Evaluating the Environmental Impacts of Aramid Fiber in Asphalt Mixtures: A Cradle-to-Grave Life Cycle Assessment

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ABSTRACT

Climate change poses a significant challenge to humanity, with greenhouse gas (GHG) emissions (e.g., carbon dioxide, methane, nitrous oxide) being a leading cause. The transportation sector contributes approximately 25% of global CO_2 emissions, with asphalt mixtures identified as among the most carbon-intensive construction materials. As sustainability becomes a critical focus in the asphalt industry, technologies that enhance pavement durability and extend service life are gaining importance.

This study assesses the environmental impact of aramid fiber in asphalt mixtures through a cradle-to-grave life cycle assessment (LCA). Building on a cradle-to-gate analysis, the research evaluates the effect of aramid fiber on time-to-pavement-intervention, using design parameters from the Man O' War Boulevard project in Lexington, Kentucky. The functional unit is defined as one square yard of installed pavement, with impacts analyzed over a 50-year reference service life and an industry-standard intervention schedule. A sensitivity analysis assumes a 20% increase in time to intervention due to aramid fiber inclusion, derived from pavement condition surveys comparing projects with and without aramid fiber.

Results show that a 20% increase in time to intervention reduces 50-year cradle-to-grave impacts by 10%, primarily by decreasing the frequency of maintenance and rehabilitation cycles. Reductions are observed in the B3-B4 life cycle phases, encompassing material production, transportation, and installation processes.

Key findings include: (1) Aramid fiber inclusion has negligible impacts on A1-A3 phases on a mass and GHG basis, and (2) extended pavement service life reduces cradle-to-grave impacts by minimizing maintenance and rehabilitation operations. These results underscore the potential of aramid fiber to enhance pavement sustainability by improving durability and reducing life cycle environmental impacts.

Keywords: Aramid fiber, life cycle assessment, cradle to grave, sustainability

INTRODUCTION

Asphalt concrete is the most widely used material for constructing flexible pavements due to its cost-effectiveness, ease of construction, and ability to provide a smooth and durable riding surface. However, asphalt pavements are susceptible to various distresses, including rutting, fatigue cracking, and thermal cracking, which can reduce their service life and increase maintenance costs [1]. To enhance the performance and longevity of asphalt pavements, researchers have explored the incorporation of fiber reinforcements to improve mechanical properties and resistance to common distresses [2]. Among the various fiber types used in asphalt mixtures, aramid fiber has gained increasing attention due to its exceptional mechanical properties and durability [3].

Aramid fiber is a synthetic high-performance fiber composed of long-chain aromatic polyamides. It is characterized by its high tensile strength, excellent thermal stability, and resistance to degradation under environmental conditions [4]. Unlike other fibers such as cellulose, glass, or polypropylene, aramid fibers do not melt under high temperatures and exhibit superior reinforcing capabilities when mixed with asphalt concrete. When added to asphalt mixtures, aramid fibers serve to bridge cracks, enhance load distribution, and improve the overall toughness of the pavement structure [5]. Recent studies have demonstrated that aramid fiber can enhance the rutting resistance, fatigue life, and cracking resistance of asphalt pavements, contributing to extended pavement service life and reduced maintenance needs [6].

Given the increasing demand for sustainable and long-lasting pavements, understanding the role of aramid fiber in asphalt concrete is crucial. The environmental impact of asphalt pavements has become a growing concern, prompting researchers and industry professionals to explore sustainable solutions that minimize carbon emissions and resource consumption. Life Cycle Assessment (LCA) is a widely used methodology for evaluating the environmental footprint of construction materials, including asphalt mixtures. Recent studies have investigated the role of aramid fibers in improving the sustainability of asphalt pavements through extended service life and reduced maintenance requirements.

One of the primary environmental benefits of aramid fiber-reinforced asphalt pavements is the reduction in material consumption and energy use over the pavement's lifecycle. By enhancing pavement durability and minimizing the need for frequent repairs, aramid fibers contribute to lower greenhouse gas (GHG) emissions associated with material production, transportation, and construction activities [7]. Environmental Product Declarations (EPDs) have provided data indicating that the incorporation of aramid fibers can lead to a decrease in overall carbon footprint, as the extended pavement lifespan offsets the initial environmental cost of fiber production [8].

Additionally, aramid fiber reinforcement has been studied in the context of high-recycled-content asphalt mixtures. The ability of aramid fibers to improve the performance of recycled asphalt pavement (RAP) mixtures has been recognized as a potential strategy for promoting circular economy practices in the asphalt industry [9]. By enhancing the cracking resistance of RAP mixtures, aramid fibers facilitate the use of higher RAP percentages without compromising pavement performance [10].

In summary, aramid fiber reinforcement offers a promising solution for improving both the structural and environmental performance of asphalt pavements. As research continues to advance in this field, further exploration of optimized fiber dosage, mixing techniques, and long-term field performance will be essential for maximizing the benefits of aramid fiber in asphalt concrete applications.

ARAMID FIBER PROPERTIES

Aramid fiber properties are synthetically manufactured, high-performance materials characterized by relatively rigid polymer chains. The structure of these fibers features strong hydrogen bonds that efficiently transfer mechanical stress, enabling the use of chains with comparatively low molecular weight. The fiber-forming substance is a long-chain synthetic polyamide (illustrated in Figure 1), with at least 85 percent of the amide linkages directly attached to two aromatic rings [11]. Aramid fibers are produced through a process that involves spinning a solid fiber from a liquid chemical blend.

There are two types of aramid fibers: meta-aramid fiber and para-aramid fiber, with para-aramid fiber currently being used in asphalt mixtures. There are differences in molecular structure, properties, and applications of these two types of aramid fiber. In terms of molecular structure, para-aramid fiber, the polymer chains are aligned parallel to the fiber axis. This arrangement results in strong hydrogen bonding between the chains which contributes to the fiber's superior tensile strength and thermal stability. Meta aramid fibers have polymer chains that are arranged in a more discorded manner, amorphous state. The aramid linkages are in the meta position on the aromatic rings and leads to a less rigid structure. Para-aramid fiber has exceptional strength-to-weight ratio, high tenacity, and excellent abrasion to heat while meta-aramid fibers excel in thermal, chemical and electrical resistance.

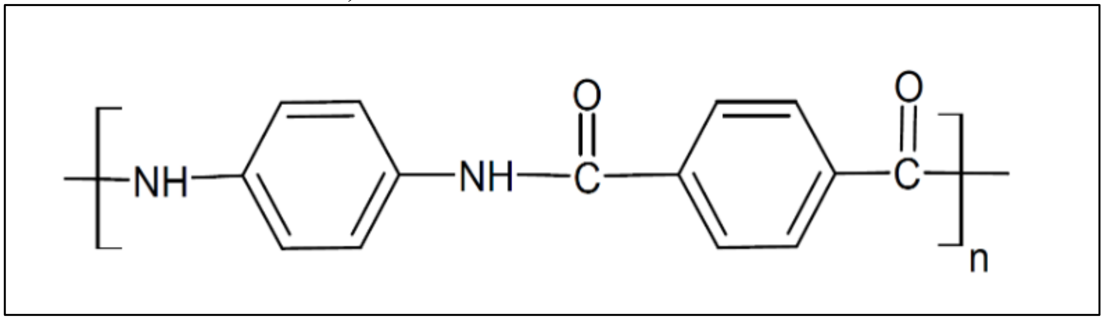

Figure 1 Chemical Structure of Aramid Fiber

Table 1 provides an overview of the typical physical properties of aramid fibers as found in ASTM D8395. It is worth noting that, in some cases, aramid fibers are coated with Sasobit or blended with polyolefin to minimize "fly away" during the production process.

Table 1 - Typical Aramid Fiber Physical Properties

Length (mm)	19 or 38
Form	Cut fiber clips
Acid/Alkali Resistance	Inert
Density (kg/m^3)	1.44
Linear Density (dTex)	>3,200
Fiber Decomposition Temperature (°C)	> 425
Tensile Strength (MPa)	> 2,700
Young's Modulus (GPa)	>80

SCOPE OF THE STUDY

The life cycle assessment of this paper covers a pavement system with and without aramid fiber. Aramid reinforced composite asphalt (ARCA) is a solution that reinforces the asphalt mixture by reducing cracking and permanent deformation, thus improving the fatigue resiliency and toughness of the mixture. The pavement design studied is a 4-layer system shown below in Table 2. Table 3 shows the mix designs for the individual asphalt concrete mixtures with and without aramid fibers. The asphalt density was assumed to be 113 lbs per square yard per inch [12]. Material inputs greater than 1% (based on total mass of the final product or estimated Green House Gas (GHG) contribution) were included within the scope of analysis according to the product category rules (PCR) for Asphalt Mixtures [13]. Material inputs less than 1% by mass or by GHG contribution were included if sufficient data was available to warrant inclusion and/or the material input was thought to have significant environmental impact.

Table 2 - Pavement Layer Thicknesses

Control Section			Aramid Fiber Section		
Pavement Layer	Mix Design Description	Layer Thickness (in)	Pavement Layer	Mix Design Description	Layer Thickness (in)
Surface Course	0.38D (20% RAP)	2	Surface Course	0.38D (20% RAP)	2
Base Course 1	1.0D (20% RAP)	4.0	Base Course 1	1.0D (20% RAP)	4.0
Base Course 2	1.0D (30% RAP)	4.0	Base Course 2	1.0D (30% RAP)	4.0
Aggregate Base		6	Aggregate Base		6
Subgrade		Semi-infinite	Subgrade		Semi-infinite

Table 3 – Mix Designs

	0.38D Typical	0.38D with Aramid Fiber	1.0D Typical	1.0D with Aramid Fiber
Upper PG Grade	64	64	64	64
Lower PG Grade	-22	-22	-22	-22
Nominal maximum aggregate size (inches)	0.38	0.38	1	1
Heating	Hot Mix 300F	Hot Mix 300F	Hot Mix 300F	Hot Mix 300F
Percent RAP by Mass (%)	18.88	18.88	28.74	18.88
RAP truck distance (miles)	7.22	7.22	7.22	7.22
Natural Stone - Limestone #8 from Kentucky (% mix by Mass)	18.88	18.88	9.58	18.88
Natural Stone - Limestone #7 from Kentucky (% mix by Mass)	0	0	14.37	0
Natural Stone - Limestone #57 from Kentucky (% mix by Mass)	0	0	23.95	0
Natural Stone - LSS (Washed) from Kentucky (% mix by Mass)	47.2	47.2	19.16	47.2
Natural Stone - Natural Sand from Kentucky (% mix by Mass)	9.44	9.44	0	9.44
Truck Distance for Aggregate (miles)	21.5	21.5	0	21.5
Virgin Binder Content, %	5.6	5.6	4.2	5.6
Truck Distance Virgin Binder (miles)	3.9	3.9	0	3.9
Aramid Fiber from Kentucky (% mix by mass)	0	0.00656	0	0.00656
Sum (% mix by mass)	100	100.01	100	100.01

ARAMID FIBER LIFE EXTENSION

The incorporation of additives such as polymers, rubber, and fibers into asphalt pavements has emerged as a pivotal strategy for enhancing the service life and performance of roadways. These additives modify the asphalt binder's properties, improving its resistance to various forms of distress such as rutting, cracking, and moisture damage. By enhancing the viscoelastic behavior of the asphalt, polymers like styrene-butadiene-styrene (SBS) increase the pavement's elasticity and temperature resistance, thereby extending its durability. Rubber, often derived from recycled tires, adds flexibility and reduces the susceptibility to thermal cracking, while fibers improve tensile strength, minimizing reflective cracking, block cracking, and thermal cracking. These enhancements not only extend the lifespan of asphalt pavements but also contribute to reduced maintenance costs and improved safety for road users. There is limited information in the literature when it comes to the service life extension of aramid fiber pavements.

Recently, a deep machine learning approach was developed and implemented to predict pavement condition index (PCI) of asphalt surfaced roadways, also known as a smart pavement monitoring (SPM) algorithm [14] [15] [16]. The approach uses a combination of you look only once (YOLO) and U-net deep learning models to automatically classify and quantify the severity of distresses in pavement images. The output of the models is used to develop a comprehensive pavement condition tool that rates each pavement image according to the type and severity of distress extracted. This technology uses a video camera mounted on a vehicle and driven at highway speeds to capture the images of the pavement. Historically, pavement distress surveys have been performed using complex collection vehicles, often combined with boots-on-the-ground surveys for verification/validation. This technology is useful from two aspects; safety and bias through human judgement. The images are captured via a camera and the YOLO and U-Net deep learning framework is used to train the model. The distress classification can be checked to ensure the model correctly identified the distress. The proposed approach is a promising new method for developing PCIs. This new approach can automate the PCI assessment process, which can save time and money. Additionally, the approach is more accurate and robust than traditional PCI methods. Additional information on the SPM technology can be seen in Buttlar et al. 2023 [16].

Blankenship Asphalt Tech and Training (BATT) Vision pavement imaging system includes a high-resolution 360-degree camera, high-definition action camera, a GPS unit tied to the video, and accelerometers to capture pavement roughness. The video frames is labeled with GPS information, which is processed by Tiger Eye Engineering (TEE) software to extract images at specified intervals to remove duplication and to cover the pavement network continuously at a spacing of 5 feet (Figure 2). The Insta 360 camera is used to collect a 360-street image like Google Street View to allow viewing of the local area as it relates to the pavement distress.

Figure 2 Video Data Collection System

Pavement condition assessment provides critically needed information allowing owner-agencies to make more cost-effective and consistent decisions as they manage their network of urban and/or rural pavements. Generally, pavement distress inspections are performed using sophisticated data collection vehicles and/or very limited foot-on-ground surveys. In either approach, the process of distress detection is sub-optimal, as it inherently contains human bias, is very costly and can be inefficient, and can introduce on-site inspector safety risks. TEE automated pavement evaluation software suite was developed by coding and integrating several machine learning and deep learning techniques for distress detection and pavement condition assessment (Figure 3). Examples of detections from 28 distinct distress types on both flexible and rigid pavement are displayed. The AI models have annotated the images, indicating the type and extent of each distress. (Figure 4).

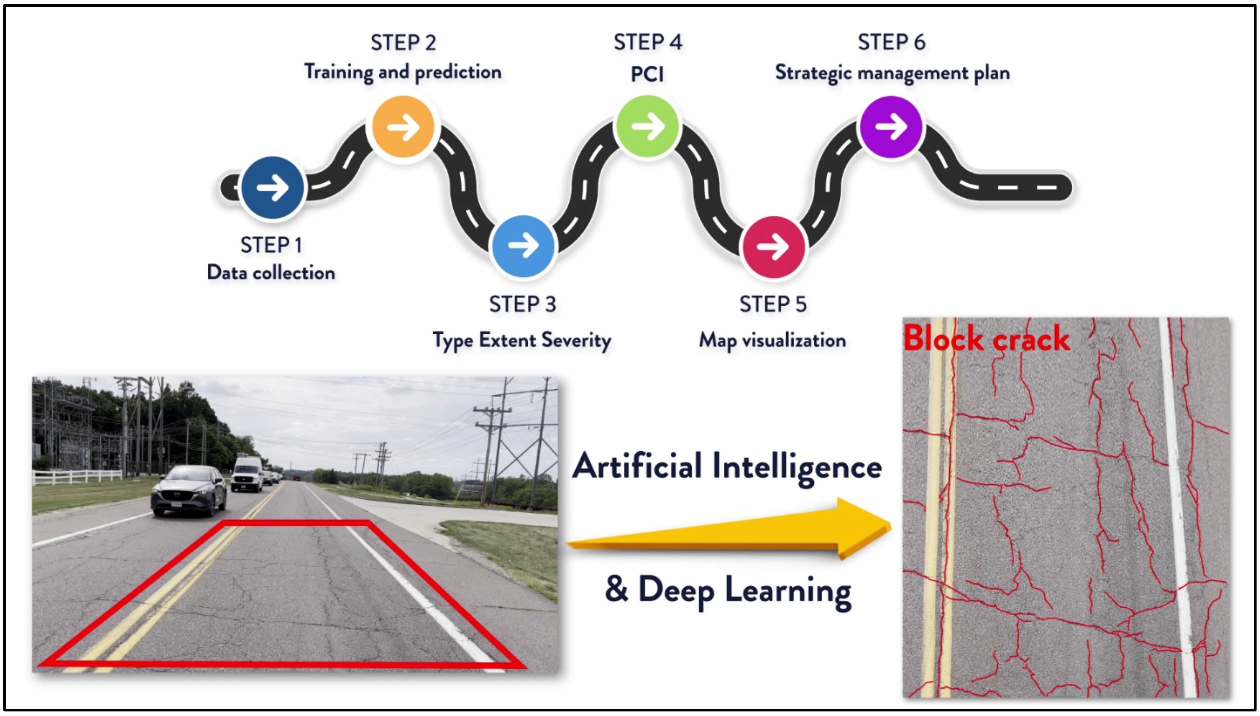

Figure 3 Application of AI to Detect Type, Extent and Severity of Distresses

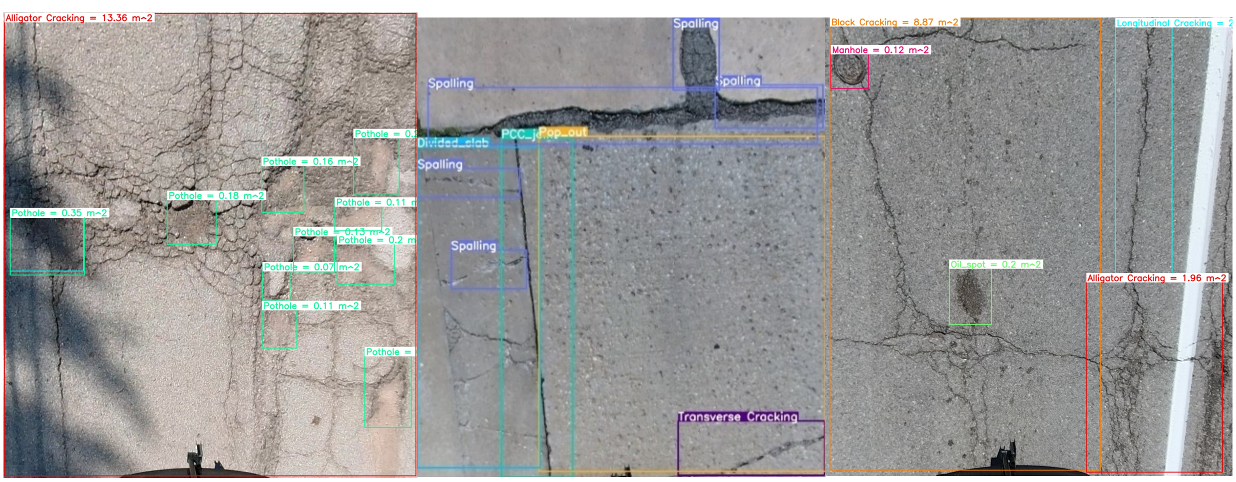

Figure 4 Representative Images and Automated Distress Detection Results for Flexible and Rigid Pavement (Generic photos not representative of from this project)

Pavements are divided into sections such as streets, direction, and/or test sections. Through the automated and consistent AI-based pavement evaluation, pavement distress types are assigned a severity and density (quantity in relation to the section measured). The PCI is then calculated using standardized equations where deduct values from distress damage are subtracted from 100 per ASTM D6433. PCI is represented on a scale ranging from 0 to 100, where higher values signify a superior condition of the pavement. Figure 5 defines these typical PCI ranges where treatment type is subjective to the pavement owner.

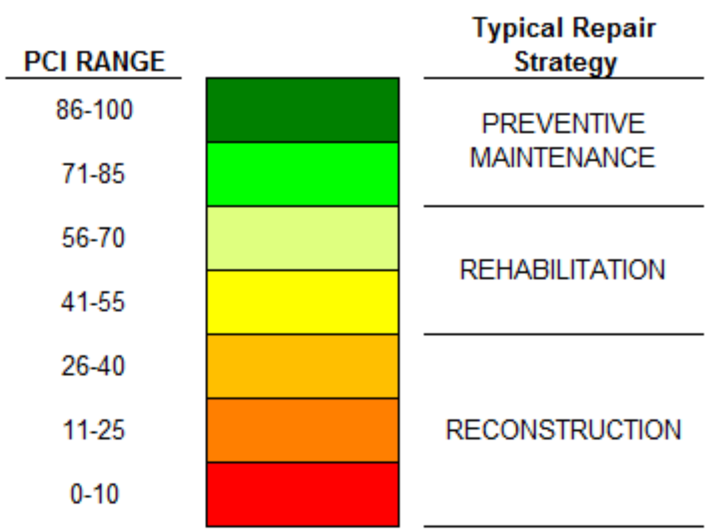

Figure 5 Pavement Condition Index (PCI) Scale and Potential Strategy

Through demonstration field projects and comprehensive pavement condition index (PCI) surveys, it is possible to approximate the service life of aramid fiber reinforced asphalt pavements. These projects provide real-world data on how additives such as aramid fibers perform under actual traffic and environmental conditions. By closely monitoring the pavement's condition over time, valuable insights are gained into the rate of deterioration and effectiveness of the enhancements. The data collected from these initiatives can be analyzed to establish a service life value, offering a reliable estimate of the pavement's longevity. Such empirical evaluations are crucial for validating the benefits of additive use, enabling stakeholders to make informed decisions about future infrastructure investments based on demonstrated performance outcomes. Table 4 provides detailed information on the observed service life values derived from these field evaluations, highlighting the tangible benefits of incorporating aramid fiber into asphalt pavements. The range of estimated life extension of aramid fiber pavements is two to four years based on the eight projects below in Table 4 that were surveyed by BATT. Current and previous research in addition to lab research studies corroborates this life extension. Case studies and field performance by Martin, Blankenship, Nazar, and West et al show a 4 to 5 year life extension when using aramid fiber [17] [18] [19] [20]. A linear relationship was fit to the PCI data over time to determine the rate of change in PCI per year. On average the control mixture deteriorates at a rate of 5.7 PCI per year compared to the aramid fiber sections which deteriorate at a rate of 3.1 PCI per year.

Table 4 – Pavement Condition Index Summary – Service Life Extension

Project Location	Year Constructed	Project Age, Years	2024 Pavement Condition Index (PCI)		Change in PCI Per Year (Linear Fit)		Life Extension Estimate Based on PCI, Years
			Control	Fiber	Control	Fiber	
Beckley Station (Louisville KY, 2015)	2015	10	26	68	-6.3	-3.0	2-3
Stafford Lane (Plainfield IN, 2018)	2018	7	72	85	-4.1	-2.4	2-3
Highway 7 (York Region, Canada, 2018)**	2018	8	53* *PCI measured in 2025*	84* *PCI measured in 2025*	-5.9	-2.0	3-4
Mercer Rd (Lexington KY, 20% vs 45% RAP + fiber/bio oil, 2020)	2020	5	70	83	-6.6	-3.6	2-3
Man O War (Lexington KY, 2020)	2020	5	65	73	-6.6	-5.8	2-3
UPS Facility (Walton KY, 2023)	2023	2	na	93			NA
Loves Truckstop (Sadieville, KY, 2015)	2015	10	70	85	-4.4	-2.0	2-3

Figure 6 and Figure 7 shows plots of PCI versus time for all projects and on a project-by-project basis, respectively. The control mixture and aramid fiber modified pavements both follow a typical PCI deterioration curve in that follows a power law type decay rate or linear decay rate. The aramid fiber pavement appears to outperform the control section. The control section reaches the preventive maintenance trigger limit a few years before the aramid fiber reaches the limit.

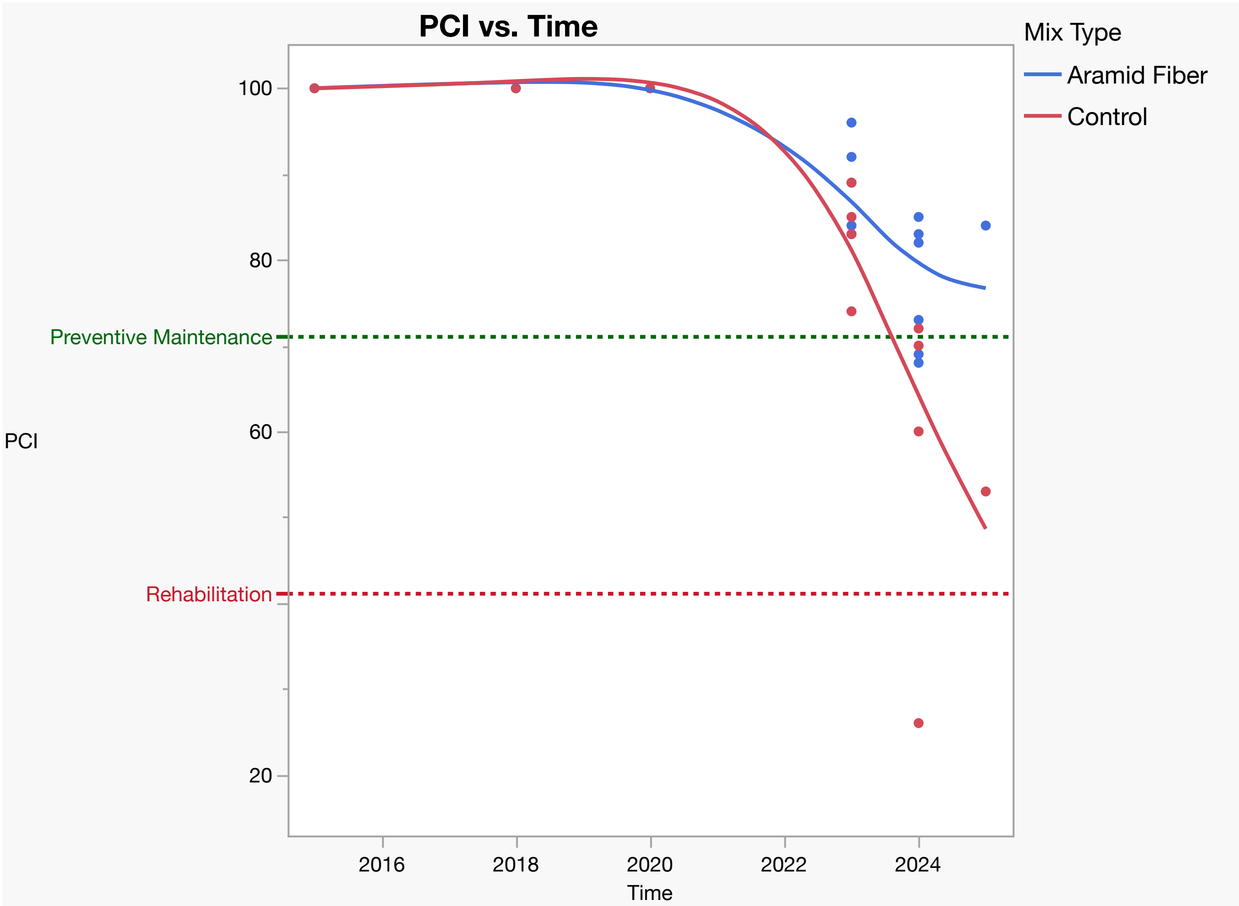

Figure 6 Pavement Condition Index (PCI) vs Time (All Projects)

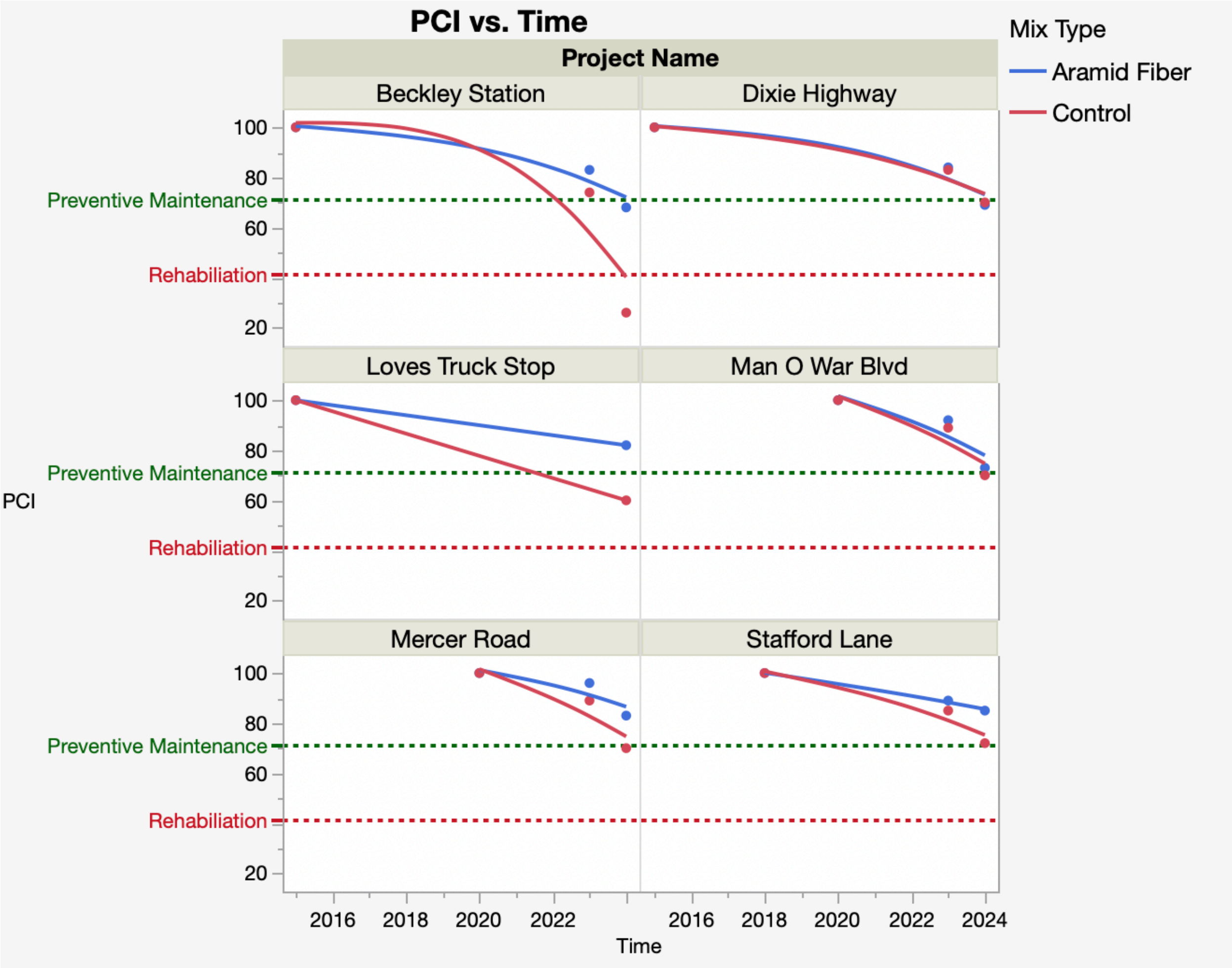

Figure 7 Pavement Condition Index (PCI) vs Time (Project Level)

REFERENCE SERVICE LIFE

The functional unit is 1 yd^2 of pavement installed in a road for a 50-year analysis period. The baseline, unmodified unit of pavement under this study is assumed to have a reference service life (RSL) of 18 years. Previous research studies have shown that the addition of aramid fiber will extend the time to pavement intervention. To capture this effect, it is assumed that for each maintenance and rehabilitation cycle, the time to intervention will be 20% longer than conventional asphalt concrete which is conservative based on the estimates above in Table 4 above and previous research that is cited. As estimates improve for the aramid fiber's effect on time to intervention, this parameter can be updated. The rehabilitation and maintenance cycle for a typical pavement system with and without aramid fiber are shown in

Table *5* [12].

Table 5 – Maintenance and Rehabilitation Cycle

Replacement Cycle and Type		Expected time of intervention for typical asphalt system (years)	Expected time of intervention for asphalt system with aramid fiber (years)
Cycle 1	M2 – Minor Reconstruction (Overband crack sealing and microsurfacing)	6.5	8
Cycle 2	M1 – Major Reconstruction (Cold Milling and Overlay)	11.5	13.5
Cycle 3	R1 – Major Reconstruction (HMA Reconstruct)	15	18

The pavement system with aramid fiber is estimated to last 18 years over a full cycle. Therefore, after initial construction in the roadway with an estimated service life (ESL) of 50 years, there will be three Cycle 1, two Cycle 2, and two Cycle 3 interventions.

SYSTEM BOUNDARY

The life cycle assessment (LCA) is a cradle-to-grave study. An overview of the boundary system is shown in Figure 8. The A1-A3 modules include the extraction and upstream production of all materials required in the pavement system, the transportation of the materials to the asphalt mix plant, and the emissions required for the manufacturing of the asphalt. The transportation to the construction job site and installation emissions are included in A4-A5. B3-B4 includes the emissions required over the lifetime of the product and module C1-C4 includes the emissions at the end of life.

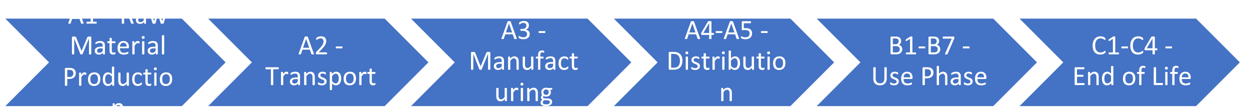

Figure 8 - System Boundary Summary

A1 Materials, A2 Transportation, and A3 Production Phases

These phases include raw material extraction, supplier processing, and delivery of the materials to the asphalt mixture production facility. Processes included and excluded from the system boundary are summarized in Table 6 and discussed extensively in the product category rules (PCR) for Asphalt Mixtures [13].

Table 6 – Items Included and Excluded in Product Stage

Included	Excluded
Extraction and processing of asphalt mixtures, aggregate, and aramid fiber	Creation of supplier facilities
Transportation of materials to the manufacturing location	Manufacturing of supplier operational equipment or transport vehicles
Manufacturing of product, including energy, water, and material usage and water disposal	Packaging of products

The A1-A3 environmental impact of each mix design was modeled using the Emerald Eco-Label environmental product declaration (EPD) tool to produce reference cradle-to-gate EPDs. All unit processes, foreground data collection, and background datasets were developed according to the NAPA PCR for Asphalt Mixtures [13]. The environmental impact of A1 including aramid fiber in the pavement mixture was modeled using an aramid fiber product-specific EPD.

Resource use estimates for A2 Transportation of raw materials to the production facility and the A3 asphalt mix production process were developed from 2019 national average asphalt plant performance data developed by the National Asphalt Pavement Association and reported in SIP 106: GHG Emissions Inventory for Asphalt Mix Production in the United States [17].

A4 Distribution and A5 Installation

Delivery of the asphalt mixture materials to the installation location is modeled using impact factors from the Carbon Footprints for HMA and PCC Pavements report [12]. Processes included and excluded from the system boundary for phases A4-A5 are summarized in Table 7.

Table 7 – Items Included and Excluded in the Distribution Stage

Included	Excluded
Transportation from the manufacturing gate to the customer, including fuel usage	Production of multi-use installation tools
Installation of pavement system in the roadway	Packaging of asphalt mixtures and aggregate

B1 to B7 Use Phase

The use phase of a pavement system incurs use-phase environmental impacts through B1 pavement-vehicle interaction, B2 maintenance operations, B3 repair processes, B4 layer replacement, B5 refurbishment, B6 operational energy use, and B7 operational water use [18]. For this LCA only the B3 repair and B4 replacement of the pavement structure were considered in the use phase. Refurbishment, cleaning, operational energy, water, and material use were excluded because there is currently insufficient data available to model these life-cycle phases.

A typical pavement intervention timeline (

Table *5*) is used to model the expected intervention schedule required for the asphalt pavement system over its lifetime. These values are based on the assumptions established in the Remaining Service Life section above regarding the baseline pavement reference service life and aramid fiber increased pavement intervention time. The number of interventions required for the asphalt pavement system dosed with an aramid fiber over the 50-year RSL is estimated to be three Cycle 1 activities, two Cycle 2 activities, and two Cycle 3 activities. Table 8 shows the year after installation that these interventions are performed.

Table 8 – Expected Timeline of Intervention Activity During the 50-year Lifetime

Intervention Cycle and Type		Expected Intervention Year for Baseline Pavement (years)	Expected Intervention Year for Aramid Fiber (years)
Cycle 1	M2 – Minor Reconstruction (Overband crack sealing and microsurfacing)	6.5	8
Cycle 2	M1 – Major Reconstruction (Cold Milling and Overlay)	11.5	13.5
Cycle 3	R1 – Major Reconstruction (HMA Reconstruct)	15	18
Cycle 1	M2 – Minor Reconstruction (Overband crack sealing and microsurfacing)	22	26.5
Cycle 2	M1 – Major Reconstruction (Cold Milling and Overlay)	26.5	32
Cycle 3	R1 – Major Reconstruction (HMA Reconstruct)	30.5	36
Cycle 1	M2 – Minor Reconstruction (Overband crack sealing and microsurfacing)	37	44.5
Cycle 2	M1 – Major Reconstruction (Cold Milling and Overlay)	41.5	
Cycle 3	R1 – Major Reconstruction (HMA Reconstruct)	45.5	

The intervention activity occurs at the end of the cycle resulting in the emissions for the intervention being realized at the end of the cycle. The final Cycle 2 and Cycle 3 interventions indicated for the baseline pavement are not included for the 50 years RSL because they would occur after the 50-year lifetime of the functional unit.

End of Life

In this stage, the product is transported to the end-of-life facility and disposed. This process estimates the transportation, milling, and end-of-life process required for the asphalt system disposal. This stage is summarized in Table 9.

Table 9 – Items Included and Excluded in the End-of-Life Stage

Included	Excluded
Energy and materials required for deconstructing the product	Production of end-of-life capital equipment and facilities
Transportation of the product to the end-of-life facility	
Waste and processing for reuse, recycling, energy recovery, and/or reclamation	

LIFE CYCLE IMPACT ASSESSMENT

Environmental impacts for each mix design were calculated using the Emerald Ecolabel software platform. Impact results for GWP have been calculated using TRACI 2.1 characterization factors shown in Table 10.

Table 10 – Life Cycle Impact Assessment Indicators

Abbreviation	Parameter	Unit
	TRACI 2.1	
GWP	Global warming potential (100 years, includes biogenic CO_2)	kg CO_2 eq

Using aramid fiber in an asphalt mixture increases A1-A3 GWP by 0.63%, an amount that falls below cut off limits (2.5 Cut-Off Criteria) and thus eligible for exclusion from the total results. Table 11 shows the total GWP results of the cradle-to-gate impacts of 1 yd^2 of the pavement system installed with or without the addition of aramid fiber. It can be reasonably concluded that aramid fiber has insignificant overall impacts as a material at the dosage rate used. Thus, the benefits from using it in a mix design can be purely realized from its ability to decrease the number of pavement interventions over a desired period.

Table 11 – Cradle-to-Gate Emissions for Asphalt Mixture Used in the Functional Unit of 1 yd^2 of the Pavement System

Indicator	A1 – A3 without aramid fiber	A1 – A3 with aramid fiber
GWP, kg CO_2 eq	31.72	31.92

A dominance analysis was performed for the product studied in the LCA to show which of the life cycle modules contributes to which indicator. Due to the relevance of these impact categories to the product type and the manufacturer's interests, this dominance analysis will be provided for TRACI 2.1 GWP results. GWP is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specified time horizon and measured relative to carbon dioxide. Figure 3 shows GWP in kg CO_2 eq contributions across the life cycle stages reported for the scenario where typical intervention schedule is increased by 20%. Over 50% of the product emissions come from the A1-A3 manufacturing and upstream production stage. The use phase accounts for roughly 30% of the product emissions and the remainder comes from installation and end of life.

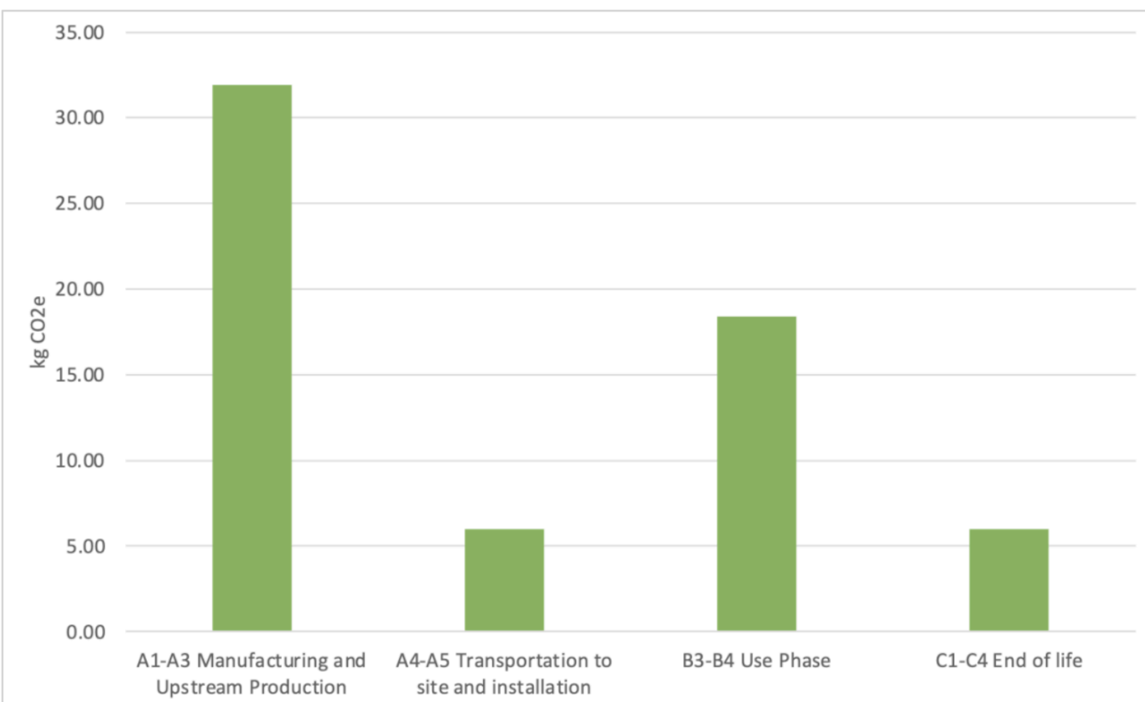

Figure 9 – GWP Separated by System Boundary for 1 yd^2 of Pavement System installed in a Roadway for 50 Years

A sensitivity analysis was performed within the life cycle assessment to determine how the results of an LCA are affected by the assumptions the LCA practitioner. Of relevance to this model are the assumptions of the replacement schedule of the pavement system. It was assumed that the use of aramid fiber will result in an increase in 20% of the time required for pavement intervention. Figure 10 shows the total CO_2 emissions from cradle-to-grave for 1 yd^2 installed in a pavement system for 50 years with an increased intervention time of 0% and 20%. The baseline case here is established from a typical maintenance schedule as shown in

Table *5*. This analysis indicates the results are sensitive to the assumptions resulting in the percentage change to pavement intervention time (Table 12). Therefore, it is important to understand the actual impacts of the addition of aramid fiber on pavement intervention cycles for this analysis to be accurate.

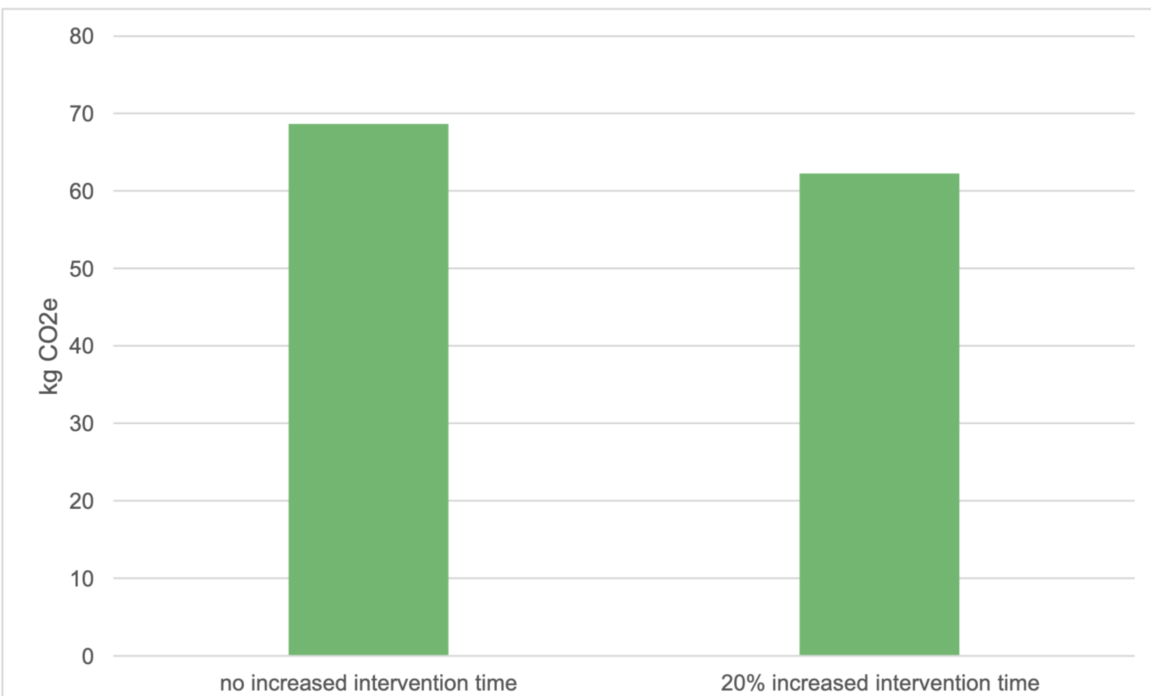

Figure 10 – GWP Variability Depending on Increased Intervention Time

Table 12 – Percent Change in GWP Resulting from Varied Replacement Schedule with the Typical Intervention Time as Baseline

Indicator	20% Longer Intervention Time
GWP, kg CO_2 eq	-10%

FIELD PERFORMANCE

Figure 11 shows the current condition of Man O' War Boulevard and mainline paving. Man O' War Boulevard undergoes regular inspections via manual and video Pavement Condition Index (PCI) surveys to monitor its condition. After four years since its implementation the aramid fiber section has a PCI of 73 (preventive maintenance stage) whereas the control is 65 (rehabilitation stage) as shown in Figure 12. The pavement at Man O' War Boulevard has exhibited remarkable resilience due to the airport traffic loading, showing minimal signs of distress such as block cracking (at one location near the south part of the project near Terminal Drive) and raveling (at a few locations near the north part of the project near Versailles Road) (Figure 13). According to Figure 13, there are some small, isolated areas of low severity and medium severity alligator cracking, edge cracking, bleeding, and oil spots. This is a testament to the effectiveness of the materials and techniques employed in its construction. Figure 14 shows a PCI color map for the entire project. This provides a project level view so one can identify areas that are in good to excellent condition, fair condition, and poor condition. Most of the project is in good to excellent condition. The fair condition areas appear to be at intersections and turn lanes.

Figure 11 – Man O' War Intersection and Mainline (2024)

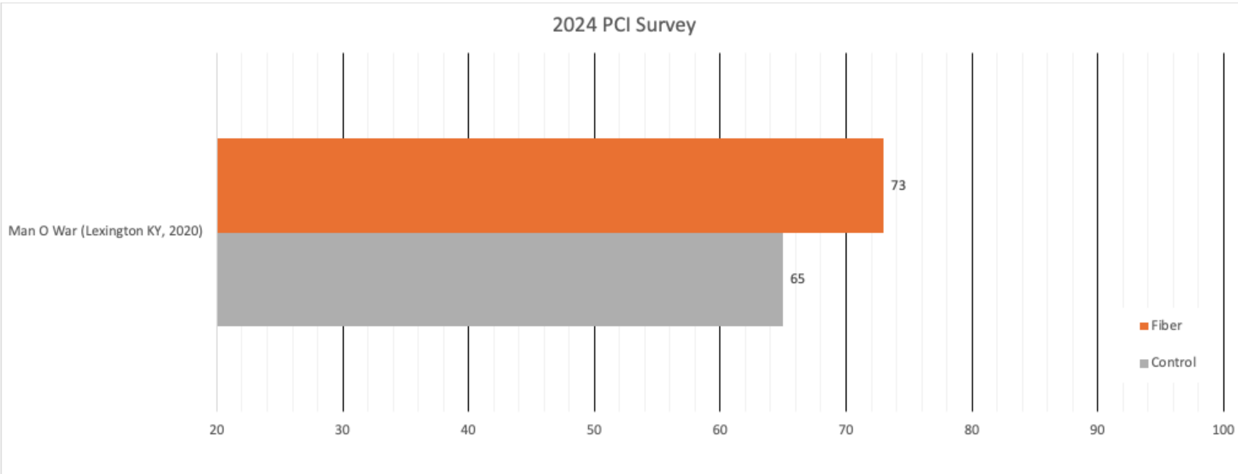

Figure 12 – Pavement Condition Index (PCI) Survey Man O' War Intersection and Mainline (2024)

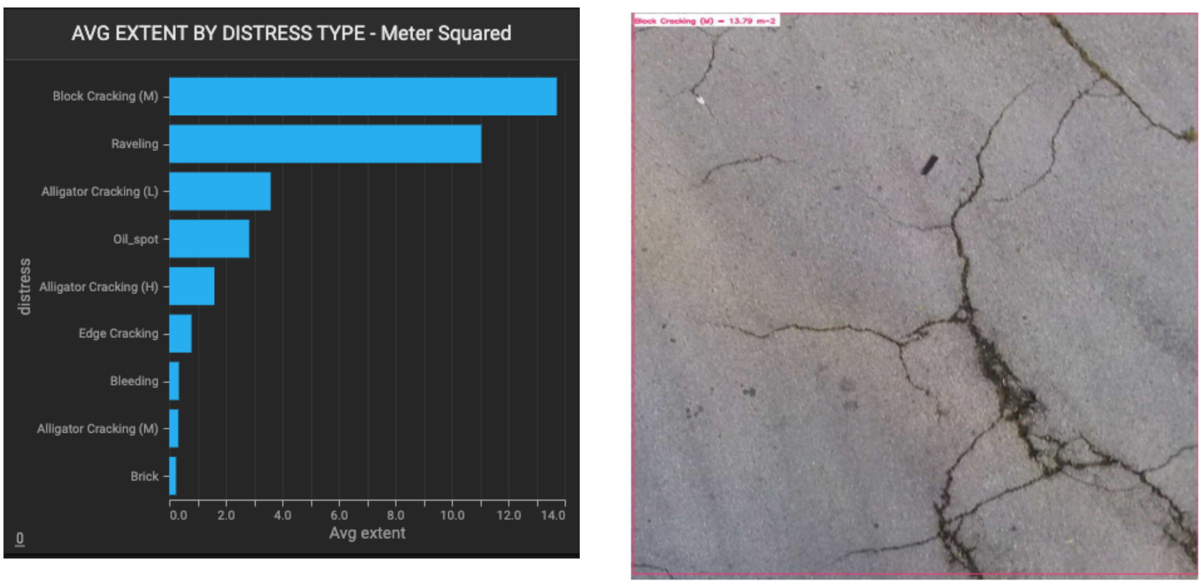

Figure 13 – Average Extent by Distress Type - Man O' War Intersection and Mainline (2024) & Block Cracking Photo

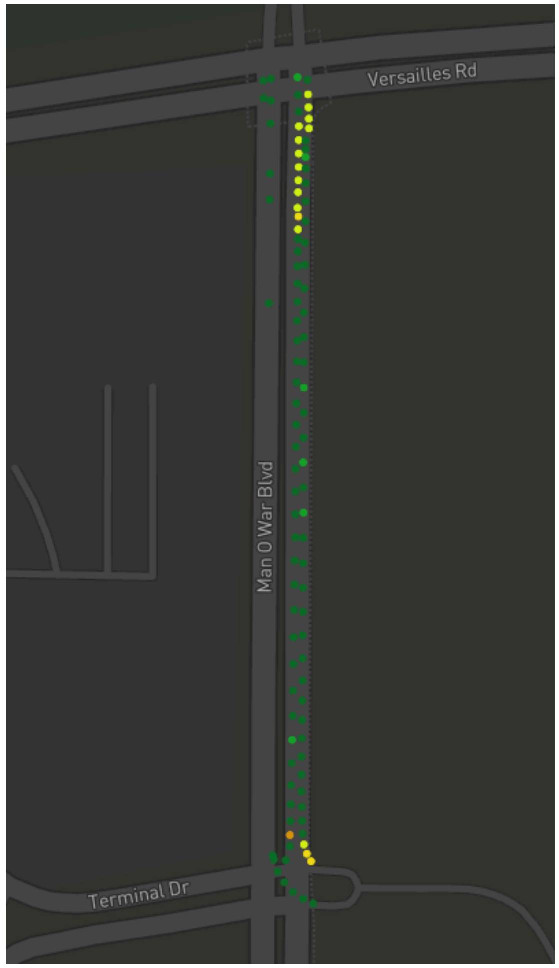

Figure 14 –Man O' War Intersection and Mainline (2024) PCI Color Map

CONCLUSIONS

This study assesses the environmental impact of aramid fiber in asphalt mixtures through a cradle-to-grave life cycle assessment (LCA). Building on a cradle-to-gate analysis, the research evaluates the effect of aramid fiber on time-to-pavement-intervention, using design parameters from the Man O' War Boulevard project in Lexington, Kentucky. The functional unit is defined as one square yard of installed pavement, with impacts analyzed over a 50-year reference service life and an industry-standard intervention schedule. A sensitivity analysis assumes a 20% increase in time to intervention due to aramid fiber inclusion (a conservative estimate), derived from pavement condition surveys comparing projects with and without aramid fiber.

Results show that a 20% increase in time to intervention reduces 50-year cradle-to-grave impacts by 10%, primarily by decreasing the frequency of maintenance and rehabilitation cycles. Reductions are observed in the B3-B4 life cycle phases, encompassing material production, transportation, and installation processes.

Key findings include: (1) Aramid fiber inclusion has negligible impacts on A1-A3 phases on a mass and GHG basis, and (2) extended pavement service life reduces cradle-to-grave impacts by minimizing maintenance and rehabilitation operations. These results underscore the potential of aramid fiber to enhance pavement sustainability by improving durability and reducing life cycle environmental impacts.

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