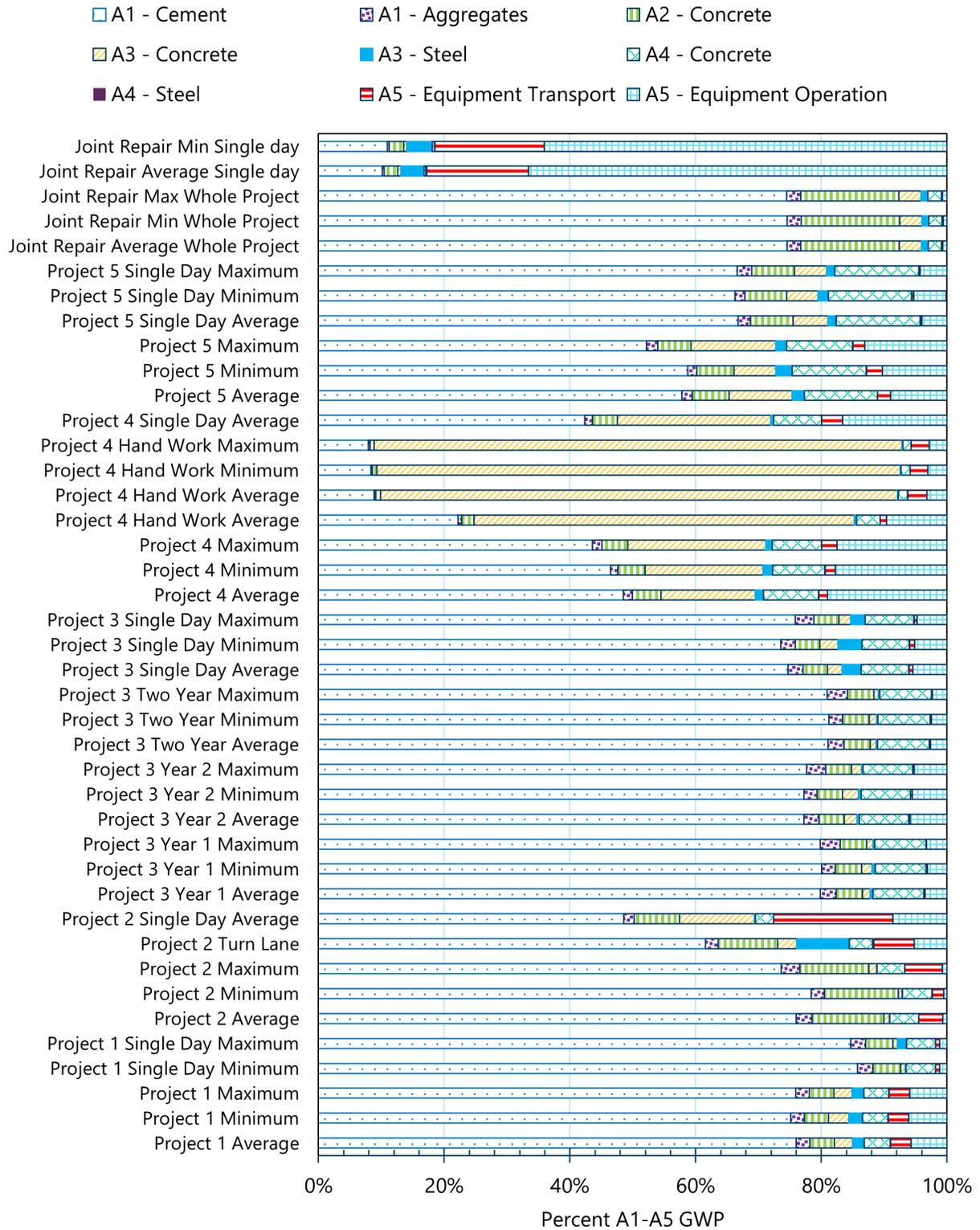


Figure 8.16 Percentage contribution of each life-cycle stage to the A1-A5 GWP across all assessed scenarios.

Figure 8.17 emphasizes the A1-A5 GWPs for the projects in comparison with their production rates. Those projects with lower A1-A5 GWPs also had higher production rates, demonstrating that the production rate has a significant influence on the GWP for the paved area. Project 5 does not appear to follow the same trend with the higher production rate due to the paver's lower fuel consumption rate compared to the other projects.



Figure 8.17 Project A1-A5 GWPs and production rates.

## 8.9 Mapping of A1-A5 LCA Results

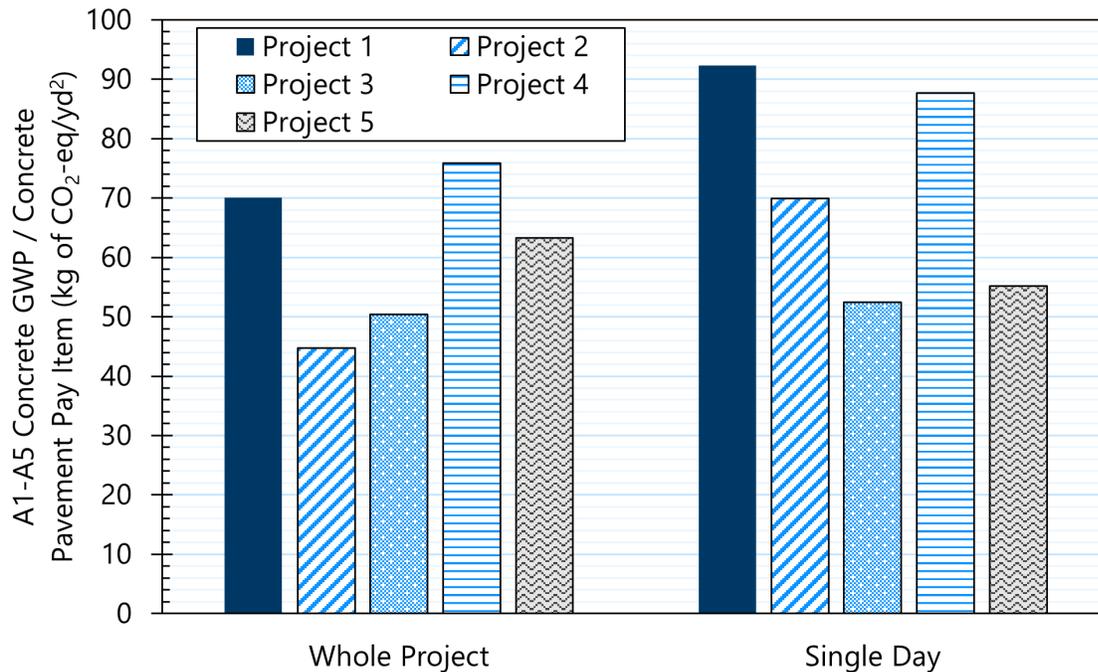
Table 8.15 displays the MnDOT pay items that relate to concrete paving and provides the averages and ranges of GWP per pay item. The average  $\pm$  standard deviation GWPs per pay item provided in the table only consider the five projects herein and therefore more data may be needed to develop distributions for GWP per pay item. Those identified pay items were used as the denominator in the environmental impacts analysis to assess variations in project sustainability based on key parameters such as the number of dowels, paved area, concrete quantity, and steel quantity. Assessing environmental impacts per pay item provides the potential to use pay items to scale the environmental impacts of the project and compare sustainability of a single pay item from project to project.

A project should become more sustainable by using more sustainable products and components and using resources more efficiently. Improving project sustainability by reducing the number of dowels or reducing paving depth may effect functionality and therefore these parameters relating to the pay items are not ideal for benchmarking from project to project. Higher resource and production efficiency as well as more sustainable materials, rather than reduced quantities affecting function and potentially out of the contractors' hands, are emphasized by providing environmental impacts in terms of the pay item.

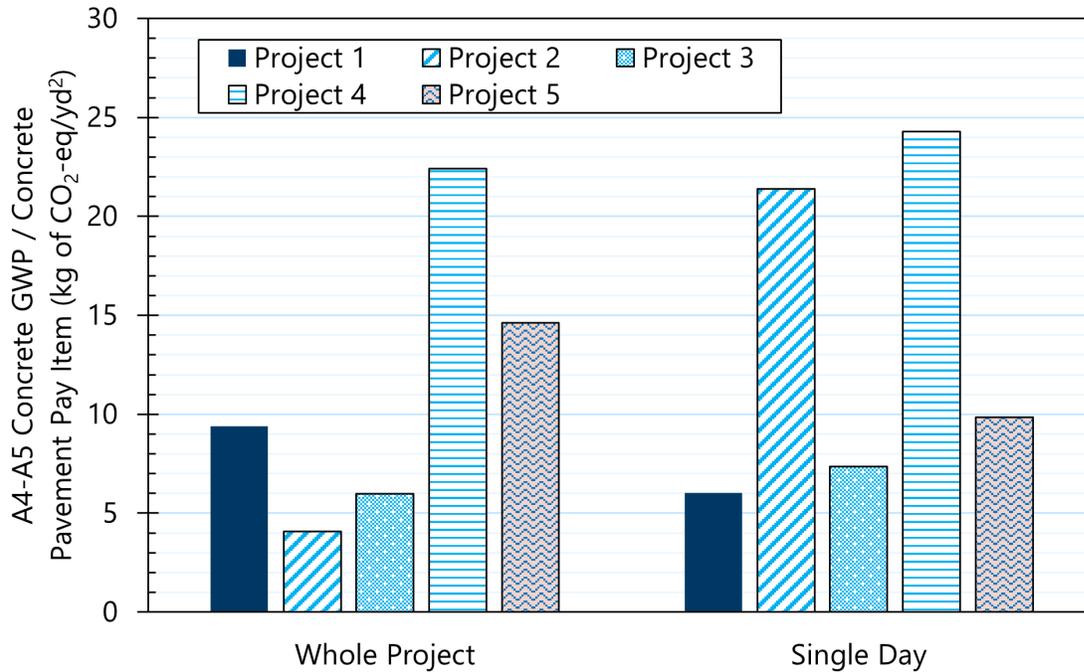
**Table 8.15 MnDOT pay items for concrete paving**

Pay Item	Materials Used	EPDs Available	EPD Declared Unit	GWP Average $\pm$ Standard Deviation per pay item (kg CO <sub>2</sub> -eq/pay item unit)	Unit of Measure
Concrete Pavement ___ and Placement	Concrete	No	yd <sup>2</sup>	(A1-A5) 58.4 $\pm$ 13.2 (A4-A5) 10.4 $\pm$ 6.95	yd <sup>2</sup>
	Concrete	No	yd <sup>2</sup>	(A1-A5) 6.32 $\pm$ 1.39 (A4-A5) 1.12 $\pm$ 0.78	yd <sup>2</sup> /in
Structural Concrete	Concrete	Yes	yd <sup>3</sup>	(A1-A3) 185 $\pm$ 20	yd <sup>3</sup>
Dowel Bar	Epoxy coated steel dowel bars or galvanized tubular dowel bars	No	metric ton	2.0 $\pm$ 0.9	Each
Supplemental Pavement Reinforcement	Steel	Yes	kg	0.42 $\pm$ 0.04	lb

Figure 8.18 displays the A1-A5 concrete GWP per square yard of pavement placed, while Figure 8.19 shows the A4-A5 GWP per square yard of pavement placed.

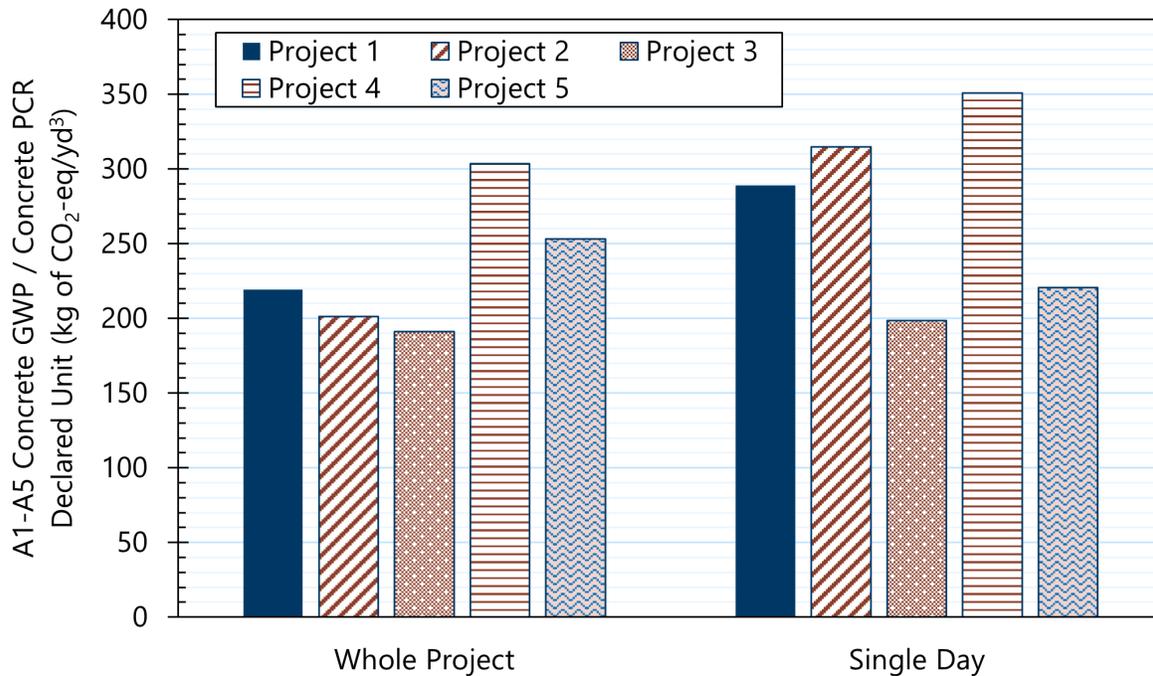


**Figure 8.18 A1-A5 concrete GWP per concrete pavement pay item in square yards**



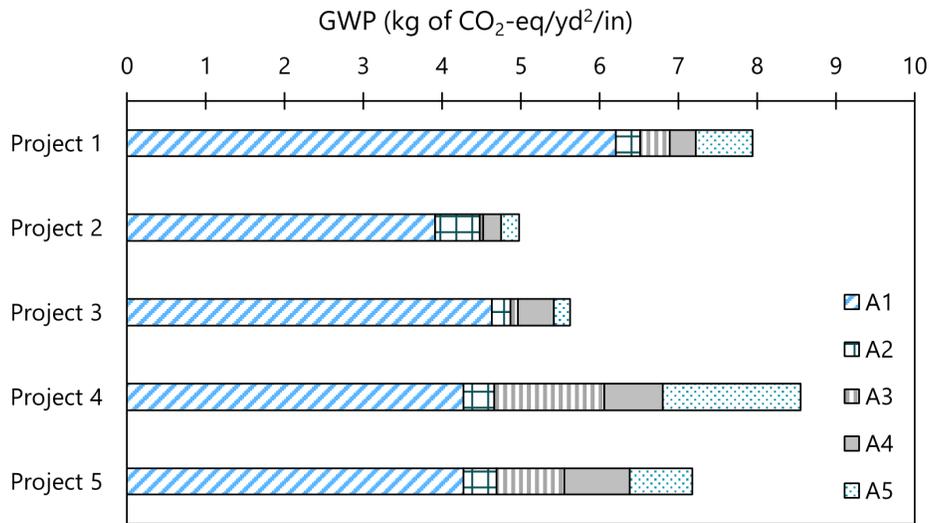
**Figure 8.19 A4-A5 concrete GWP per concrete pavement pay item in square yards**

In addition to mapping the GWP to pay items, the units identified in the concrete PCR for developing EPDs should also be considered. The current concrete PCR allows for A4 and A5 to optionally be included, though reported separately, in EPDs. The authors know of no EPDs that include A4 and A5. However, when those options are included, they must use the declared units that are required per the PCR, which is cubic meters or cubic yards. Figure 8.19 reports the A1-A5 concrete GWP per cubic yard for the mainline paving projects. In these units, the GWP ranged from 191 to 351 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>. To calculate the GWPs in these units, the outputs from the LCIM were divided by the pavement thicknesses, which were converted to yards.



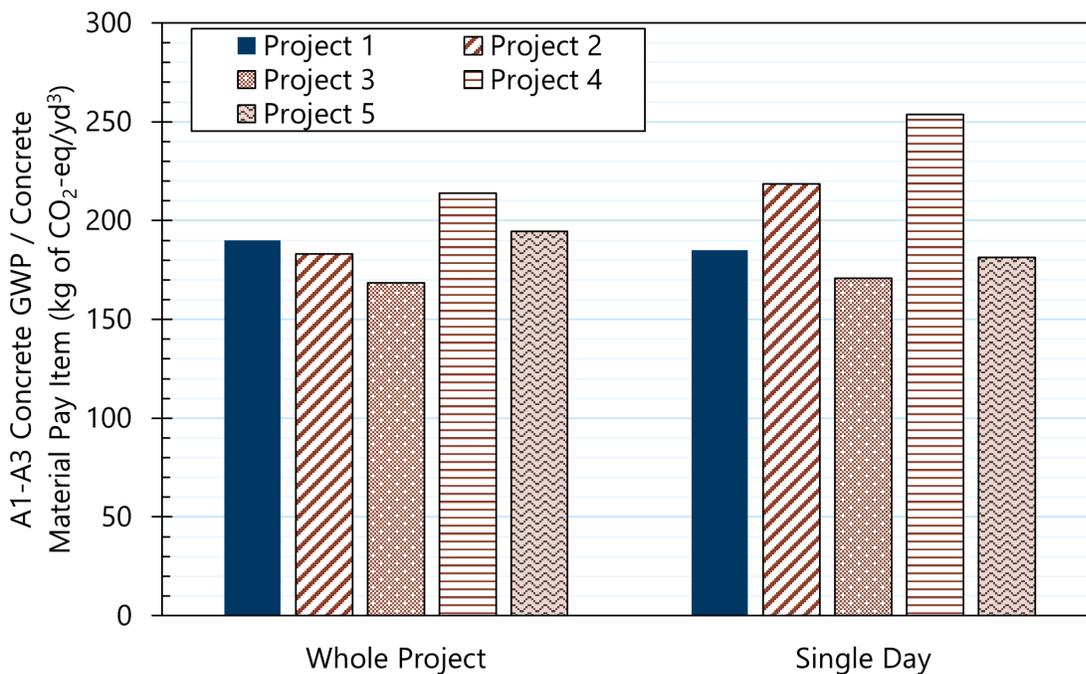
**Figure 8.20 A1-A5 concrete GWP per cubic yard, as required by the concrete PCR**

Similarly to Figure 8.20 incorporating pavement thickness, Figure 8.21 displays the same concept in a different manner, more directly relating the GWP to pavement thickness to allow for potential scalability. Figure 8.21 shows the GWP per square yard per inch, which normalizes the GWP by the pavement depth to negate potential impacts arising from the pavement design. The A1-A5 GWP per square yard per inch is relatively consistent (between 5 and 9) from project to project. The figure also separates GWP from each life-cycle stage to demonstrate the changes in those impacts depending on the project and geometry. A1, for instance, shows consistent GWP of about 4-6 kg of CO<sub>2</sub>-eq/yard<sup>2</sup>/in, while the A3 and A5 impacts vary more significantly, likely due to production rates of the batch plants and construction equipment.



**Figure 8.21 GWP by life-cycle stage when dividing that GWP by pavement thickness**

Figure 8.22 displays the A1-A3 concrete GWP per cubic yard, depicting a materials-level sustainability quantification. The A1-A3 concrete GWP per cubic yard ranges from 168 to 214 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>.



**Figure 8.22 A1-A3 concrete GWP per concrete material pay item in cubic yards.**

Figure 8.23 shows the GWP per dowel, and emphasizes the comparatively lower environmental impacts of the dowel bars compared to concrete due to the smaller quantities of material needed. Project 1 has much higher impacts per dowel due to increased diameter and length requiring more steel per dowel bar.

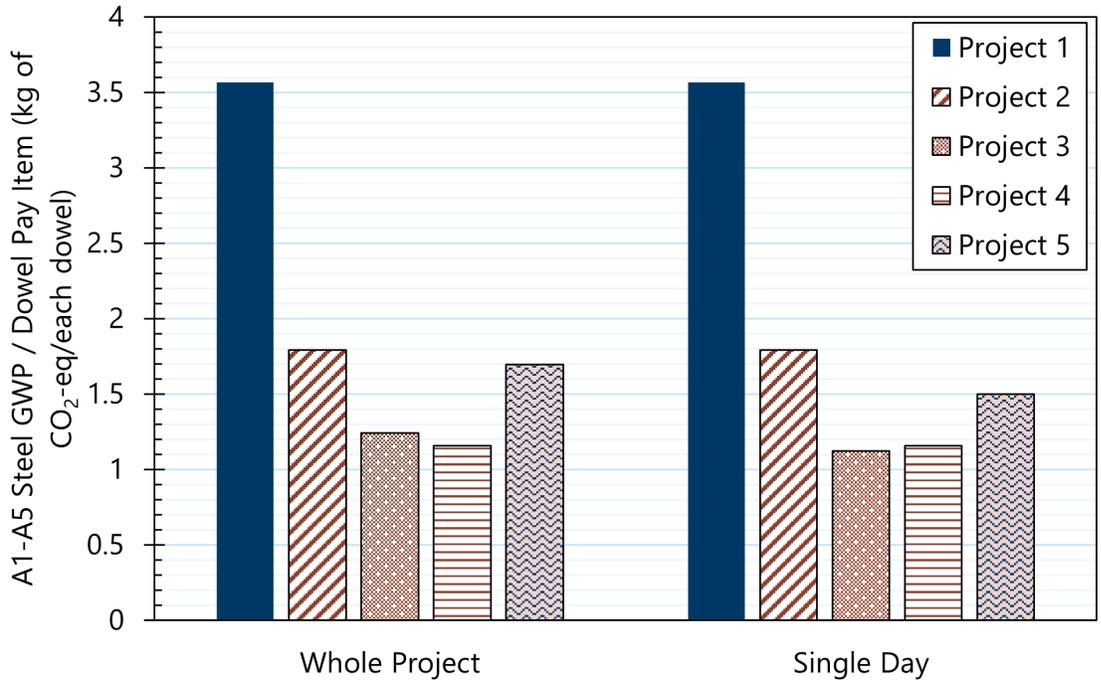


Figure 8.23 A1-A5 steel GWP per dowel pay item.

Figure 8.24 shows the A1-A5 steel GWP per pound (lb) of reinforcing steel. Reinforcing steel is typically used for periodic wheel baskets and along turn lanes.

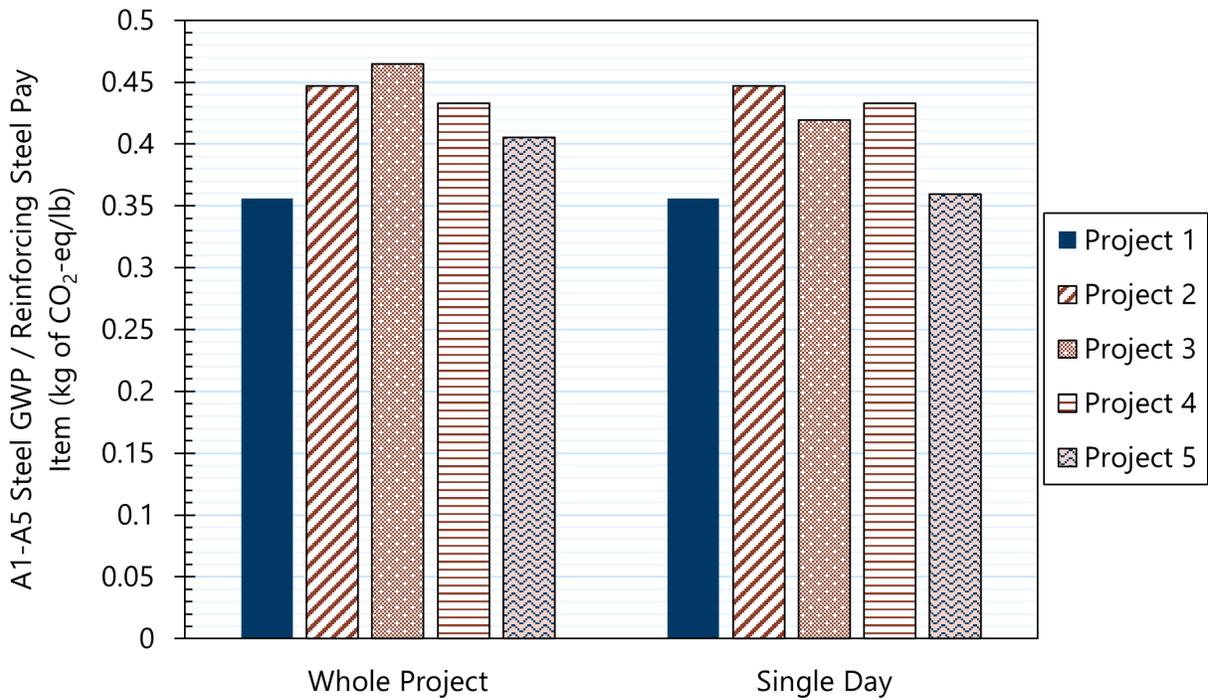


Figure 8.24 A1-A5 steel GWP per reinforcement pay item in lbs of steel.

Figure 8.25 displays the  $R^2$  values which correlate various input parameters with GWP per pay item across the projects. The figure focuses on the GWP per pay item relating to the concrete mixed and paved rather than the steel because most of the environmental impacts of the projects derive from the concrete. The darker shades of red depict high correlations while darker shade of blue depict extremely poor correlations.

Figure 8.25, more importantly, demonstrates how benchmarking in different ways can result in different overarching parameters. A1-A5 GWP/yd<sup>2</sup> shows moderate correlation production rate, loader fuel consumption, and belt placer fuel consumption. As expected, paste content, cement content, w/cm, and production rate have significant correlations with A1 GWP and A1-A3 GWP/yd<sup>2</sup>. The mixture design related parameters significantly affect A1-A3, while pavement design and production rate parameters have significant effects on A3-A5. A1-A5 and A4-A5 GWP/yd<sup>2</sup> have moderate correlations with concrete consumed and the paved area, both of which are directly related to pay items. A1-A3 GWP/yd<sup>2</sup> compared to A1-A3 GWP/yd<sup>3</sup> show how different parameters highly influence the results depending on whether the project-level (/yd<sup>2</sup>) or materials-level (/yd<sup>3</sup>) approach is taken.

MnDOT will need to determine whether A1-A5 GWP/yd<sup>2</sup> should be considered in its entirety to determine project sustainability, or whether a materials-level approach should be taken for the concrete and combined with the transportation and construction operations. A1-A3 GWP/yd<sup>3</sup> and A4-A5 GWP/yd<sup>2</sup> may be separately benchmarked and considered for project use and determinations of sustainable project procurement.

	Paste Content	Cement Content	W/CM	Production Rate	Concrete Consumed	Paved Area	Paving Lane Distance	Paving Width	Paving Depth	Mobile Batch Plant Generator Fuel Consumption	Equipment Transport Distance	Paver Fuel Consumption	Backhoe Fuel Consumption	Loader Fuel Consumption	Belt Placer Fuel Consumption	Days of Production
A1-A5 GWP/yd <sup>2</sup>	0.0658	0.1865	0.2284	0.1144	0.2956	0.3596	0.0794	0.259	0.254	0.0068	0.3887	5.00E-05	0.0683	0.4362	0.5358	0.007
A1-A5 Concrete GWP/yd <sup>3</sup>	0.0002	0.0015	4.00E-06	0.1878	0.31	0.2635	0.112	0.0677	0.001	0.1278	0.0971	5.22E-02	0.0299	0.3214	0.3302	0.0822
A1-A3 Concrete GWP/yd <sup>2</sup>	0.1334	0.5602	0.6632	0.1223	0.0728	0.1542	0.029	0.2014	0.6335	0.0055	0.433	0.006	0.0652	0.3281	0.5127	0.0933
A1-A3 Concrete GWP/yd <sup>3</sup>	0.0453	0.093	0.0463	0.1285	0.0803	0.0699	0.1078	0.0027	0.0028	0.1773	0.0561	0.1138	0.0238	0.289	0.3921	0.0802
A4-A5 GWP/yd <sup>2</sup>	0.0337	0.0019	0.001	0.2048	0.5171	0.4674	0.0982	0.2001	0.0015	0.0583	0.1793	0.0105	0.0404	0.35	0.316	0.0374
A1 GWP/yd <sup>2</sup>	0.9805	0.762	0.9448	0.0223	0.0025	0.016	0.0007	0.138	0.9452	0.1118	0.3564	0.0669	0.0274	0.1177	0.2503	0.2696
A2 GWP/yd <sup>2</sup>	0.9953	0.0002	0.0356	0.0782	0.2689	0.3769	0.056	0.6689	0.334	0.4553	0.3886	0.3299	0.0019	0.089	0.0383	0.1455
A3 GWP/yd <sup>2</sup>	0.0121	0.0218	0.0246	0.2356	0.4951	0.4152	0.0883	0.1387	0.0091	0.0769	0.0988	0.0275	0.0277	0.0625	0.2321	0.0625
A4 GWP/yd <sup>2</sup>	0.1309	0.0142	0.0255	0.079	0.4719	0.4088	0.4924	0.2168	0.0066	0.3349	0.3368	0.0895	0.2353	0.437	0.1902	0.1331
A5 GWP/yd <sup>2</sup>	0.0101	3.00E-05	0.0008	0.233	0.4344	0.4004	0.0113	0.1543	0.0078	0.0042	0.0961	0.0742	0.0028	0.2491	0.3142	0.0093

Figure 8.25 How parameters affect environmental impacts and therefore will affect material versus project benchmark.

## 8.10 QA/QC Metrics

MnDOT's primary quality assurance metric is to measure the fresh concrete's water content, and therefore water-to-cementitious materials ratio (w/cm), using the Phoenix test method. For this reason, the A1-A3 concrete GWP per cubic yard and A1-A5 concrete pavement GWP per square yard are compared with the w/cm for the concrete mixtures. Figure 8.26 demonstrates that no correlation exists between the w/cm and the GWP.

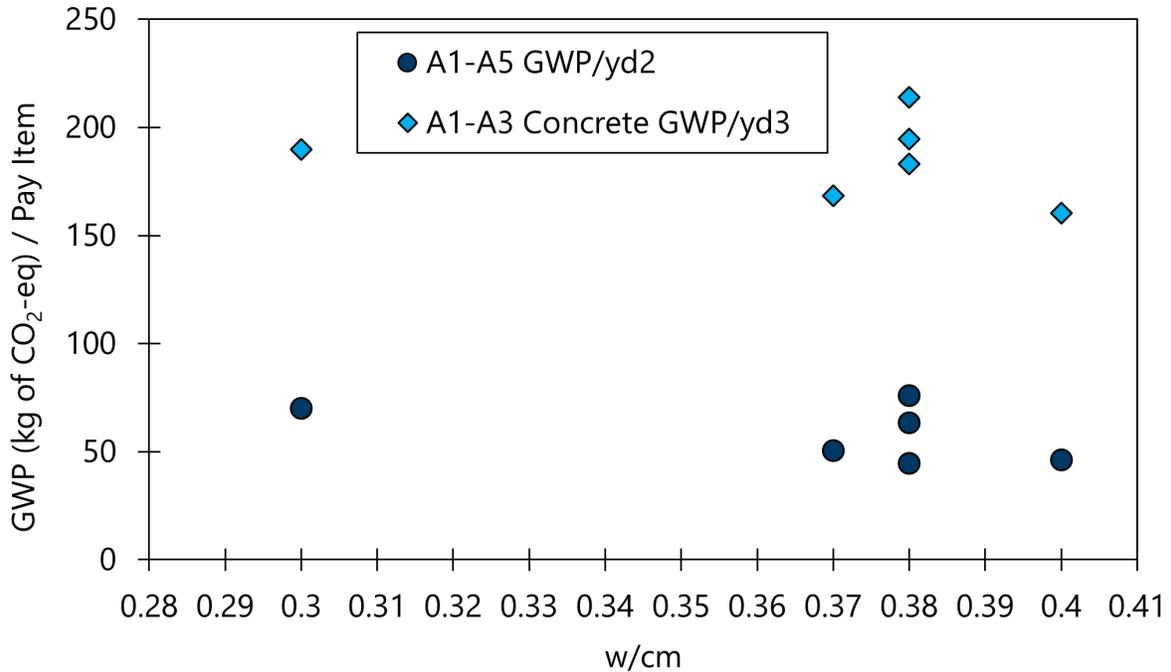


Figure 8.26 w/cm compared to GWP per pay item for both A1-A5 per yd<sup>2</sup> and A1-A3 per yd<sup>3</sup>

## Chapter 9: Recommendations for Integrating EPDs into the Procurement Process

Based on the insights within this investigation, the following recommendations are made for integrating environmental impacts into the procurement process:

- Require contractors to commit to providing EPDs for the materials to be placed on the project at the time of material submittal, such as mix design submittal, prior to the material's delivery on site.
- An EPD Submittal Package shall be submitted to the owner agency (1) no later than two weeks prior to delivery of the material(s) to site and (2) once at the end of the project or, for multiyear projects, at the end of each calendar year to reflect actual products and quantities delivered. The EPD Submittal Package shall follow the requirements provided in the Specification for EPD Submittal Package in Appendix C. Providing the EPD Submittal Package is recommended to be a separate project line item.
- EPDs should be submitted in accordance with the EPD Submittal Package for ready-mixed and mobile batch plant produced concrete and steel.
  - For ready-mixed concrete, a sufficient number of EPDs have been developed and collected to use the information provided in the EPD Submittal Package to make decisions against benchmarks and develop thresholds.
  - At this time, there is limited availability of EPDs for concrete produced at mobile batch plants. Concrete produced by mobile batch plants should not be rejected or disincentivized based on environmental impacts while EPDs for concrete produced at mobile batch plants are collected. After two construction seasons of EPD collection for concrete produced by mobile batch plant, the EPDs should be compared to the ready-mixed concrete benchmarks to determine whether new benchmarks, modification to the existing benchmarks, or the existing benchmarks are sufficient to include mobile batch plant concrete.
- Use of thresholds and/or incentives is only recommended when the material information (such as mixture design, product grade and dimensions, etc.) is provided such that they can be directly associated with the EPD provided to the owner agency, such as through the EPD Submittal Package. An agency interface for EPD software is under development to allow infrastructure owners to see this data for their received EPDs.
- Request EPDs directly from the program operator and accept only securely transmitted EPDs. A secure transmission would be digital and entail the use of a verified data exchange format such as Open EPD or similar, therefore ensuring preliminary conformance. EPA and AASHTO are developing a data transfer protocol, either of which can be adopted. The secure digital transfer of EPDs will ensure conformance with standards, facilitate robust program operator audits, and build trust between EPDs and their users.

- Prior to implementing GWP acceptance and/or incentive thresholds for materials based on EPDs, the infrastructure owner may consider developing a policy to address whether the transfer of carbon credits associated with the project materials should affect incentives distributions. Carbon credits place monetary value on improving sustainability and are based on voluntary carbon markets. The calculation of carbon credits may vary by distributor. The environmental impact potentials reported in EPDs are not influenced by carbon credits. However, there is potential for a cement with low GWP, for example, to be used in a concrete mixture that consequently achieves a low GWP on its EPD. The EPD with low GWP due to the low cement GWP would then be provided to the infrastructure owner for acceptance and incentives. The difference between an industry average cement GWP and the cement product used on the project (one possible method for a distributor to determine carbon credit value) may be monetized and sold on the voluntary carbon market, irrespective of whether low concrete GWPs were mandated or incentivized by the infrastructure owner. Once sold, another cement producer may claim those sustainability benefits for their products (though not through EPD). Therefore, the infrastructure owner may decide that the transfer of carbon credits does or does not result in a sustainable product.
- Table 9.1 provides recommendations for thresholds to consider environmental impacts at the materials level for ready-mix concrete. For paving applications, project-based GWP thresholds, for multiple mixes used on the project for instance, are less likely to have an impact on materials selection. The variety in mixture design selection (and therefore differences in A1) during concrete paving proved in this study to be minimal.
- Table 9.1 provides recommendations for incentives to consider project environmental impacts based on the reference GWP values developed in section 7.0. Though the benchmarks and incentives were developed based on environmental impacts of ready-mixed concrete, concrete produced by mobile batch plant meeting the incentive benchmarks should also receive incentives.
- The thresholds and incentives recommended herein are specific to concrete paving. Similar thresholds and incentives are provided for other applications, though more research may be needed. A project-level approach for materials sustainability is recommended for structural applications where multiple concrete mixture designs serving fundamentally different purposes are anticipated to be used on the same project. For example, bridge girders are likely to require different concrete mixtures than bridge decks. Achieving sustainable project procurement is possible, but a project-level approach will promote optimized materials selections across the project while fitting materials to performance needs. Similarly, precast concrete has its own PCR different from the concrete PCR that was mentioned frequently throughout this document. The thresholds identified herein from other jurisdictions, NRMCA, FHWA, etc. should not be applied to precast concrete. A future research project may be needed to perform data collection and benchmarking of precast concrete EPDs so that thresholds may be developed.
- The NRMCA statistical addendum and FHWA LCTM 20<sup>th</sup> percentile threshold for the north central region is lower than those calculated in this study for HES and all applications of Minnesotan concrete (Salazer et al. 2024, FHWA 2024b). The 40<sup>th</sup> percentile and average

threshold values for the north central region are higher than those calculated for HES and all applications of Minnesotan concrete, which entails a much smaller range of values. The thresholds for paving applications for Minnesotan concrete, however, are much lower than the NRMCA and FHWA thresholds because of the high optimization of the paving concrete mixture designs that reduced A1 GWP.

**Table 9.1 Summary of recommended acceptance and incentives thresholds for concrete.**

For acceptance				
Scenario	Production method	GWP limit (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )		Threshold basis
All applications	Mobile batch concrete	No limit		Limited EPDs
	Ready-mix concrete	305		NRMCA north central industry average
For incentives				
Scenario	Production method	GWP limit (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Incentive	Threshold basis
Paving	Mobile batch concrete	235 <sup>+</sup>	2.0%	20 <sup>th</sup> percentile
		240 <sup>+</sup>	1.5%	40 <sup>th</sup> percentile
		245 <sup>+</sup>	1.0%	Average
	Ready-mix concrete	235	2.0%	20 <sup>th</sup> percentile
		240	1.5%	40 <sup>th</sup> percentile
		245	1.0%	Average
High-early-strength	Ready-mix concrete	271	2.0%	20 <sup>th</sup> percentile
		276	1.5%	40 <sup>th</sup> percentile
		280	1.0%	Average
All other applications	Ready-mix concrete	270	2.0%	20 <sup>th</sup> percentile
		275	1.5%	40 <sup>th</sup> percentile
		279	1.0%	Average
Structural	Ready-mix concrete by material or by project ( $\sum GWP_i \times volume_i$ )	270	2.0%	20 <sup>th</sup> percentile
		275	1.5%	40 <sup>th</sup> percentile
		279	1.0%	Average

<sup>+</sup> indicates that the value will be revisited once more data is collected.

- Though A4 and A5 are currently optional life-cycle stages that can be included in concrete EPDs, no concrete EPDs incorporating A4 and A5 exist to the authors' knowledge. A4 and A5 life-cycle stages are not recommended to be incorporated into EPDs due to the scenario-specific nature of the inputs. While their incorporation would transition EPDs from the materials-level to the pay item-level, the applications and scenarios would need to be well depicted within the EPD to provide relevant clarity towards benchmarking and threshold development.

- MnDOT can, if desired, develop specifications requiring that A4 and A5 be included in EPDs used on their projects. Subclassifications of the pay items would need to be formally defined such that mainline paving is benchmarked separately from intersection handwork, for instance. Developing this requirement would also transfer the onus of data collection from materials suppliers to the general contractor. The EPD is owned by the company providing the primary data and, thus, A1-A5 EPDs would likely involve receiving cement and other constituent EPDs that feed into an A1-A3 EPD from the concrete supplier, which then feeds into another EPD that includes A4 and A5 for the general contractor. Specifications for A1-A5 EPDs should include benchmarking requirements associated with subclassifications of pay items (see table 8.15), as appropriate, and should require the EPD's project report. Every EPD is required to have a project report according to ISO 21930, though receipt of EPD project reports is not typically necessary for A1-A3 life-cycle stages when software tools dominate EPD development and therefore the project report is similar for all EPDs developed by the same tool.
- A1-A5 analyses are the gateway to including more holistic life-cycle analysis in project decision-making. Trade-offs should be considered when benchmarking for A4 and A5. There are project-level considerations that should not be discouraged and are unavoidable. For example, where a mobile batch plant is located in relation to the site may be limited by space availability (e.g., the batch plant can only be as close to site as staging area and property development in the area allow), and the production rate may be limited by traffic allowances (e.g., not being able to close the roadway during certain times). Oftentimes, the parameters that the contractor can change to reduce environmental impacts are the same strategies employed to improve efficiency and reduce costs. The area to be paved over the project duration, pavement geometry, and pavement thickness are parameters that will significantly affect the environmental impacts of the project, but which should not be shortchanged for the purpose of decreasing environmental impacts; To do so would jeopardize the function of the infrastructure. Therefore, low-carbon construction means and methods and interventions are the next step to low-carbon concrete.
- EPDs with A4 and A5 life-cycle stages would need to provide application-specific information to allow for appropriate subclassifications. Mainline paving demonstrated relatively low variability in A1-A5 GWP when mapped per pay item compared with other scenarios. However, only the results from five mainline paving projects in the north central region were included in this analysis. Performing A4 and A5 LCAs for more projects will likely reinforce the GWP ranges estimated in this study and allow for the development of a representative distribution of A4 and A5 for mainline paving. Furthermore, the data collection protocol in Appendix B can be used for this purpose. Once distributions are developed for A4 and A5, the project-level impacts can be scaled by multiplying the GWP per pay item with a highly influential parameter. Identifying the scalar parameter for A4 and A5 impacts was attempted in this study. More data, however, is needed to determine the scalar parameter. This methodology will allow for less long-term cost and effort, and provide rapid project-level estimations that can be used for sustainable project procurement decisions. Furthermore, it allows the environmental impacts to be mapped based on pay item rather than using the declared unit in the PCR, which makes little sense for mainline

paving. By developing benchmarks based on the scenario, such as mainline paving, the possibility of incentivizing concepts contrary to high performance is removed.

Figure 9.1 provides a flow chart that summarizes the recommended actions for integrating EPDs into the procurement process, and Figure 9.2 describes the stakeholder interactions needed for successful, secure EPD delivery.

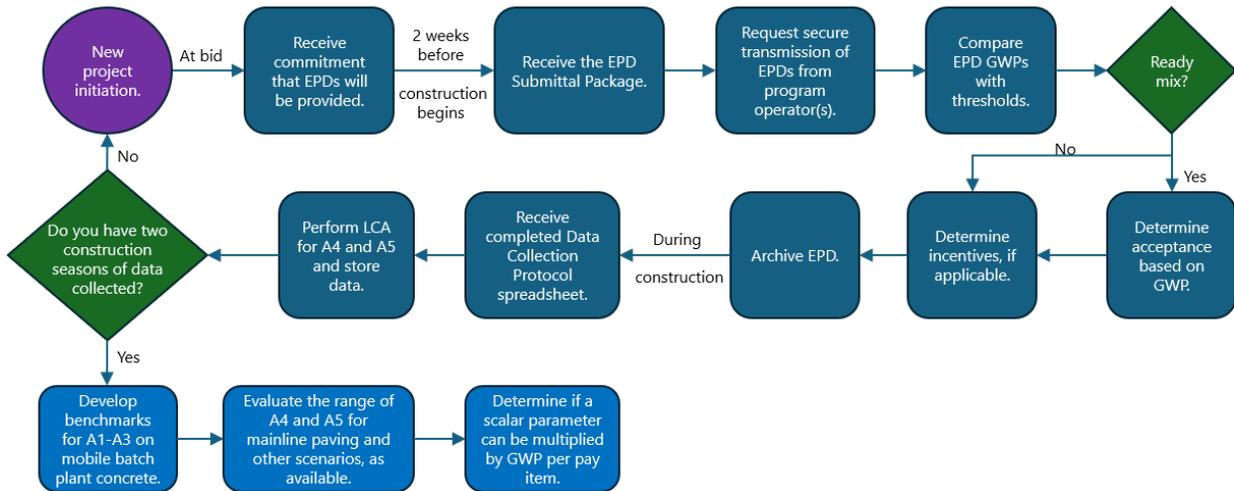


Figure 9.1 Flow chart summarizing the recommendations for integrating EPDs into the procurement process.

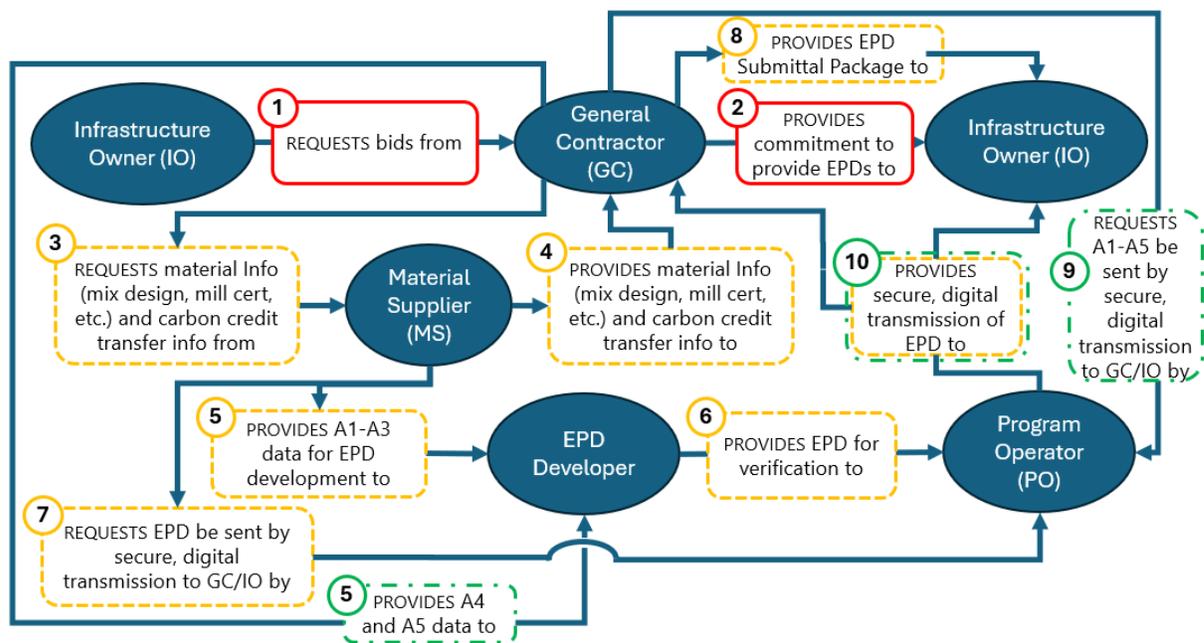


Figure 9.2 Interaction diagram for stakeholders' requests and actions.

## Chapter 10: Summary and Conclusions

In this work, we **introduced the concepts of LCAs and EPDs**. We explained that PCRs are the standard rules that an LCA must follow to develop results that can be reported in an EPD. The purpose of EPDs is to provide a standard reporting system that the user can immediately identify as consistent with rules set by product stakeholders specifically for the product of interest. EPDs involve partnership between product manufacturers, upstream suppliers, industry, LCA practitioners, product consumers, and product users. EPDs are third-party reviewed prior to their publication and are created so that no proprietary information is included in the EPD, allowing them to be freely and publicly available. Using EPDs develops trust in the environmental information communicated to the user and allows for comparability between similar products.

**Resources for high-level concrete GWP estimations** as well as the **tools that can produce concrete EPDs** are discussed. The high-level concrete GWP estimating tools use industry-average constituent emissions factors, regional-average transportation distances from the NRMCA benchmarking report (Athena 2021), and regional-average ready-mix concrete production plant emissions from the NRMCA benchmarking report. Therefore, the high-level concrete GWP estimating tools should be used with the understanding that GWPs reported in EPDs for the same concrete mix design are likely to be different than those indicated when using the tool. However, use of high-level estimating tools is typically free and can provide valuable insights for preliminary GWP indications, particularly for mix design proportioning. There are currently three known developers of concrete EPDs.

A workshop was conducted in November 2022 that educated Minnesota's concrete industry about EPDs, how to interpret the results presented on an EPD, and the synergy between strategies for improving concrete sustainability and performance. This document provided a **workshop summary** and outlined the concerns, challenges, and lessons learned that were discussed during the session. Key takeaways included concerns for: the amount of data that will need to be collected, tracked, and shared; how EPDs will be incorporated into specifications, quality assurance, and incentives programs; how mobile batch plants will be incorporated into the LCA process; how to account for changes in mix design that are made in real time to modify field constructability; and whether a minimum project size that is affected by EPD requirements will be implemented. The workshop concluded with discussion of a few strategies for reducing GWP that can be used immediately using conventional materials and processes, such as reducing clinker content, reducing cement content, and reducing paste content.

Multiple organizations have instituted requirements for environmental impacts, typically focused on GWP, of construction materials. This work **discusses the GWP requirements adopted** or in the process of being adopted **by other entities**. Oregon's City of Portland, California's Marin County, New York state, Colorado, FEMA, and ACI have developed their own definitions and thresholds for identifying low-carbon materials. EPA developed a definition for substantially lower levels of carbon emissions for EPA, FHWA, and GSA to use.

More than 850 published **concrete EPDs were collected** that claimed to pertain to Minnesota. Following the collection of these EPDs, **recommendations for formal data collection and archival** were developed.

In addition, 32 concrete mixture designs approved for use in Minnesota were collected. The high-level estimating tools previously described were used to approximate the A1 GWP of the concrete mixture designs based on their proportions. From these mixture designs, scenarios were created that represented valid mixtures for benchmarking. From the collected EPDs, A2 and A3 data was mined and used to develop separate A2 and A3 GWP distributions. The distributions were used to develop benchmarks for Minnesota's concrete based on the criteria proposed by other jurisdictions. The EPA's criteria for substantially lower levels of embodied carbon emissions, for example, was applied to the Minnesota concrete A1 scenario GWP combined with the 20th and 40th percentile and average values of the A2 and A3 distributions. In this manner, **recommendations for Minnesotan concrete GWP benchmarking** were developed.

These thresholds were developed, however, using EPDs specifically for ready-mix concrete. A limited number of EPDs exist nationally for concrete produced by mobile batch plants. During this work, **four concrete pavement reconstruction projects and one joint repair project were visited**. Data was collected from the five projects, as well as one project from the Iowa Climate Challenge, to **estimate the A1-A5 environmental impacts**, which incorporated constituent materials production, transport of constituents to the batch plant, concrete production at the mobile batch plants, transportation of the concrete to site, and construction operations. More specifically, the data collected during construction site visits included materials data, transportation distances, pavement geometry, mobile batch plant fuel consumption rates, construction equipment fuel consumption rates, and production rates. A **data collection spreadsheet and protocol** were created to facilitate future data collection efforts by MnDOT.

An **LCIM was developed and published** to estimate the environmental impacts across life-cycle stages A1-A5. An analysis was conducted to identify the benefits and risks associated with collecting EPDs and relevant GWP estimating data at bid, after successful bid, and during construction. The analysis revealed that the optimal time for collecting EPDs was two weeks prior to construction initiation.

The **fuel consumption of construction equipment was analyzed** for its potential range across projects. The construction equipment was characterized into classes that suggest its fuel consumption rate, with mobile batch plant generators, pavers, and boom trucks have the highest fuel consumption per day and highest variability in fuel consumption from project to project. Mobile batch plant fuel consumption varied by project depending on the concrete production rate of the plant as well as ages of the generator and mobile batch plant equipment. Newer equipment was reported to be typically twice as efficient as older generators.

The fuel consumption statistics along with production rates informed the **estimations of A1-A3 environmental impacts for concrete produced at mobile batch plants**. The A1-A3 GWPs of concrete produced by mobile batch plants were estimated to range 2 to 66 kg of CO<sub>2</sub>-eq/m<sup>3</sup> higher than the average A1-A3 GWPs for the same concrete mixes produced at ready-mix plants. The high variability in GWP and high magnitude of impact potentially associated with using mobile batch plant instead of ready-mix suggest that **the thresholds for low-carbon concrete that apply to ready-mix may not be suitable for concrete produced at mobile batch plants**. However, the estimations performed in this study incorporate emissions and production rates on a single project for each mobile batch plant. The

environmental impacts, which were shown to closely correlate with production rate, may decrease if 12 months of project production data are incorporated into the analysis. Thresholds may need to be separately developed for ready-mix concrete and mobile batch plant concrete to ensure that mobile batch production is not disincentivized or negatively impacted. EPD collections are recommended to continue and, after two construction seasons of further EPD collection, the applicable benchmarks can be revisited.

Along with **recommendations for integrating EPDs into the procurement process**, a **specification or special provision for an EPD submittal package** was developed that MnDOT can apply to projects to assist in achieving sustainable project procurement. The requirements set forth within the specification provide MnDOT with the information necessary to perform a high-level estimation of the GWP presented in an EPD. The recommendations **highlight the importance for program operators to develop an audit program for EPDs** that allows **for LCA input verification and EPD secure digital transmission** from program operators to infrastructure owners.

**A4 and A5 environmental impact estimations** were additionally developed using the LCIM, such that A1-A5 environmental impacts were aggregated. A4 and A5 contributed 16.5% of the project A1-A5 GWP on average. These contributions varied by project and by scenario relating to the project. Contributions from steel and dowel bars were minimal compared to those of concrete because of the relative quantities used in Minnesota, given that most are jointed plain concrete pavements.

**A1-A5 environmental impacts were estimated** using the LCIM. For mainline paving construction, the trends identified from the GWP were followed among the other environmental impact categories. For the joint repair, the GWP was not as clearly a leading indicator for the other environmental impact categories, though the reason for this was unclear. The A1-A5 GWP was assessed for turn lane, intersection handwork, mainline, and joint repair scenarios. Due to the lower production rates associated with starting and stopping operations as well as less paving output for a full day of active mobile batch plant operation, the turn lane and intersection productions resulted in much higher GWPs than mainline paving. For most scenarios, particularly those for mainline paving and having typical production rates, a majority of the environmental impacts arose from the A1 life-cycle stage due to the cement's impacts.

The **GWP results were mapped against the MnDOT pay items** to develop guidance on the range of GWP per pay item. The MnDOT pay items included dowel bars, concrete pavement and placement, structural concrete, and supplemental pavement reinforcement, for which the GWP average and standard deviations were, respectively,  $2.0 \pm 0.9$  kg of CO<sub>2</sub>-eq/each dowel,  $58.4 \pm 13.2$  kg of CO<sub>2</sub>-eq/yd<sup>2</sup>,  $185 \pm 20$  kg of CO<sub>2</sub>-eq/yd<sup>3</sup>, and  $0.42 \pm 0.04$  kg of CO<sub>2</sub>-eq/lb. In addition to mapping against pay items, the environmental impacts results were mapped against the concrete PCR declared unit of cubic yards, with the projects herein having A1-A3 ranges of 168 to 214 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>, and A1-A5 ranges of 191 to 351 kg of CO<sub>2</sub>-eq/yd<sup>3</sup>. For all 5 projects, when factoring in pavement thickness, GWP ranged from 5 to 9 kg of CO<sub>2</sub>-eq/yd<sup>2</sup>/in. The **GWP separately and in aggregation for the life-cycle stages per pay item and declared unit were correlated to the input parameters for the LCIM.**

MnDOT's primary quality-assurance metric and incentivization metric include quantifying the w/cm for fresh concrete mixtures upon production using the Phoenix test. The **w/cm for the mixtures used on the projects in this study poorly correlated with the A1-A5 GWP/yd<sup>2</sup> and the A1-A3 concrete GWP/yd<sup>3</sup>.**

Following these analyses with the LCIM for A1-A3, A4-A5, and A1-A5, **recommendations were provided regarding GWP intervals for acceptance and integrating EPDs into the procurement process.** A summary of the intervals for acceptance were provided in Table 9.1 while a flow chart and interaction diagram summarizing the recommendations were illustrated in Figures 9.1 and 9.2. In addition, Appendix E and Appendix H summarized the recommendations.

## References

- AASHTO. (2022). Standard method of test for compressive strength of cylindrical concrete specimens. AASHTO, Washington, DC.
- ACI Committee 323. (2024). Low-carbon concrete – Code requirements and commentary. ACI, Farmington Hills, MI. [https://www.concrete.org/Portals/0/Files/PDF/Previews/323-24\\_preview.pdf](https://www.concrete.org/Portals/0/Files/PDF/Previews/323-24_preview.pdf)
- Ahn, C.R., & S.H. Lee. (2013). Importance of operational efficiency to achieve energy efficiency and exhaust emission reduction of construction operations. *Journal of Construction Engineering and Management*, 139(4), 404-413. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000609](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000609).
- Ahn, C.R., P. Lewis, M. Golparvar-Fard, & SH Lee. (2013). Integrated framework for estimating, benchmarking, and monitoring pollutant emissions of construction operations. *Journal of Construction Engineering and Management*, 139(12). [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000755](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000755)
- Ashtiani, M.Z., & S.T. Muench. (2022). Using construction data and whole life-cycle assessment to establish sustainable roadway performance benchmarks. *Journal of Cleaner Production*, 380(1), 135031. <https://doi.org/10.1016/j.jclepro.2022.135031>
- Athena Sustainable Materials Institute. (2021). A cradle-to-gate life-cycle assessment of ready-mixed concrete manufactured by NRMCA members – Version 3.2. National Ready Mixed Concrete Association. Retrieved from [https://www.nrmca.org/wp-content/uploads/NRMCA\\_LCAReportV3.2\\_2023.pdf](https://www.nrmca.org/wp-content/uploads/NRMCA_LCAReportV3.2_2023.pdf)
- Barati, K., & X. Shen. (2016). Operational level emissions modelling of on-road construction equipment through field data analysis. *Automation in Construction*, 72(2016), 338-346. <https://www.sciencedirect.com/science/article/pii/S0926580516301649>
- Bhat, C.G. (2020). Life-cycle information models with parameter uncertainty analysis to facilitate the use of life-cycle assessment outcomes in pavement design decision-making (Open Access Dissertation, Michigan Technological University.) Retrieved from <https://doi.org/10.37099/mtu.dc.etr/1144>
- Bilec, M., R. Ries, H.S. Matthews, & A.L. Sharrard. (2006). Example of a hybrid life-cycle assessment of construction processes. *Journal of Infrastructure Systems*, 12(4). [https://doi.org/10.1061/\(ASCE\)1076-0342\(2006\)12:4\(207\)](https://doi.org/10.1061/(ASCE)1076-0342(2006)12:4(207))
- Building Transparency. (2021). Embodied carbon in construction calculator (EC3). Retrieved from <https://www.buildingtransparency.org/>
- Buy Clean California Act. (2017). California Legislative Information, 3500–3505. Retrieved from [https://leginfo.ca.gov/faces/codes\\_displayText.xhtml?division=2.&chapter=3.&part=1.&lawCode=PCC&article=5](https://leginfo.ca.gov/faces/codes_displayText.xhtml?division=2.&chapter=3.&part=1.&lawCode=PCC&article=5)

Cass, D., & A. Mukherjee. (2010). Calculation of greenhouse gas emissions associated with highway construction projects using an integrated life-cycle assessment approach. In Proceedings of the 2010 Construction Research Congress, pp. 1406-1415.

Cass, D., & A. Mukherjee. (2011). Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: Case study for pavement operations. *Journal of Construction Engineering and Management*, 137(11).  
[https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000349](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000349)

Cass, D., P. Tang, & A. Mukherjee. (2011). Managing construction operations to minimize greenhouse gas emissions. Paper presented at the 2nd International Conference on Transportation Construction Management, Feb. 7-10, Orlando, FL.

Caterpillar. (2014). *Owning & Operating Costs: Hourly Fuel Consumption Tables – Excavators*. Caterpillar, Edition 46(25),16-19.  
<https://static1.squarespace.com/static/58877529414fb5283ed14a6b/t/5888f8fb8a79b5efa002f01/1485371584196/Fuel+Table+-+Excavators.pdf>

City of Portland. (2022). Notice of new requirements for concrete. Portland, OR. Retrieved from <https://www.portland.gov/procurement/sustainable-procurement-program/documents/city-portland-concrete-embodied-carbon/download>

Climate Earth. (2024). EPDs made easy. Climate Earth, Point Richmond, CA. Retrieved from <https://climateearth.com/>

Colorado. (2023). Buy Clean Colorado Act. Office of the State Architect. Retrieved from <https://osa.colorado.gov/energy-environment/buy-clean-colorado-act>

Colorado. (2024). Buy Clean Colorado Act: Maximum acceptable global warming potential (GWP) limits. Colorado Office of the State Architect, Division of State Property. Retrieved from <https://osa.colorado.gov/sites/osa/files/documents/EE-5.1%20%281%29.pdf>

Commercial Metals Company. (2016). Environmental product declaration for concrete reinforcing steel. Retrieved from <https://cmcproduction.blob.core.windows.net/media/cmcmetals/media/pdf/environmental%20commitment/cmc-epd-knoxville-production-and-fabrication.pdf>

Cooper, M.A., & A. Mukherjee. (2024a). EPD tools and resources. Retrieved from <https://sites.google.com/mtu.edu/mndotworkshop/tools>.

Cooper, M.A., & A. Mukherjee. (2024b). MNDOT Research Project: Development of Process to Lower GWP of Construction Materials. Retrieved from <https://sites.google.com/mtu.edu/mndotworkshop/home>

- Cooper, M.A., & A. Mukherjee. (2024c). Environmental product declarations. Retrieved from <https://sites.google.com/mtu.edu/mndotworkshop/epds>
- Cooper, M.A., & A. Mukherjee. (2024). Data specificity of concrete mixture environmental product declarations. *International Symposium on Pavement, Roadway, and Bridge Life-Cycle Assessment*, 51, 187–197.
- Cooper, M.A., & A. Mukherjee. (2025). Developing a benchmarking methodology for concrete global warming potentials in North America. *ASCE Journal of Transportation Engineering, Part B: Pavements*, 151(2), <https://doi.org/10.1061/JPEODX.PVENG-1667>
- Cooper, M.A. (2025). Leveraging product and process characteristics across the concrete pavement life cycle to integrate global warming potential into project procurement processes. Michigan Tech University, Houghton, MI.
- CP Tech. (2024). Guide for reducing the cradle-to-gate embodied carbon emissions of paving concrete. Iowa State University, Ames, IA. [https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2024/03/guide\\_for\\_reducing\\_cradle-to-gate\\_emissions\\_w\\_cvr.pdf](https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2024/03/guide_for_reducing_cradle-to-gate_emissions_w_cvr.pdf)
- Department of Energy. (2022). Federal buy clean initiative. Office of the Federal Chief Sustainability Officer. Retrieved from <https://www.sustainability.gov/buyclean/>
- EcoInvent. (2024). Data with purpose. Zurich, Switzerland. Retrieved from <https://ecoinvent.org/>
- EPA. (2005). Greenhouse gases equivalencies calculator – Calculations and references. Retrieved from <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references>
- EPA. (2022a). Tool for reduction and assessment of chemicals and other environmental impacts (TRACI). Retrieved from <https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci#:~:text=TRACI%20is%20an%20environmental%20impact,industrial%20ecology%2C%20and%20sustainability%20metrics>
- EPA. (2022b). Interim determination on low-carbon materials. Retrieved from [https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20Interim%20Determination%20on%20Low%20Carbon%20Materials%20under%20IRA%2060503%20and%2060506\\_508.pdf](https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20Interim%20Determination%20on%20Low%20Carbon%20Materials%20under%20IRA%2060503%20and%2060506_508.pdf)
- EPA. (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 (EPA-430-F-21-011). Retrieved from <https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf>
- Federal LCA Commons. (2022). Federal Highway Administration/MTU pavement framework dataset. Retrieved from <https://www.lcacommons.gov/lca-collaboration/>

FEMA. (2024). Building clean, climate-resilient communities through FEMA's grant programs. FEMA, Washington, DC. Retrieved from <https://www.fema.gov/grants/policy-guidance/low-carbon-goals>

FHWA. (2017). Highway statistics 2016. Office of Highway Policy Information. Retrieved from <https://www.fhwa.dot.gov/policyinformation/statistics/2016/hm12.cfm>

FHWA. (2022). LCA pave tool. Office of Preconstruction, Construction, and Pavements. Washington, DC. Retrieved from <https://www.fhwa.dot.gov/pavement/lcatool/>

FHWA. (2023a). Community of scholars. Retrieved from <https://sites.google.com/mtu.edu/community-of-scholars/home>

FHWA. (2023b). Fact sheets: Low-carbon transportation materials grants. Retrieved from [https://www.fhwa.dot.gov/inflation-reduction-act/fact\\_sheets/lctm\\_grants.cfm](https://www.fhwa.dot.gov/inflation-reduction-act/fact_sheets/lctm_grants.cfm)

FHWA. (2023c). Using life-cycle assessment (LCA) to inform the pavement treatment selection process (FHWA-HIF-23-014). FHWA, Washington, DC. [https://www.fhwa.dot.gov/pavement/sustainability/case\\_studies/hif23014.pdf](https://www.fhwa.dot.gov/pavement/sustainability/case_studies/hif23014.pdf)

FHWA. (2024a). EDC-7: EPDs for sustainable project delivery. Retrieved from [https://www.fhwa.dot.gov/innovation/everydaycounts/edc\\_7/sustainable\\_epds.cfm](https://www.fhwa.dot.gov/innovation/everydaycounts/edc_7/sustainable_epds.cfm)

FHWA. (2024b). Low-carbon transportation materials grants program thresholds: Concrete. Retrieved from <https://www.fhwa.dot.gov/lowcarbon/thresholds/concrete.cfm>

GreenDelta. (2024). OpenLCA (software). Version 2.0.4. <https://www.openlca.org/>.

GSA. (2023). Inflation Reduction Act low embodied carbon concrete requirements. Retrieved from [https://www.gsa.gov/system/files/Concrete%20-%20GSA%20IRA%20Low%20Embodied%20Carbon%20Requirements%20%28Dec.%202023%29\\_508.pdf](https://www.gsa.gov/system/files/Concrete%20-%20GSA%20IRA%20Low%20Embodied%20Carbon%20Requirements%20%28Dec.%202023%29_508.pdf)

Gursel, A.P., E. Masanet, A. Horvath, & A. Stadel. (2014). Life-cycle inventory analysis of concrete production: A critical review. *Cement and Concrete Composites*, 51(2014), 38-48. [https://www.researchgate.net/publication/261184161\\_Life-cycle\\_inventory\\_analysis\\_of\\_concrete\\_production\\_A\\_critical\\_review](https://www.researchgate.net/publication/261184161_Life-cycle_inventory_analysis_of_concrete_production_A_critical_review)

Heidari, B., & L. C. Marr. (2015). Real-time emissions from construction equipment compared with model prediction. *Journal of the Air & Waste Management Association*, 65, 2, 115-125. <https://doi.org/10.1080/10962247.2014.978485>

Helsel, M.A., M. Rangelov, L. Montanari, R. Spragg, & M. Carrion. (2023). Contextualizing embodied carbon emissions of concrete using mixture design parameters and performance metrics. *Structural Concrete*, 24(2), 1766-1779 <https://doi.org/10.1002/suco.202200634>

Hendrickson, C., A. Horvath, S. Joshi, & L.B. Lave. (1998). Economic models for input-output lifecycle analysis. *Environmental Science and Technology*, 29(9), 184-191.

Inflation Reduction Act. (2022). H.R.5376. Retrieved from <https://www.congress.gov/bill/117th-congress/house-bill/5376/text>

Iowa DOT. (2024). Iowa DOT: Climate challenge project. Federal Highway Administration Sustainable Pavements Program. Retrieved from <https://www.fhwa.dot.gov/infrastructure/climatechallenge/projects/IA.pdf>

ISO. (2006). Environmental management – Life-cycle assessment – Principles and framework. International Organization of Standards, Geneva, Switzerland.

ISO. (2017). Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services. International Organization of Standards, Geneva, Switzerland.

ISO. (2020). Sustainability in buildings and civil engineering works – Indicators and benchmarks – Principles, requirements and guidelines. International Organization of Standards, Geneva, Switzerland.

Jiang, R., & P. Wu. (2019). Estimation of environmental impacts of roads through life cycle assessment: A critical review of future directions. *Transportation Research Part D: Transport and Environment*, 77, 148-163. <https://doi.org/10.1016/j.trd.2019.10.010>

Kendall, A., G.A. Keoleian, & G.E. Helfand. (2008). Integrated life-cycle assessment and life-cycle cost analysis model for concrete bridge deck applications. *Journal of Infrastructure Systems*, 14(3). Retrieved from [https://doi.org/10.1061/\(ASCE\)1076-0342\(2008\)14:3\(214\)](https://doi.org/10.1061/(ASCE)1076-0342(2008)14:3(214))

Labeling Sustainability. (2022). Making sustainability inclusive. Retrieved from <https://www.labelingsustainability.com/>

Lewis, M.P. (2009). Estimating fuel use and emission rates of nonroad diesel construction equipment performing representative duty cycles. North Carolina State University, (PhD Thesis). Retrieved from <https://repository.lib.ncsu.edu/server/api/core/bitstreams/19dd22bf-b5d0-446c-9bcf-602988601646/content>

Loijos, A., N. Santero, & J. Ochsendorf. (2013). Life cycle climate impacts of the US concrete pavement network. *Resources, Conservation and Recycling*, 72, 76-83. <http://dx.doi.org/10.1016/j.resconrec.2012.12.014>.

Marceau, M.L., M.A. Nisbet, & M.G. VanGeem. (2006). Life-cycle inventory of Portland cement manufacture. Portland Cement Association, Skokie, IL.

Marin County. (2019). Marin County Code Chapter 19.07 added to Marin County Code Title 19: Low-carbon concrete requirements. Marin County, California. Retrieved from <https://www.marincounty.org/-/media/files/departments/cd/planning/sustainability/low-carbon-concrete/12172019-update/low-carbon-concrete-code.pdf?la=en>

Minnesota Department of Administration. (2024). Minnesota Department of Administration launches 'Buy Clean' construction materials pilot program. Retrieved from <https://mn.gov/admin/media/news/?id=36-630478>

Muga, H., A. Mukherjee, J.R. Milhelcic, & M.J. Kueber. (2009). An integrated assessment of continuously reinforced and jointed plain concrete pavements. *Journal of Engineering Design and Technology*, 7, 1, 81–98.

NETL. (2019). Grid Mix Explorer Version 4.1 (web page). Retrieved from <https://www.netl.doe.gov/energy-analysis/details?id=bb9b0ec8-68b1-4406-8655-5bb4b095c7eb>

NYS. (2022a). Lower carbon concrete. New York State Office of General Services. Retrieved from <https://ogs.ny.gov/greenyy/lower-carbon-concrete>

NYS. (2022b). NYS buy clean concrete guidelines. New York State Office of General Services. Retrieved from <https://ogs.ny.gov/nys-buy-clean-concrete-guidelines-0>

NREL. (2012). U.S. life-cycle inventory database. Retrieved from <https://www.nrel.gov/lci>

NRMCA. (2021). NRMCA member industry-average EPD for ready-mixed concrete. National Ready Mixed Concrete Association, Alexandria, VA. [https://www.nrmca.org/wp-content/uploads/NRMCA\\_EPDV3.2\\_2023.pdf](https://www.nrmca.org/wp-content/uploads/NRMCA_EPDV3.2_2023.pdf)

NRMCA. (2023). Environmental product declarations: Concrete product EPDs verified under NRMCA's EPD. National Ready Mixed Concrete Association, Alexandria, VA. <https://www.nrmca.org/association-resources/sustainability/environmental-product-declarations/>

NRMCA. (2024). NRMCA concrete carbon calculator. LCA tool. Retrieved from <https://www.nrmca.org/association-resources/sustainability/>

NSF International. (2024). Product category rule for environmental product declarations: PCR for concrete v2.3- 2024 extension. NSF International, Ann Arbor, Michigan.

Office of the Federal Chief Sustainability Officer. (2024). Federal buy clean initiative. Retrieved from <https://www.sustainability.gov/buyclean/#:~:text=In%20March%202023%2C%20the%20Biden,welcomed%20Minnesota%20into%20the%20partnership>

Oregon State Legislature. (2022). HB 4139; Relating to reductions of greenhouse gas emissions in the state's transportation system; and prescribing an effective date. Retrieved from <https://olis.oregonlegislature.gov/liz/2022r1/Measures/Overview/HB4139>.

PCA. (2023a). Environmental product declaration—Portland cement (per ASTM C219 and specified in ASTM C150, ASTM C1157, AASHTO M 85, or CSA A3001). Portland Cement Association, Skokie, IL. [https://www.cement.org/docs/default-source/default-document-library/pca\\_epd\\_portland\\_athena\\_final\\_revised\\_nov2023.pdf?sfvrsn=f8a9febf\\_2](https://www.cement.org/docs/default-source/default-document-library/pca_epd_portland_athena_final_revised_nov2023.pdf?sfvrsn=f8a9febf_2)

PCA. (2023b). Environmental product declaration—Portland-limestone cement (per ASTM C219 and specified in ASTM C150, ASTM C1157, AASHTO M 85, or CSA A3001). Portland Cement Association, Skokie, IL. [https://www.cement.org/docs/default-source/default-document-library/pca\\_epd\\_plc\\_athena\\_final\\_revised\\_nov2023.pdf?sfvrsn=aafefb\\_2](https://www.cement.org/docs/default-source/default-document-library/pca_epd_plc_athena_final_revised_nov2023.pdf?sfvrsn=aafefb_2)

Rangelov, M., H. Dylla, A. Mukherjee, & N. Sivaneswaran. (2020). Use of environmental product declarations (EPDs) of pavement materials in the United States of America to ensure environmental impact reductions. *Journal of Cleaner Production*, 283, 124619.

Salazar, J., L. Miller, B. Ciavola, & A. Mukherjee. (2024). Statistical addendum for a cradle-to-gate life-cycle assessment of ready-mixed concrete manufactured by NRMCA members – Version 3.2. WAP sustainability via NRMCA. Retrieved from [https://www.nrmca.org/wp-content/uploads/NRMCA\\_Statistical\\_Addendum.pdf](https://www.nrmca.org/wp-content/uploads/NRMCA_Statistical_Addendum.pdf)

SimaPro. (2024). LCA software for informed changemakers. Pre-sustainability B.V. Retrieved from <https://simapro.com/>

Singh, A., P. Vaddy, & K.P. Biligiri. (2020). Quantification of embodied energy and carbon footprint of pervious concrete pavements through a methodical lifecycle assessment framework. *Resources, Conservation and Recycling*, 161, 104953. <https://doi.org/10.1016/j.resconrec.2020.104953>

SCA. (2015). Industry average EPD for slag cement. Slag Cement Association, Farmington Hills, MI.

SCA. (2022). Slag cement life-cycle assessment calculator. Slag Cement Association, Farmington Hills, MI. <https://www.slagcement.org/lca-calculator>

SmartEPD. (2024). Part B product category rules for supplementary cementitious materials (Standard 1000-002, version 1.0). Retrieved from <https://smartepd.com/pcr-library>

Szamocki, N., M-K. Kim, C.R. Ahn, & I. Brilakis. (2019). Reducing greenhouse gas emission of construction equipment at construction sites: Field study approach. *Journal of Construction Engineering and Management*, 145(9), 05019012. [https://doi.org.10.1061/\(ASCE\)CO.1943-7862.0001690](https://doi.org.10.1061/(ASCE)CO.1943-7862.0001690)

Tang, P., D. Cass, & A. Mukherjee. (2013). Investigating the effect of construction management strategies on project greenhouse gas emissions using interactive simulation. *Journal of Cleaner Production*, 54, 78-88.

United States Government. (2022). Fact sheet: Biden-Harris administration announces new buy clean actions to ensure American manufacturing leads in the 21st Century. The White House. Retrieved from <https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-buy-clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/>

Union Pacific Railroad. (2022). Union Pacific Railroad application for development project approval. Retrieved from [http://ictf-jpa.org/document\\_library/application\\_development\\_project\\_approval/App%20B.pdf](http://ictf-jpa.org/document_library/application_development_project_approval/App%20B.pdf).

WAP Sustainability Consulting. (2024). Theta EPD: The buy clean compliance software.

WAP sustainability, Brentwood, TN. Retrieved from <https://wapsustainability.com/software/theta-epd/>

White House. (2021). The long-term strategy of the United States: Pathways to net-zero greenhouse gas emissions by 2050. United States Department of State and the United States Executive Office of the President. Retrieved from <https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf>

Xu, X., M. Akbarian, J.R. Gregory, & R. Kirchain. (2019). Role of the use phase and pavement-vehicle interaction in comparative pavement life-cycle assessment as a function of context. *Journal of Cleaner Production*, 230(3). <https://doi.org/10.1016/j.jclepro.2019.05.009>

Yu, B., & Q. Lu. (2012). Life-cycle assessment of pavement: Methodology and case study. *Transportation Research Part D*, 17, 380-388, <http://dx.doi.org/10.1016/j.trd.2012.03.004>

Zhang, H., M.D. Lepech, G.A. Keoleian, S. Qian, & V.C. Li. (2009). Dynamic life-cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration. *Journal of Infrastructure Systems*, 16(4). [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000017](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000017)

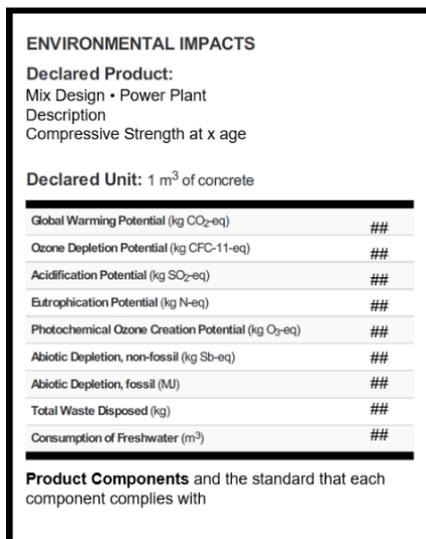
Zhen Wang, B., Z. Hua Zhu, E. Yang, Z. Chen, & X. Hong Wang. (2018). Assessment and management of air emissions and environmental impacts from the construction industry. *Journal of Environmental Planning and Management*, 61(14), 2421-2444. <https://doi.org/10.1080/09640568.2017.1399110>

**Appendix A**  
**EPDs Introduction**

# ENVIRONMENTAL PRODUCT DECLARATIONS (EPDS)

## For Construction Materials: Background and Best Practices

**What is an EPD?** In general, EPDs can successfully estimate the environmental impacts of a product, such as concrete. An environmental product declaration (EPD) is a report providing an estimated quantification of the environmental impacts of a specific product as determined in accordance with its corresponding standard. EPDs include the environmental impact indicators of global warming potential, ozone depletion potential, eutrophication potential, acidification potential, photochemical ozone creation potential, abiotic depletion nonfossil, and abiotic depletion fossil, as well as total waste disposed and consumption of freshwater depending on the product. These estimated environmental impacts are presented within an EPD in a format akin to nutrition facts labels typically seen on food products (Figure 1).



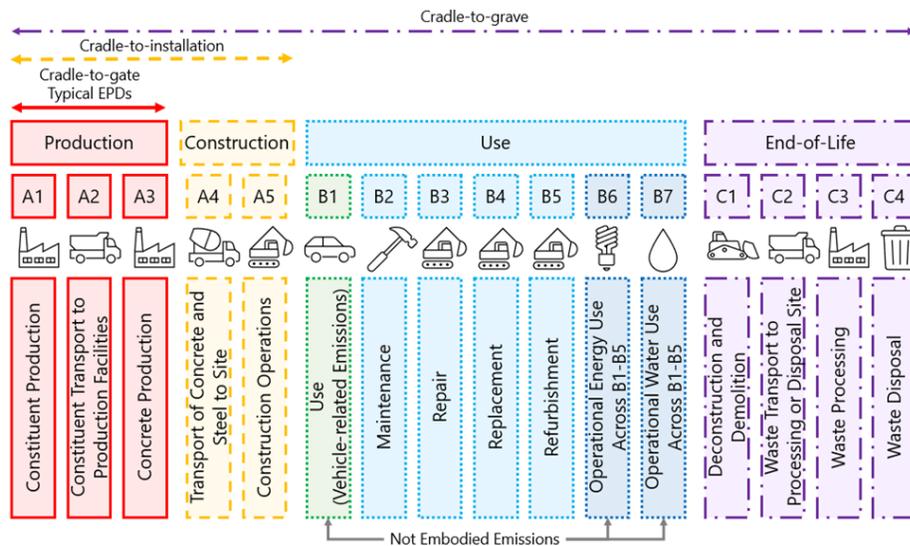
The image shows a sample Environmental Product Declaration (EPD) for concrete. It includes a title 'ENVIRONMENTAL IMPACTS', a 'Declared Product' section with 'Mix Design • Power Plant' and 'Description Compressive Strength at x age', and a 'Declared Unit' of '1 m<sup>3</sup> of concrete'. Below this is a table of environmental impact indicators, each with a value of '##'. The indicators are: Global Warming Potential (kg CO<sub>2</sub>-eq), Ozone Depletion Potential (kg CFC-11-eq), Acidification Potential (kg SO<sub>2</sub>-eq), Eutrophication Potential (kg N-eq), Photochemical Ozone Creation Potential (kg O<sub>3</sub>-eq), Abiotic Depletion, non-fossil (kg Sb-eq), Abiotic Depletion, fossil (MJ), Total Waste Disposed (kg), and Consumption of Freshwater (m<sup>3</sup>). At the bottom, it says 'Product Components and the standard that each component complies with'.

ENVIRONMENTAL IMPACTS	
<b>Declared Product:</b> Mix Design • Power Plant Description Compressive Strength at x age	
<b>Declared Unit:</b> 1 m <sup>3</sup> of concrete	
Global Warming Potential (kg CO <sub>2</sub> -eq)	##
Ozone Depletion Potential (kg CFC-11-eq)	##
Acidification Potential (kg SO <sub>2</sub> -eq)	##
Eutrophication Potential (kg N-eq)	##
Photochemical Ozone Creation Potential (kg O <sub>3</sub> -eq)	##
Abiotic Depletion, non-fossil (kg Sb-eq)	##
Abiotic Depletion, fossil (MJ)	##
Total Waste Disposed (kg)	##
Consumption of Freshwater (m <sup>3</sup> )	##
<b>Product Components</b> and the standard that each component complies with	

**Figure 1. Example EPD output.**

EPDs can be facility-specific and/or product-specific or an industry-average. A facility-specific, product-specific EPD is preferable to an industry-average because of the quality and precision of the data provided. In instances where facility-specific and/or product-specific data is not available, industry-average data can be used. However, depending on how the EPD data will be utilized, an industry average EPD may not be sufficient. EPDs can be developed using a combination of facility-specific and industry-average data for different components.

EPDs for construction materials, as prescribed in their PCRs, typically include life-cycle stages from A1 to A3 (Figure 2), which include materials extraction, transportation to the production facility, and production energy. A4 (transportation from the production facility to the job site) and A5 (construction operations or installation) are currently optional life-cycle stages that can be included in the EPD's scope, but often are not included.



**Figure 2. Life-cycle stages and the scope of a current concrete EPD**

**How are EPDs developed?** EPDs are developed using primary data collected, such as concrete mixture proportions, and background dataset inventories, such as electricity. The background datasets, scope, and calculation methodology may be dictated by the product category rule (PCR), which is the standard for a class of products by which EPDs are developed. A PCR is developed for a class of products using a transparent, stakeholder consensus approach.

The development of an EPD is analogous to the performance of a compressive strength test. To perform a compressive strength test, a technician first reads a standard that describes the materials, equipment, and procedure needed to perform the test. This standard was developed using a transparent, consensus-based approach from a variety of industry stakeholders to increase the consistency of the test performance within the laboratory and between laboratories, such that the results could potentially be compared with the results received on the same material in a different laboratory; the same is true for a PCR. The test is then performed using the materials, equipment, and procedure outlined in the standard; this test is analogous to an LCA. The test results are then reported, also in accordance with the standard, in specific units with notes and descriptions of the material tested, date of test, and any other relevant or required information; this reporting is analogous to an EPD, which reports the results of the LCA as performed in accordance with the governing PCR.

## How do you use an EPD?

EPDs can be used to:

- **Inform an LCA.** LCAs can include some or all life-cycle stages of a product. EPDs can act as building blocks during the development of an LCA.
- **Inform interested parties** (such as the owner or the public) of the estimated environmental impacts associated with a product.
- **Quantify** the environmental impacts associated with a **product or supply chain change**.
- **Inform strategy implementation** to reduce environmental impacts.
- **Compare two similar materials** with the **same function** whose EPDs were developed using the **same PCR**.

*Note:* PCRs are evolving documents that change at least every five years. Therefore, the information herein regarding EPDs is subject to change over time. This document was developed in July 2023 and is accurate to the PCR and EPD process applicable at that time. Future versions of this document may be developed to account for changes in the PCR as needed.

## How shouldn't you use an EPD?

EPDs should not be used:

- To compare two dissimilar materials or compare two materials with different functions or compare materials that use two different PCRs.
- As a replacement to materials testing or quality assurance.
- As a priority over performance or constructability.

## **Appendix B**

### **Data Collection Protocol for A1-A5**

## **Construction Processes Data Collection Form**

Developed by: Michelle Cooper  
Last Updated: Oct. 9, 2023  
Completed by: \_\_\_\_\_ Date: \_\_\_\_\_

### **Instructions**

Use this template to facilitate your own data collection of construction operations on project sites. Use the notes section to type any details not accounted for in the form, or when the "other" option is chosen for a pull-down list.

### **Notes**

**Project Specific**

Notes

Project Type Highway Pavement Reconstruction

Length

Time on Project 1 weeks

Number of lanes

Lanes per direction

Both directions?

Shoulder I width

Shoulder II width

Thickness of material being poured:

If multiple thicknesses:

Units	Quantity	Thickness (in.)	Notes

Water Access from:

**Design**

Concrete panel Size by

Rebar Location  
Bar diameter  
Bar spacing  
Grid area  
Grid spacing

**Batch Plant**

Notes

**Concrete Trucks**

Number of concrete trucks: typical \_\_\_\_\_  
 busy day \_\_\_\_\_  
 light day \_\_\_\_\_

Amount of concrete per truck: \_\_\_\_\_

Truck cycle time: typical \_\_\_\_\_  
 busy day \_\_\_\_\_  
 light day \_\_\_\_\_

Concrete Truck Fuel Consumption \_\_\_\_\_ gallons of diesel per day

**Equipment and Fuel Consumption**

Equipment	Qty	Fuel Consumption Each	
Loader	2	80	gallons of diesel per day
Generator	1	200	gallons of diesel per day
			gallons of diesel
			gallons of diesel
			gallons of diesel

**Batch Plant Production**

Concrete produced: \_\_\_\_\_  
 per \_\_\_\_\_

**Batch Plant Transport**

Number of trucks to transport the batch plant: \_\_\_\_\_

Type of truck to transport equipment: \_\_\_\_\_

Range of transport of plant: Typical \_\_\_\_\_  
 Minimum \_\_\_\_\_  
 Maximum \_\_\_\_\_

Time to mobilize plant \_\_\_\_\_

**Batch Plant Equipment**

Equipment	Weight	Units



**Production Rates**

Notes

Mainline paving (typical)	yd2	per	1 day(s)
minimum		per	
maximum		per	
Ramp paving (typical)		per	
minimum		per	
maximum		per	
Shoulder paving (typical)		per	
minimum		per	
maximum		per	
Grinding (typical)		per	
minimum		per	
maximum		per	
Grading / Trimming (typical)		per	
minimum		per	
maximum		per	
Roller Compacting (typical)		per	
minimum		per	
maximum		per	
Curing machine (typical)		per	1 day(s)
minimum		per	
maximum		per	
Texturing machine (typical)		per	1 day(s)
minimum		per	
maximum		per	
Saw cutting (typical)	linear ft	per	1 day(s)
minimum		per	
maximum		per	
Hand Compacting (typical)		per	
minimum		per	
maximum		per	
Hand-spray Curing (typical)		per	
minimum		per	
maximum		per	
Milling (typical)		per	
minimum		per	
maximum		per	

Concrete Removal Rate (typical)		per	
minimum		per	
maximum		per	
Dowel Bar Insertion Rate (typical)		per	
minimum		per	
maximum		per	
Concrete Pour Rate (typical)		per	
minimum		per	
maximum		per	
Dowel Hole Drilling Rate (typical)		per	
minimum		per	
maximum		per	
Concrete Hauling Rate (typical)		per	
minimum		per	
maximum		per	
Other		per	
minimum		per	
maximum		per	

**Concrete Mixture Design 1**

Notes

Quantity of Concrete Mixture Design 1 on Project:

	_____	yd <sup>3</sup>	
GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/	m3
A1	_____	kg of CO <sub>2</sub> -eq/	m3
A2	_____	kg of CO <sub>2</sub> -eq/	m3
A3	_____	kg of CO <sub>2</sub> -eq/	m3

Application \_\_\_\_\_

Product Specific? \_\_\_\_\_

Facility Specific? \_\_\_\_\_

Cement	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____ Other	
	Content	_____	kg/m3
	Mode 1	_____	Mode 1 Distance _____ miles
	Mode 2	_____	Mode 2 Distance _____ nautical miles

SCM	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____	
	Content	_____	kg/m3
	Mode 1	_____	Mode 1 Distance _____ miles
Mode 2	_____	Mode 2 Distance _____ nautical miles	

Fine Aggregate	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____	
	Content	_____	kg/m3
	Mode 1	_____	Mode 1 Distance _____ miles
Mode 2	_____	Mode 2 Distance _____ nautical miles	

Intermediate Aggregate 1	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____	
	Content	_____	kg/m3
	Mode 1	_____	Mode 1 Distance _____ miles
Mode 2	_____	Mode 2 Distance _____ nautical miles	

Intermediate Aggregate 2	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____	
	Content	_____	lbs/yd3
	Mode 1	_____	Mode 1 Distance _____ miles
Mode 2	_____	Mode 2 Distance _____ nautical miles	

Coarse Aggregate	GWP from Provided EPD:	_____	kg of CO <sub>2</sub> -eq/metric ton
	Type	_____	
	Content	_____	kg/m3
	Mode 1	_____	Mode 1 Distance _____ miles
Mode 2	_____	Mode 2 Distance _____ nautical miles	

Water	Content _____ lbs/yd <sup>3</sup>		
	Source _____ or Distance _____		miles
Admixture I	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Type <u>Air Entrainment</u>		
	Content _____ kg/m <sup>3</sup>		
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Admixture II	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Type <u>Plasticizer or Superplasticizer</u>		
	Content _____ kg/m <sup>3</sup>		
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Admixture III	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Type _____		
	Content _____		
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Admixture IIII	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Type _____		
	Content _____		
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Dowel Bar	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Diameter _____		
	Length _____		
	Spacing _____		c-c
	OR _____		per panel
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Ties	GWP from Provided EPD: _____		kg of CO <sub>2</sub> -eq/kg
	Diameter _____		
	Length _____		
	Spacing _____		c-c
	OR _____		per panel
	Mode 1 _____ Mode 1 Distance _____		miles
	Mode 2 _____ Mode 2 Distance _____		nautical miles
Other Material	Type _____		
	Length _____		
	Width _____		
	Area _____		
	Thickness _____		
	Spacing _____		c-c
	Source _____ or Distance _____		miles
Other Material	Type _____		
	Length _____		
	Width _____		
	Area _____		
	Thickness _____		
	Spacing _____		c-c
	Source _____ or Distance _____		miles

# **Appendix C**

## **Specification for EPD Submittal Package**

# Environmental Product Declaration (EPD) Submittal Specification

This specification outlines the requirements for an environmental product declaration (EPD) submitted to the Agency and additional requirements for information that shall be included in the EPD Submittal Package. This specification requires the Contractor to provide EPDs for an asphalt mixture, concrete mixture, and steel major work items within the contract calling this Specification.

The EPD Submittal Package shall be submitted to the Agency (1) no later than two weeks prior to delivery of the material to site and (2) once at the end of the project or, for multiyear projects, at the end of each calendar year to reflect actual products and quantities delivered.

## Terminology

**Asphalt Mixture.** A composite material consisting of aggregates, asphalt binder, reclaimed material, filler, and/or additives. An asphalt mixture may refer to hot mix asphalt or warm mix asphalt.

**Concrete Mixture.** A composite material consisting of cement, supplementary cementitious materials, alternative cementitious materials, aggregates, admixtures, water, fibers, pigments, and/or fillers that gains strength and hardens by means of a pozzolanic, hydraulic, and/or carbonation reaction.

**Environmental Product Declaration.** A valid, Type III, third-party verified, standardized reporting of environmental impacts of a product quantified using a life-cycle assessment according to ISO 14025, ISO 21930, and the applicable sub-category product category rule.

**EPD Submittal.** A fixed contract item established to pay for an EPD and the required supplementary information identified in this document for each eligible material identified in this document.

**Product Category Rule.** A standardized set of rules for performing life-cycle assessments and reporting those results in an EPD for a group of products that have equivalent functions. A product category rule is developed by consensus of representatives from across the product supply chain and users.

**Steel.** A metal primarily consisting of carbon that is used as reinforcing steel or other steel needed to develop infrastructure.

## Required documentation to be Included

The required documentation of the EPD Submittal Package shall be provided in a single digital file, such as a pdf document or zipped folder. The EPD Submittal Package shall include:

- Project identifying details, including:
  - The project name, number, or title as determined by the Agency.
  - The contract number.
  - The project location.

- The types of materials used within the project for which an EPD is provided within the package. For example, cement, concrete, and steel if at least one EPD is provided for each of those materials.
- Identification of the Submitter, including:
  - The name of the company who compiled the EPD Submittal Package.
  - The name of the individual responsible for compiling the EPD Submittal Package.
  - Contact information for the responsible parties for compiling the EPD Submittal Package.
- A table summarizing the EPDs included in the EPD Submittal Package (see Table 1), including:
  - The material associated with each EPD.
  - The EPD unique identifier associated with each EPD provided within the package.
  - The classifier or mixture identifier used by the Agency that corresponds with the mixture design or Job Mix Formulas (JMF) approved and presented in the EPD.
  - The type of application for every material and mixture for which each EPD is provided, including associated pay items.
  - The quantity of material used that is connected with each EPD. For example, if two concrete mixtures are used for major work items on a paving project, then two concrete mixture EPDs shall be provided and a statement made the one EPD is associated with 45,000 yd<sup>3</sup> and the other EPD is associated with 40,000 yd<sup>3</sup>. For steel, the quantity of steel used for major work items on the project shall be reported with relation to each EPD provided.

**Table C-1. Example table for summarizing EPDs within the EPD Submittal Package.**

<b>Material</b>	<b>Material's Specification or Class per Agency Requirements</b>	<b>EPD Unique ID</b>	<b>Agency Product/Mix ID</b>	<b>Application</b>	<b>Quantity</b>
Example Input: Concrete Mixture	Class A	123000001	MnDOT1	Mainline Paving	40,000 yd <sup>3</sup>

- An EPD for every concrete and asphalt mixture used to produce major work items on the project. If multiple mixtures are used on the project, then multiple EPDs shall be provided.
- A product- and facility-specific EPD for every constituent(s) supplying over 30% of the mixture (asphalt or concrete) GWP used to produce major work items on the project. If multiple cements

are used within the concrete(s), then multiple cement EPDs shall be provided. If product- and facility-specific EPDs are not available for any given constituent, then a signed statement shall be provided certifying that the constituent(s) EPD(s) were requested but do not yet exist and therefore were not received, and for this reason were also not used to develop the concrete EPD(s).

- An EPD for every steel used to produce major work items on the project.
- All concrete and asphalt mixture designs used to produce major work items on the project and for which EPDs are provided.
  - The corresponding EPD's unique identifier number shall be provided on all mixture design documentation.
  - The mixture design identifier used by the Agency shall be directly linked to the mixture design's corresponding EPD.
  - For concrete mixtures, a statement shall be provided identifying whether the concrete EPD used product- and facility-specific, regional average, or national average cement data.
- All steel product information used to produce major work items on the project for which EPDs are provided.
  - The corresponding EPD's unique identifier number shall be provided on all product documentation.
  - Steel metallurgical test reports (MTRs) shall be provided.
- A statement attesting whether any carbon credits were or will be sold or transferred on the voluntary market in relation to any materials for which an EPD was provided, such as concrete or cement with reduced emissions. The Agency has the right to reduce, remove, or deny any low-carbon materials incentives that may be offered within the Contract if carbon credits were or will be sold or transferred on the voluntary carbon market as a result of reduced emissions of any of the materials used on this project.
- A statement affirming that all EPDs provided within the Submittal are representative of the materials placed and used in the project for the major work items within the Contract.

An example cover page of the EPD Submittal Package is provided below. The mixture designs and associated EPDs shall additionally be attached within the EPD Submittal Package following the cover page.

## Example EPD Submittal Specification

### Project Details

Project MNROAD Contract XYZ123  
 Location I-94 Otsego MN Materials Concrete mixture  
High volume MNROAD

### Submitter

Name John Doe Contact (123) 456-7890  
 Company ABC Concrete Inc.

Material	Material's Specification or Class per Agency Requirements	EPD Unique ID	Agency Mix ID	Application	Quantity
Concrete Mixture	Class A	123000001	MnDOT1	Mainline Paving	40,000 yd <sup>3</sup>

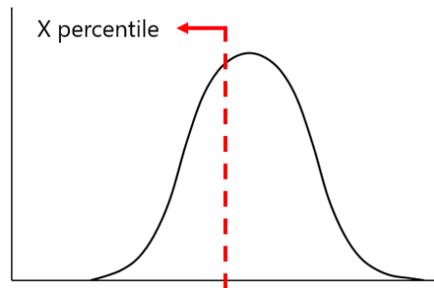
I, the Submitter on behalf of the Contractor, attest that:

- NO carbon credits were sold or transferred on the voluntary market in relation to any materials which were used in the project major work items or provided in this Submittal.
- Carbon credits may have been or may be sold or transferred on the voluntary market in relation to any materials which were used in the project major work items or provided in this Submittal. I understand that the Agency has the right to reduce, remove, or deny any low-carbon materials incentives that may be offered within the Contract.
- All EPDs provided within the Submittal are representative of the materials placed and used in the project for the major work items within the Contract.

**Appendix D**  
**Minnesota Benchmarking**

## Minnesota Concrete Mixture Benchmarking

**What is Benchmarking?** Benchmarking is defined in ISO 21678 as the “process of collecting, analyzing, and relating performance data of comparable...construction products” and results in “values indicating the relative performance required for a particular attribute [environment impacts and sustainability, in this case] on a relative scale.” In the context of transportation materials’ sustainability, benchmarking ensures that the environmental performance of a materials is being assessed within the constraints of its market, discounting factors outside a contractor’s control. Figure 1 provides a graphical representation of a benchmark on a distribution of global warming potentials (GWPs).



**Figure 1. Representation of a benchmark.**

**How was benchmarking performed for Minnesotan concrete mixtures?** The Minnesota concrete mixture benchmarking process is described in Figure 2. Three A1 scenarios were identified based on approved concrete mixture designs from MnDOT: (1) paving, (2) high-early-strength (HES), and (3) all applications. The GWPs for the A1 scenarios were determined using the quantification method described in the Appendix of the *Guide for Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete*. A2 and A3 GWP distributions were developed from environmental product declarations (EPDs) for Minnesotan ready-mixed concrete that were gathered in cooperation with Minnesotan concrete producers, the EC3 tool, and the NRMCA website. However, these A3 distributions are not representative of the mobile batch plant A3 emissions. The A1 scenario GWPs for paving, HES, and all applications were added to the 20<sup>th</sup> percentile, 40<sup>th</sup> percentile, 50<sup>th</sup> percentile, and average values from the A2 and A3 distributions, as described in Figure 3.

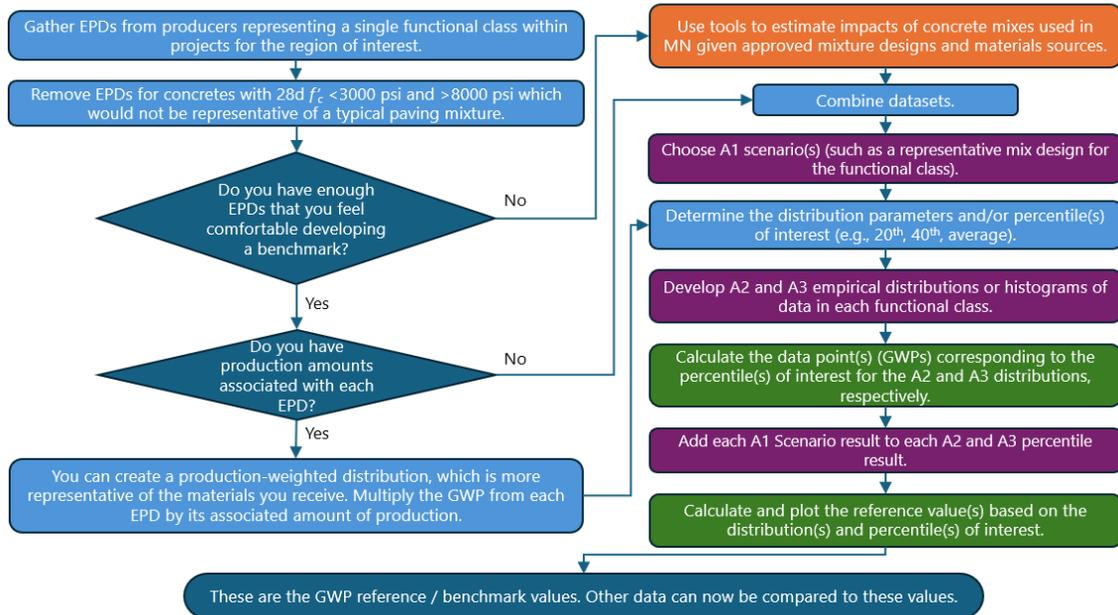


Figure 2. Benchmarking flow chart.

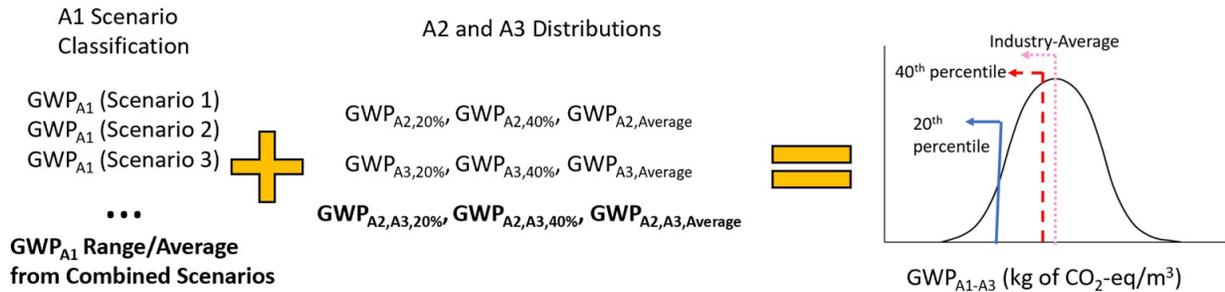
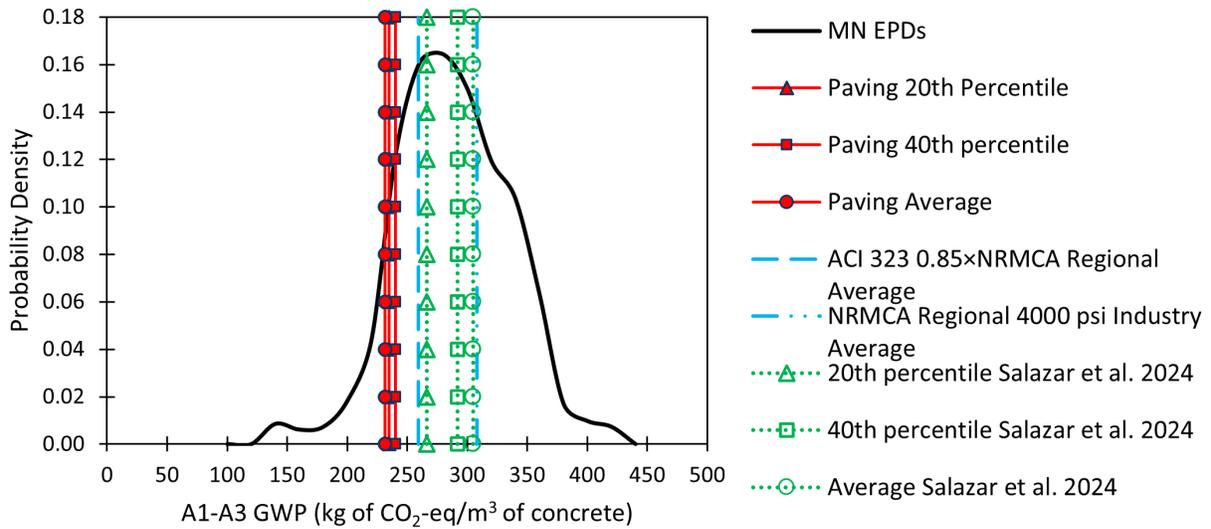


Figure 3. Methodology for benchmarking.

**What resulted from the Minnesotan Benchmarking?** Figure 4 and Table 1 describe the results of the Minnesota benchmarking for the three scenarios. While the benchmarking flow chart in Figure 2 mentions production-weighting of the concrete mixture GWPs, production information was not available for this analysis and therefore was not considered in the making of these distributions or during scenario development. Figure 4 compares the results developed using the described methodology to benchmarks developed by the industry from NRMCA and the draft ACI 323 Low-carbon Concrete Code. The same process described herein can be used again in the future from EPDs collected by MnDOT with production information for each concrete mixture to allow for increased representative accuracy of the Minnesotan concrete market.

**Table 1. Benchmark GWPs developed from the methodology described herein.**

Life-Cycle Stage	Parameter	Paving Concrete	HES Concrete	All Applications
A1-A3 GWP	20 <sup>th</sup> percentile	234.75	270.77	269.61
	40 <sup>th</sup> percentile	240.02	276.04	274.88
	50 <sup>th</sup> percentile	241.97	277.99	276.83
	Average	245.05	280.36	279.20



**Figure 4. GWP distribution and benchmarks for Minnesotan concrete paving mixture designs.**

## **Appendix E**

### **GWP Acceptance and Incentives Thresholds**

# Global Warming Potential (GWP) Acceptance and Incentives Thresholds

**What are the recommended acceptance thresholds?** Figure 1 displays the recommended acceptance thresholds. No GWP limits are recommended for determining acceptance of mobile batch plant-produced concretes. Acceptance limits for ready-mix concrete are equal to the industry-average GWP value most recently published for the north central region. The most recent value published in December 2024 is 305 kg of CO<sub>2</sub>-eq/m<sup>3</sup>. The north central industry average GWP was chosen to provide a basis for continuous GWP reductions as the region improves mixture proportioning and efficiency leading to improved concrete sustainability.

Table 1. Recommended acceptance thresholds for concrete based on GWP.

For acceptance			
Scenario	Production method	GWP limit (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Threshold basis
All applications	Mobile batch concrete	No limit	Limited EPDs
	Ready-mix concrete	305	NRMCA north central industry average

**What are the recommended incentives thresholds?** Figure 2 displays the recommended incentives thresholds for concrete based on GWP. Separate thresholds were determined for paving, high-early-strength, structural, and all other applications. The paving thresholds were further separated by mobile batch plant- and ready-mix-produced concrete, though the thresholds for those subcategories are currently the same due to lack of published EPDs for mobile batch plant concretes. If EPDs are developed for mobile batch plant concretes meeting the recommended thresholds for paving concrete by ready-mix production, then it is recommended that the incentives be awarded.

GWPs for paving concrete in Minnesota have demonstrated higher levels of material proportion optimization which have reduced paste contents and therefore favorably reduced GWP. High-early-strength and other concrete applications typically have higher GWPs, which is demonstrated by the higher values recommended for incentivization that are also consistent with those published for the Federal Highway Administration’s Low-Carbon Transportation Materials Grant Program and the NRMCA regional GWP percentile values. For structural applications, such as bridges, the GWP thresholds are recommended to be project-based by volume of mixture to allow for the highly variable functions of different bridge elements.

**Why these thresholds?** The thresholds were chosen at 20th percentile, 40<sup>th</sup> percentile, and average values to be consistent with current federal practice and grant programs.

**Why 1% to 2% incentives?** The incentive values were also chosen for consistency with federal practice and grant programs. It is recommended that these suggestions be enacted on a pilot basis to determine the success of the program, thresholds, and incentives. After two construction seasons, the success of the program at further reducing concrete GWP should be evaluated.

**Table e-1. Recommended incentives thresholds for concrete based on GWP.**

Scenario	Production method	For incentives		
		GWP limit (kg of CO <sub>2</sub> -eq/m <sup>3</sup> )	Incentive	Threshold basis
Paving	Mobile batch concrete	235 <sup>+</sup>	2.0%	20 <sup>th</sup> percentile
		240 <sup>+</sup>	1.5%	40 <sup>th</sup> percentile
		245 <sup>+</sup>	1.0%	Average
	Ready-mix concrete	235	2.0%	20 <sup>th</sup> percentile
		240	1.5%	40 <sup>th</sup> percentile
		245	1.0%	Average
High-early-strength	Ready-mix concrete	271	2.0%	20 <sup>th</sup> percentile
		276	1.5%	40 <sup>th</sup> percentile
		280	1.0%	Average
All applications	Ready-mix concrete	270	2.0%	20 <sup>th</sup> percentile
		275	1.5%	40 <sup>th</sup> percentile
		279	1.0%	Average
Structural	Ready-mix concrete by material or by project ( $\sum GWP_i \times volume_i$ )	270	2.0%	20 <sup>th</sup> percentile
		275	1.5%	40 <sup>th</sup> percentile
		279	1.0%	Average

<sup>+</sup> indicates that the value will be revisited once more data is collected.

**Why is there lower confidence in the thresholds for mobile batch plant concretes?** Limited EPDs have been developed for mobile batch plant concrete, and thus the industry does not yet have enough information to know whether:

- a) the same GWP limits should be applied to ready-mix concrete and mobile batch plant concrete,
- b) modified GWP limits are needed to represent both types of concrete, or
- c) ready-mix and mobile batch plant concrete should have different GWP limits.

Results from this study suggested that mobile batch plant concretes may have GWPs up to 40 percent higher than their ready-mix counterparts. However, the GWP estimations in this study only incorporated mobile batch plants powered by diesel-operated generators and production from a single project for each. Batch plants powered by other means or incorporating 12-months of project production may have GWP estimations more similar to ready-mix counterparts. Therefore, more data needs to be collected. Once a sufficient number of mobile batch plant data EPDs have been collected (at least two construction seasons worth of data is recommended to be obtained), the acceptance and incentives thresholds can be revisited.

## **Appendix F**

# **Estimating A1-A3 GWP of Mobile Batch Plant Concrete**

# Estimating A1-A3 GWP of Mobile Batch Plant Concrete

**What do we know about A1-A3 GWP of mobile batch plant concrete?** A limited number of EPDs have been developed for mobile batch plant-produced concrete. In early 2024, the concrete PCR published an annex that allowed and provided guidance for developing EPDs for concrete produced at mobile batch plants. Due to their recent inclusion in the concrete PCR, none of the published benchmark or industry-average analyses have included environmental impact potentials associated with mobile batch plant concrete.

**What work has been done to address this gap in knowledge?** This study developed a life-cycle information model (LCIM) which assesses A3 emissions from mobile batch plant concrete and incorporates those analyses with a modified version of an existing LCIM published by FHWA in the Federal LCA Commons that estimates A1-A2 emissions. The framework was used to estimate A1-A3 concrete environmental impact potentials on over five projects, demonstrating that the framework is implementable and applicable to real world projects. The LCAs may serve as take-off points for inclusion of mobile batch plants into the concrete PCR as more than just an annex.

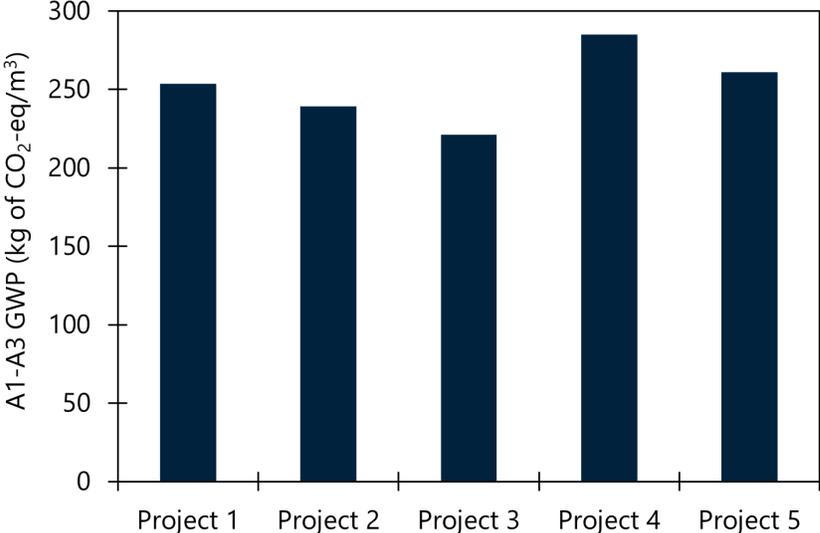
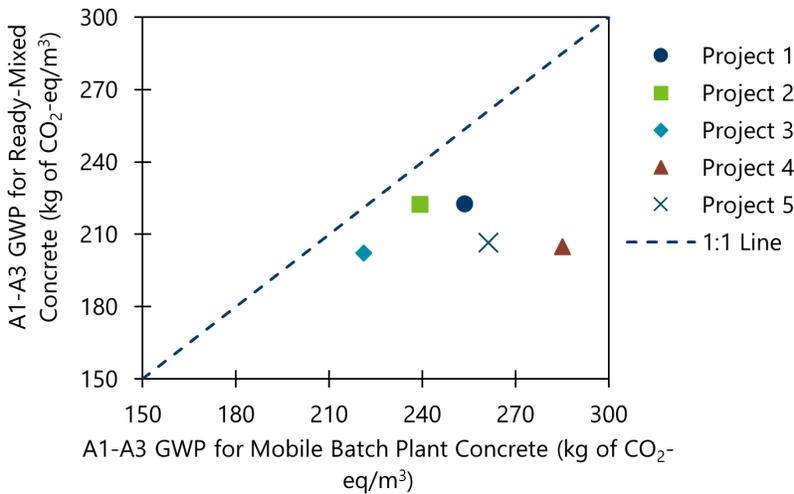


Figure F-1. A1-A3 GWP of concrete produced at mobile batch plants.



**Figure F-2. Mobile batch vs. Ready-mix concrete GWP.**

**How do A1-A3 GWPs for mobile batch plant concrete compare with those for ready-mix concrete?** The GWP associated with concrete production at a mobile batch plant ranged from 8% to 39% higher than the concrete’s GWP when produced at an average ready-mixed facility. These emissions variations are expected to be related to differences in production rate, which change the efficiency of the plant, as well as differences in efficiency of the mobile batch plant generator and even the number of generators. Older generators were reported to require up to 500 gallons of diesel fuel per day, while newer generators were reported to need as little as 150 gallons of diesel fuel per day. Additionally, the environmental impacts for mobile batch plant concrete were estimated using the production rates across singular projects for each plant. When production rates for each plant across a 12-month period are considered, the environmental emissions may decrease and become more comparable to ready-mix concrete.

**What are the limitations?** Limitations of the A1-A3 estimations include:

- *The A1-A3 results from this LCIM are not an EPD, despite the LCA being performed in a manner consistent with the concrete PCR.* The results from this LCIM are not an EPD, have not been third-party verified in the manner of an EPD, and may not match the results reported in an EPD if an EPD is developed for the same concrete mixture. The estimates resulting from use of the LCIM align closely with the concrete PCR background dataset requirements for emissions factors and methodology.
- *A1-A3 emissions for mobile batch plant concrete production are in units of per yd<sup>2</sup>.* A1-A3 emissions can be translated from per yd<sup>2</sup> to per yd<sup>3</sup> by dividing the results by the pavement thickness.
- *A1-A3 emissions for mobile batch plant concrete production were estimated based on the fuel use of the generator at the plant site,* which was observed to use diesel fuel to power all equipment on the mobile batch plant site except loaders for all projects.
- *A3 emissions for mobile batch plant concrete production included one-way transportation of the mobile batch plant to the site.* The inclusion of mobile batch plant mobilization in this LCIM aligns with the concrete PCR despite mobile batch plant transport typically accounting for a small percentage of A3 emissions.

## **Appendix G**

### **Estimating A1-A5 GWP of a Concrete Pavement**

# Estimating A1-A5 GWP of a Concrete Pavement

**Can A4 and A5 be included in concrete EPDs?** Life-cycle stages A4 and A5 are optional inclusions to concrete EPDs. However, the authors know of no EPDs that incorporate A4 and A5.

**What are the limitations preventing inclusion of A4 and A5 in concrete EPDs?** There are a few challenges to including A4 and A5 into concrete EPDs:

- So far, the concrete industry has placed the onus for EPD development on the materials suppliers. Including A4 and A5 in concrete EPDs will create onus on the general contractor to develop EPDs in addition to the material suppliers. The general contractor will need to receive an A1-A3 EPD from material supplier and provide the A1-A3 EPD along with the necessary A4 and A5 information to the LCA developer. Then the LCA will be performed and EPD created and verified. This process will require time and cost for EPD development.
- A4 and A5 will require project-specific information such as locations, contractor means and methods, and production rates for various activities. Figure 1 shows the types of information that need to be collected. Figure 2 demonstrates the influence of production rate on GWP. Keeping concrete EPDs at the A1-A3 life-cycle stages has allowed for the potential that a single EPD applies to a concrete mixture sent to multiple projects and multiple locations. Incorporating A4 and A5 will limit EPD applicability to a single project.
- The authors know of no A1-A5 LCAs performed to date that could act as the underlying LCA for the concrete PCR to support the development of the EPD.
- The verification process for concrete EPDs is currently managed by the National Ready-Mixed Concrete Association, which has no motivation to extend EPDs past the point of material supply.
- A5 is the point of installation on a project, which often incorporates more than a single material. For example, dowel bars have a fundamental functional contribution to a concrete pavement and should not be excluded from accounting for environmental impact potentials of a project, though they should be excluded from a concrete EPD.

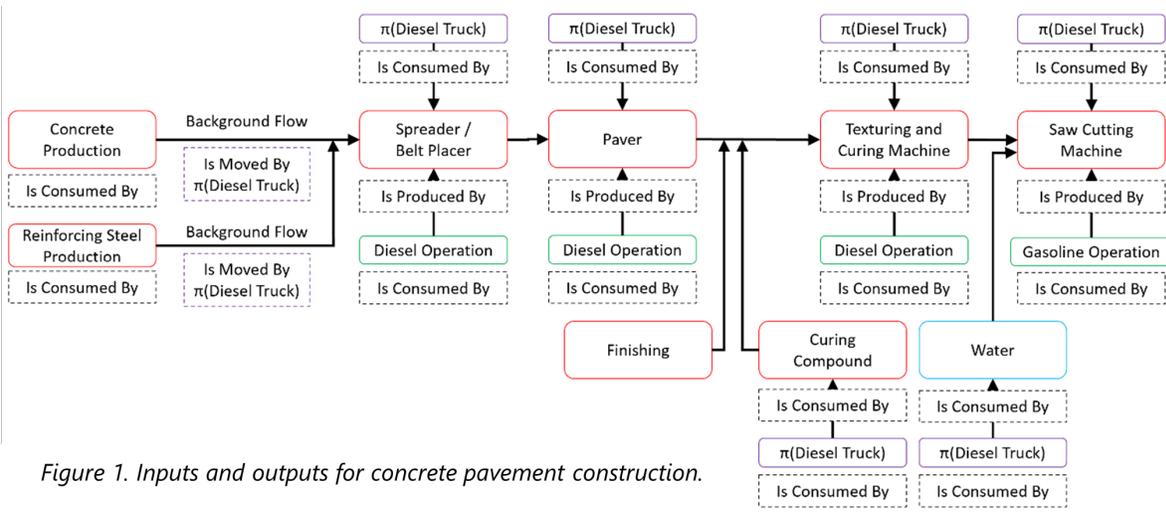
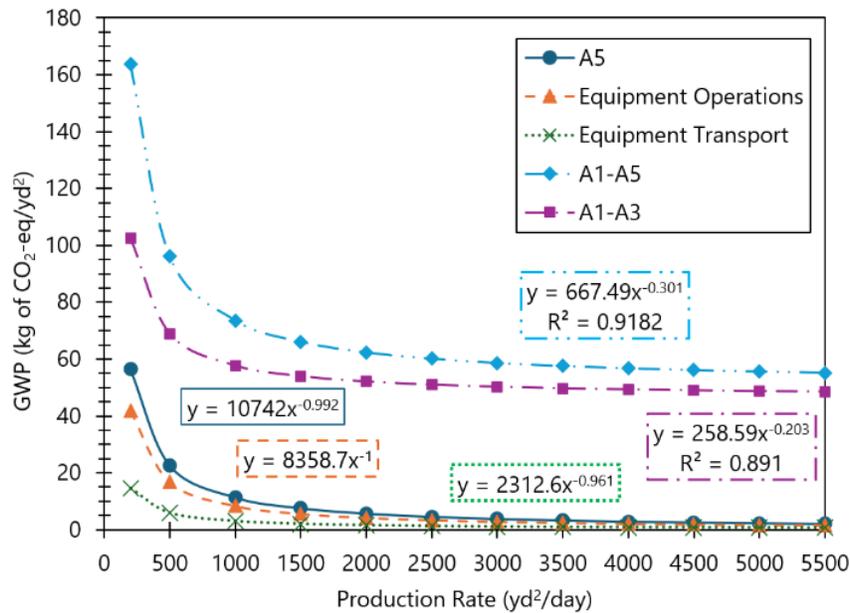


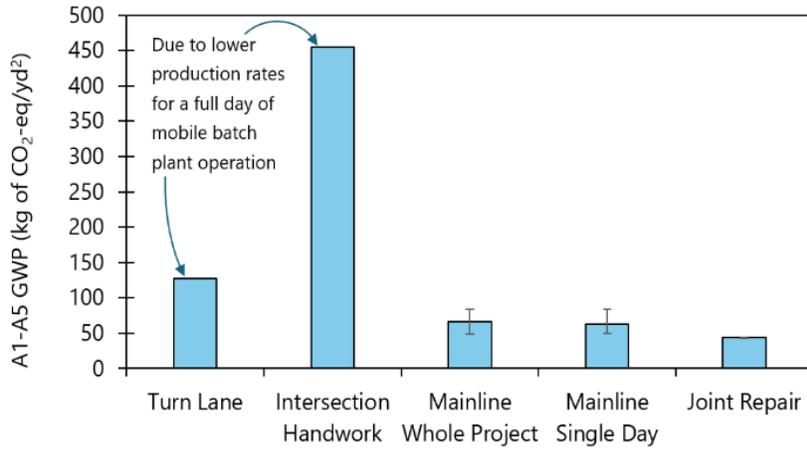
Figure 1. Inputs and outputs for concrete pavement construction.

**What is needed to successfully include A4 and A5 in EPDs?** To successfully include A4 and A5 into sustainable project procurement strategies to extend sustainability-related decision making from materials to infrastructure, the following are needed:

- More data collected and LCAs performed for life-cycle stages A4 and A5 to determine the significance and variability of the environmental impact potentials across a range of subclassifications (e.g., mainline paving, turn lane paving, intersection handwork) for many projects (see Figure 3).
- PCRs extending beyond materials associated (i.e., concrete pavement PCR) may be needed to allow inclusion of the other materials needed to develop infrastructure. For example, a concrete pavement EPD for A1-A5 could be informed using material EPDs for concrete, dowel bars, and curing compound.
- Work performed in this study can act as the underlying LCA to a concrete pavement PCR or for a concrete A1-A5 PCR.
- An audit program is needed along with an infrastructure owner interface to allow owners access to the project-specific information used to develop the EPD.



**Figure 2. Production rate has significant influence on GWP.**



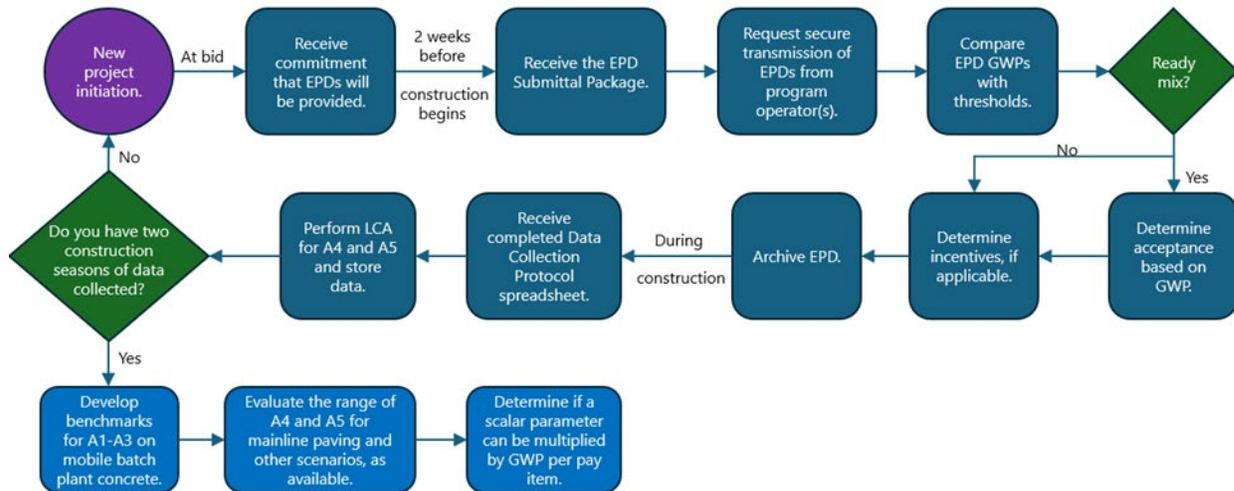
**Figure 3. A1-A5 GWP by subclassification.**

## **Appendix H**

# **Integrating EPDs into the Procurement Process**

## Integrating EPDS into The Procurement Process

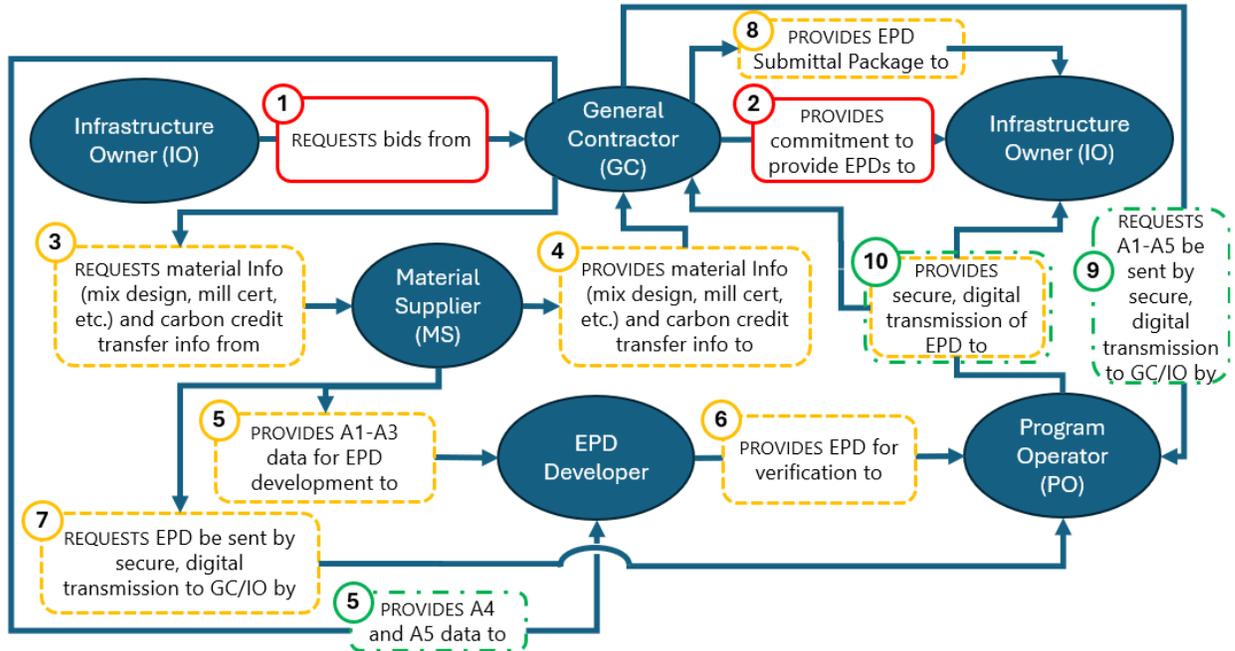
**How can EPDs be integrated into the procurement process?** Multiple steps can be followed to successfully integrate EPDs into the procurement process. Prior to following these steps, benchmarks must be developed, and partnerships must be formed to ensure all stakeholders understand and are committed to their part in sustainable project procurement.



**Figure 1. Recommendations summary.**

- At time of bid: Bidders should commit to providing EPDs for the materials placed on the project.
- The materials suppliers should provide relevant materials information to the general contractor for inclusion in the EPD Submittal Package.
- The materials supplier should provide the necessary information for A1-A3 EPD development to the LCA developer.
- The general contractor should provide the necessary information for A4 and A5 to the LCA developer.
- The LCA developer should provide the EPD(s) to the program operator for verification and to the owner of the EPD (material supplier or general contractor who provided the information).
- The material supplier and/or general contractor should request that the program operator send the verified EPD(s) to the infrastructure owner.
- The general contractor should submit an EPD Submittal Package for every project (a) two weeks prior to material delivery, (b) at the end of the project, and (c) at the end of calendar year.
- The program operator should send the verified EPD(s) to the infrastructure owner to be used in conjunction with and in the context of the project indicated within the EPD Submittal Package.

Figure 2 describes the steps of stakeholder interactions described to this point that should occur for successful integration of EPDs into the procurement process.



**Figure 2. Stakeholder interactions diagram.**

- Once the EPD Submittal Package is received by the infrastructure owner, the EPDs should be considered by the infrastructure owner and compared with the determined thresholds. The infrastructure owner will match the approved ready-mix concrete mixtures with their EPDs using the information in the EPD Submittal Package and determine if the GWP is less than the north central industry average.
- The infrastructure owner will then compare the GWPs reported in the EPDs for the approved concrete mixtures (ready-mix and mobile batch plant- produced) with the incentives thresholds. Concretes with GWPs less than or equal to the 20<sup>th</sup> percentile value may receive a 2% incentive. Concretes with GWPs less than or equal to the 40<sup>th</sup> percentile value but greater than the 20<sup>th</sup> percentile value may receive a 1.5% incentive. Concretes with GWPs between the average and 40<sup>th</sup> percentile value may receive a 1% incentive.

**Appendix I**  
**Recommendations to Environmental Standards**  
**Procurement Task Force**

Based on the findings in this study as well as current precedent for sustainable project procurements processes around the United States, our recommendations to the Environmental Standards Procurement Task Force include:

- Concrete classifications should consist of:
  - Concrete type. Delineations between ready-mixed or mobile batch plant concrete should be made until more information is collected regarding the environmental impact potentials of mobile batch plant concrete. Precast concrete and concrete masonry have their own, separate PCRs.
  - Application. The intended function of the concrete varies by application and therefore should be considered as a classification category. Paving concrete, for instance, is intended to behave differently and therefore have a notably different concrete mixture design than a bridge pier.
  - Lightweight versus normal-weight concrete. Lightweight aggregates are known to have different performance than conventional aggregates but can also have farther transportation needs.
  - High-early-strength. The need for high-early-strength is often related to traffic needs and allowable construction scheduling as dictated by the infrastructure owner. Therefore, constraints apply to these mixture designs that may limit possible environmental impact potential reductions. This classification category relates back to application.
  - Exposure class. Exposure class, such as air entrainment and permeability requirements, has a significant influence on the mixture design chosen for an element. Exposure class may be an unnecessary classification category for an infrastructure owner with consistent environmental exposures. However, if internal and external elements or elements near and within waterways are subjected to the sustainability requirements, then exposure class is a critical component to the mixture design and performance.
- Minimum material quantities subjected to sustainability requirements are recommended to be:
  - New constructions or reconstructions greater than 50,000 square feet or, for paving, two or more lane-miles.
- Performance incentives are recommended to be used for encouraging sustainable project procurement. Performance incentives place emphasis on sustainability as a performance category alongside strength and durability. As demonstrated in this project, performance incentives for sustainability can align with incentives programs already in place. Furthermore, many changes in supply chain availability can occur between the time of bid and the time of project completion. Performance incentives can be applied to materials and infrastructure after installation, ensuring that the infrastructure placed is reaching the sustainability targets. Incentives applied at the time of bid may result in misleading decision making because changes in supply chain availability may occur prior to placing the intended low-carbon materials. It would be challenging to ensure that incentives applied during bidding were navigated appropriately during the project to ensure a low-carbon outcome was achieved.

- The increased demand for EPDs in the construction materials industries have made costs for EPD development more reasonable. However, there may still be supply, geographical, and/or business operation challenges that will require waivers or exemptions. With proper justification, such as significant time delay, significant project cost increase, and small business producer, requirements to provide EPDs may be waived. However, the general contractor must provide written justification and evidence of good faith that EPDs were at least asked for and that the material supplier(s) was not able or willing to provide the EPD(s).
- By integrating EPDs into the procurement process in the manner described in this report, material GWP reductions should not occur at the expense of materials durability. Sustainability performance is identified as a priority alongside the existing durability requirements through specifications and incentivization. MnDOT currently has performance-related specifications and incentives programs in place to improve durability of the materials placed on paving projects. Other performance specifications, such as an example specification available from the Federal Highway Administration's Resource Center, exist for possible consideration.
- Based on the insights within this study, more data needs to be collected for mobile batch plants, A4, and A5 of construction projects. Therefore, it is recommended that EPD integration into the procurement process, as laid out in Figure 9.1 of this report, begin in 2025. This timeframe allows two construction seasons of data to be collected for those areas where more information is needed, which would come due in 2027. In 2027, the integration process, acceptance thresholds, and incentives thresholds should be reevaluated. A successful integration of EPDs could be determined based on the increase in amount of paid out incentives over time.