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PAVEMENT SUSTAINABILITY, RESILIENCE, AND PERFORMANCE EVALUATION USING A COMPREHENSIVE SYSTEMS APPROACH

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ABSTRACT: Improving the sustainability, resilience, and performance of pavements is a major concern for both the public and private sectors. One of the largest related challenges is accurately quantifying the positive and negative impacts of options for design and materials over the full life cycle of the pavement. This assessment has become more complicated with the necessity of evaluating sustainability and resilience factors in addition to the trafficking and maintenance performance of pavement structures. A comprehensive systems approach to pavement design is critical with respect to life cycle analyses for sustainability, resilience, and performance. Design decisions should be made based on their impact on pavement performance as a system, incorporating the entire structure and covering its full life cycle. Environmental Product Declarations (EPDs) provide information needed for this assessment; however, it is critical to understand their proper use to ensure that projects are evaluated accurately. Successful application of a systems approach to this challenge depends upon properly defining the scope of consideration for the analysis. This paper discusses the challenges of selecting the proper scope of consideration and provides example cases which demonstrate the effects on Life Cycle Analysis.

KEYWORDS: Environmental Product Declaration, Life Cycle Assessment, Sustainability, Resilience, Pavement.

1 INTRODUCTION

Improving the sustainability, resilience, and performance of pavements is a major concern for both the public and private sectors. One of the largest related challenges is accurately quantifying the positive and negative impacts of options for design and materials, especially over the full life cycle of the pavement. This assessment has become more complicated with the necessity of evaluating sustainability and resilience factors in addition to the trafficking and maintenance performance of pavement structures.

This paper demonstrates the importance of a comprehensive systems approach to pavement design with respect to life cycle analyses for sustainability, resilience, and performance. Pavements are often evaluated as a collection of discrete components (e.g., asphalt cement concrete, aggregate, subgrade), rather than as a single system. As new materials such as geosynthetics have been introduced into pavement design, as the scope of evaluation has expanded to include considerations such as sustainability and resilience, and as design improvements have allowed more precise assessments of life cycle costs, it is critical that we treat the pavement structure as an integrated system. Design decisions should be made based on their impact on pavement performance as a system, incorporating the entire structure and covering its full life cycle.

With respect to sustainability, Environmental Product Declarations (EPDs) provide information needed for this assessment; however, it is critical to understand their proper use to ensure that projects are evaluated accurately. Adopting the wrong scope of consideration for sustainability will produce inaccurate results.

Multiple authors have addressed the question of system boundaries for Life Cycle Analysis (LCA) over the past 30 years. This work has primarily focused on LCAs for individual products. Defining system boundaries in this context considers the individual product and its intended function, while accounting for cross-boundary effects due to product differences (e.g., production by-products, recycling processes). While this approach provides important insights and necessary information at the product level, it is not sufficient for conducting and LCA for a constructed project which may include dozens, or in some cases thousands, of products.

In the field of design and construction, significant work has been done and many standards have been developed which support LCAs for buildings. In this case, the determination of the system boundary for the analysis is relatively straightforward: while some cross boundary effects may need to be addressed, the building itself is almost always the proper level at which to draw the system boundary.

When we look at other types of constructed projects, however, the definition of the proper system boundary or scope of consideration can become more difficult, because design alternatives using many different approaches and components may be used to accomplish the same function. This paper considers the case of a flexible pavement design, which is one small example of this problem, and considers the use of one specific design change within the pavement system: the addition of a stabilization geogrid to the aggregate base layer. This simplified scenario is used to illustrate the impact of design decisions on LCAs. As more design options are considered, adherence to the concept demonstrated is important for obtaining valid results from LCAs on infrastructure projects.

As we expand our analysis to include resilience and total life cycle costs, it is critical that we include the performance benefits of innovative materials within the complete pavement system. This paper will discuss the application of a systems approach to pavement design and provide examples which will demonstrate its importance to proper evaluation of design alternatives.

2 PAVEMENT DESIGN BACKGROUND

2.1 Design Methodology Used in Analysis

For this analysis, the design methodology used is the 1993 empirical design formula published by the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 1993). For the enhanced design using mechanical stabilization of the aggregate layer, additional guidance provided by AASHTO in Publication R 50-09 (AASHTO, 2009) is also followed. A comprehensive explanation of the proper design of both conventional pavements and pavements incorporating a mechanically stabilized aggregate layer is complex and is beyond the scope of this paper. The concepts illustrated here regarding the importance of adopting an appropriate scope of consideration for sustainability analyses are independent of both the design method used and the structure to be built. Methodology is noted simply to assure the reader that the examples chosen are realistic.

2.2 Quantification and Application of Geogrid Stabilization Benefit

In the AASHTO 1993 empirical design formula (Equation 1 below), the predicted pavement life is a function of the structural number (SN), subgrade resilient modulus, serviceability limits, and reliability. Pavement life using a geogrid is calculated from an enhanced SN based on the increased stiffness of the mechanically stabilized layer (MSL). The "a" value of the geogrid stabilized MSL is the key component of the enhanced SN value (Equation 2) that is calculated for the pavement section.

The "a" value is representative of aggregate quality and degree of enhanced confinement achieved with a particular geogrid. Calibration and validation of this "a" value must be performed with an extensive catalogue of pavement structures (layer thicknesses & material types), subgrade conditions, and performance data. Algorithms that are based on the "a" value calibrations have been created and incorporated into the design methodology. The software used for this analysis is Tensar Plus (Tensar, 2022), which follows this methodology. The program automatically assigns the proper calibrated "a" value to the MSL for the user-defined input conditions, and uses the assigned layer coefficient in the AASHTO design analysis.

$$\log_{10}(W_{18}) = Z_R S_o + 9.36\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log_{10} M_R - 8.07 \tag{1}$$

Where:

- W_{18} = predicted number of 18,000 lb. (80 kN) Equivalent Single Axle Loads (ESALs)
- Z_R = standard normal deviate
- S_0 = combined standard error of the traffic prediction and performance prediction
- ΔPSI = difference between the design initial serviceability index and the design terminal serviceability index
- M_R = subgrade resilient modulus in pounds per square inch

SN = a1D1 + a2D2m2 + a3D3m3 (2)

Where:

- ai = layer coefficients representative of surface and aggregate base courses
- Di = actual thickness (in inches) of surface and aggregate base courses
- mi = drainage coefficient for aggregate base course

Layer coefficients presented in the AASHTO 1993 Design Manual for pavement materials are empirically derived correlations to material properties. As such, the layer coefficient is a measure of the relative ability of the material to function as a structural component within the pavement. The use of enhanced layer coefficients for MSLs is consistent with this approach. It is important to note that the new increased layer coefficient is not a reflection of the aggregate material alone but is adjusted to account for the improved long-term performance due to inclusion of the geogrid, yielding a stiffened composite of aggregate and geogrid. In addition, current AASHTO correlations for the resilient modulus of a granular base layer and its layer coefficient are not valid for a composite material that consists of granular aggregate material and a stabilization geogrid.

Because of increased contact forces and stresses around the geogrid resulting from efficient aggregate confinement, stiffness compared to the unbound aggregate increases significantly and improves overall pavement performance. This increase in, and retention of, stiffness results in a reduction in the amount of rutting and increased fatigue life of the pavement.

As illustrated in the example below, the performance benefit from the incorporation of the MSL may be used by the designer to achieve multiple objectives. Before sustainability became a design consideration, the performance benefit would typically be used to either reduce the cost of the pavement, extend its design life, or some combination of the two. With the addition of Life Cycle Analyses on sustainability criteria, this design approach also provides the opportunity to optimize the design based on carbon footprint, if the analysis is conducted properly.

To realize this opportunity, the pavement must be evaluated as a system, taking into account the effects of any design change on each performance criterion.

3 EXAMPLE CASES

To demonstrate how this comprehensive systems approach can improve the results of a sustainability Life Cycle Assessment (LCA), the example of a typical asphalt pavement with a width of ten (10) meters and a length of one (1) kilometer (km) is considered. Figure 1 shows the pavement section to be evaluated.

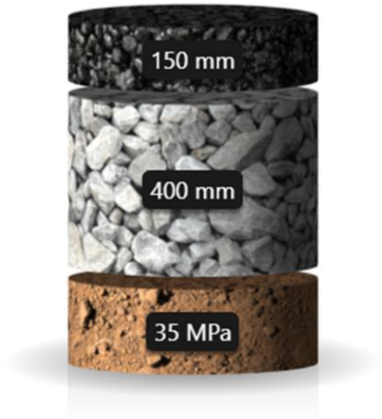

Figure 1. Asphalt Pavement Section

As discussed in Section 2, the pavement designer might decide to add a geogrid to the pavement section to stabilize the aggregate layer and thereby increase the traffic capacity of the pavement. If the designer is required to evaluate the carbon footprint of the project, expressed as Global Warming Potential (GWP), he or she would likely consult the EPD for the geogrid. If all other factors in the system are held constant, the scope of consideration for the analysis would include only the geogrid, and its addition would result in an increase in GWP due to emissions from its production and transportation to the project site.

Restricting the scope of consideration to the product alone is a valid approach when the evaluation consists only of deciding between interchangeable products. Most EPDs are written to support this case, especially those for consumer products. But an accurate analysis for engineering and construction decisions may be significantly more complex, because design changes usually involve multiple materials and products. A pavement design using an MSL instead of a conventional unbound aggregate layer is one such case.

To accurately evaluate the GWP of a conventional pavement design as compared to a design using an MSL, it is necessary to compare the entire pavement system for each alternative. Each of the materials used in the pavement structure has an environmental impact, and each contributes to the traffic capacity of the structure. The designer must therefore match the scope of consideration for the LCA to the scope of the design.

In this case, the designer has multiple options for making use of the performance benefit provided by the geogrid in the MSL design. The following analysis demonstrates how these options affect the environmental impact of the design, as a system, in terms of embodied carbon emissions.

For this analysis, data related to environmental impacts for the multiaxial geogrid are taken from the Tensar EPD published for the product. The EPD uses the GaBi v10.6.2.9 Software System for Life Cycle Engineering, a recognized LCA modeling software program. All background datasets relevant for production and disposal were taken from this software, including the Sphera database and the USLCI database. Additional detail regarding the development of the EPD is presented in the document itself.

A simplified calculation of embodied CO_2 equivalent ($kgCO_2e$) for the pavement structure at the completion of construction is used in lieu of a full evaluation of GWP or a more detailed LCA. For the geogrid, the Product and Construction Process Stages (A1 – A5) from the EPD are used.

The result of an LCA of a pavement project is highly dependent on the location of the project due to the specifics of the manufacture and delivery of pavement materials. The ideal example for this analysis would be an actual pavement construction project for which these specifics are available, such as the asphalt plant used, the specific asphalt mix(es), the aggregate quarry used, traffic data, and planned maintenance intervals. The analysis here is simplified to clearly demonstrate the concept which is being discussed. A qualitative discussion of factors impacting a more detailed analysis is presented below.

Based on typical values and assumptions, the embodied CO_2 equivalent is calculated as the sum of:

- The embodied carbon within the construction materials at their respective "factory gates"
- Emissions related to delivery of materials to the site
- Completion of construction of the pavement

The distances to the project site from the aggregate quarry, the asphalt plant, and the geogrid manufacturing plant are all assumed to be approximately 50 km. The analysis was conducted using Tensar Plus software. The embodied carbon of each design component will vary somewhat depending on the specifics of the project location, material sources, asphalt mix design, and similar factors. The values used here are assumed to be typical. A precise LCA for any project would require more detailed evaluation of each of the material and energy inputs.

Table 1 summarizes the design parameters used for the determination of the traffic capacities of the pavement sections.

Table 1. Pavement Design Parameters for Evaluated Sections

AASHTO 1993 Design Parameter	Value
Asphalt Layer Coefficient	0.42
Unbound Aggregate Layer Coefficient	0.14
Initial Serviceability	4.2
Terminal Serviceability	2.0
Aggregate Drainage Factor	1.0
Reliability	95%
Standard Deviation	0.49

The calculated traffic capacity of the conventional pavement section as shown in Figure 1, using AASHTO 1993 methodology, is 2,619,000 Equivalent Single Axle Loads (ESALs). The embodied carbon of the structure using the assumptions above is 273 tonnes CO_2e.

Two alternative pavement section designs using an MSL illustrate how embodied carbon values are affected by the entire pavement structure, instead of just the addition of a geogrid. These alternatives are shown in Figure 2.

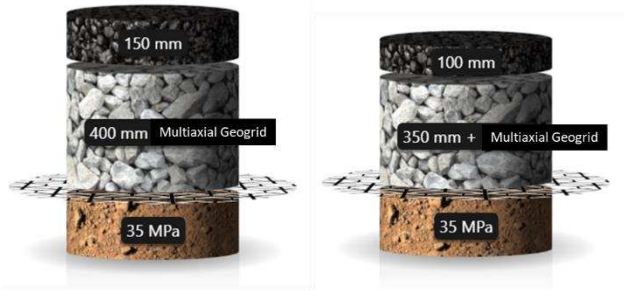

Figure 2. Alternative Pavement Sections Using an MSL

The first alternative section uses the same aggregate thickness as the conventional design, but with a geogrid added to create an MSL. As discussed above, this results in a small increase (5%) in the embodied carbon of the pavement structure, to 286 tonnes CO_2e. However, it also increases the traffic capacity of the pavement 468%, to 14,888,200 ESALs.

The second alternative section uses a reduced asphalt cement concrete thickness and a reduced aggregate thickness in the MSL, taking full advantage of the performance enhancement provided by the geogrid. This section delivers traffic capacity of 3,040,800 ESALs, which is 16% better than the conventional section. But because of the significant reduction in the asphalt cement concrete and aggregate required, the embodied carbon of this design is much lower than that of the conventional section. Using the same assumptions as before, the embodied carbon is reduced to 211 tonnes CO_2e (23% reduction).

A basic cost analysis indicates that this second alternative section would also cost approximately $5.00-10.00 US less per square meter of pavement surface.

Traffic capacities and embodied carbon values for each pavement section are summarized in Table 2.

Table 2. Calculated Traffic Capacities and Embodied Carbon for Evaluated Pavement Sections (Analysis Unit = 10 m wide x 1 km)

Pavement Section	**Calculated Traffic Capacity (ESALs)**	**Embodied Carbon (tonnes CO_2e)**
Conventional Design, 150mm/400mm	2,619,000	273
MSL Design, 150mm/400mm	14,888,200	286
MSL Design, 100mm/350mm	3,040,800	211

A detailed breakdown of the embodied carbon for the components of each alternative pavement section is presented in Table 3. It should be noted again that the values presented include only the emissions through the completion of construction.

Table 3. Embodied Carbon Detail, tonnes CO_2e

	Conven-tional Design 150mm/ 400mm	**MSL Design 150mm/ 400mm**	**MSL Design 100mm/ 350mm**
Asphalt Cement Concrete			
Source	155	155	103
Delivery	7	7	5
Compaction	34	34	23
Aggregate			
Source	39	39	34
Delivery	18	18	15
Compaction	21	21	19
Geogrid			
Source		12	12
Delivery		0	0
Total	**273**	**286**	**211**

Now consider a different scenario also starting with the initial unstabilized pavement section, using the same design parameters for analysis in the AASHTO methodology. In this scenario, the designer wishes to increase the traffic capacity of the pavement structure from the initial 2.6 million ESALs to 14.8 million ESALs. Similarly to the first scenario, the designer could evaluate the options of using conventional materials to achieve the required traffic capacity, or mechanically stabilizing the aggregate base layer to increase its structural capacity.

The analysis in the first scenario demonstrates that the increased traffic capacity can be achieved by adding a multiaxial geogrid to the original pavement section. Alternatively, the designer could consider using a thicker conventional pavement section, increasing the thickness of the asphalt cement concrete and/or aggregate layers. Using the same design parameters, one solution using this approach would be to increase the thickness of the asphalt cement concrete layer from 150 mm to 225 mm. This results in an increase in the traffic capacity of the section to 15,438,700 ESALs. Figure 3 shows the two design options, each of which will meet the new traffic capacity requirement of 14.8 million ESALs. (The designs do not result in identical traffic capacities due to constructability considerations – specifically, it is not realistic to specify differences in asphalt cement concrete thickness less than 5 mm.)

Figure 3. Alternative Pavement Sections Using an MSL vs. Increased Thickness

In this scenario, the designer has added to the cost of the section in both cases, in order to deliver increased traffic capacity. The impact of these changes on the cost of the pavement will depend on the costs of the geogrid, the aggregate, and the asphalt cement concrete. For this specific case, if the cost of the geogrid is less than the cost of the additional 75 mm of asphalt cement concrete, then the MSL design would result in a lower cost for the pavement. Conversely, if the geogrid is more expensive than the additional asphalt, the conventional section would cost less than the MSL design.

A basic cost analysis indicates that the sections would have equivalent costs per ESAL of traffic capacity if the cost of the geogrid is \$8.00 US per m^2 and the cost of asphalt cement concrete is \$65 per tonne in place. These values are at the high end of the expected range for geogrid and the low end of the expected range for asphalt. However, this again demonstrates the necessity of considering the pavement system as a whole when conducting the design analysis.

While it is possible that a conventional design might cost less in this scenario when asphalt is extremely inexpensive, the cost in embodied carbon for the conventional design is significantly higher, by nearly 30 percent. Traffic capacities and embodied carbon values for these pavement sections are summarized in Table 4.

Table 4. Calculated Traffic Capacities and Embodied Carbon for Evaluated Pavement Sections (Analysis Unit = 10 m wide x 1 km)

Pavement Section	**Calculated Traffic Capacity (ESALs)**	**Embodied Carbon (tonnes CO_2e)**
Conventional Design, 225mm/400mm	15,438,700	371
MSL Design, 150mm/400mm	14,888,200	286

A detailed breakdown of the embodied carbon for the components of each alternative pavement section is presented in Table 5. This illustrates the impact of the additional asphalt needed to achieve the higher traffic capacity. Mechanical stabilization of the unbound aggregate layer is a much less carbon intensive method for improving the traffic capacity than additional asphalt thickness. (It should be noted again that the values presented include only the emissions through the completion of construction.)

Table 5. Embodied Carbon Detail, tonnes CO_2e

	Conventional Design 225mm/400mm	**MSL Design 150mm/400mm**
Asphalt Cement Concrete		
Source	232	155
Delivery	11	7
Compaction	51	34
Aggregate		
Source	39	39
Delivery	18	18
Compaction	21	21
Geogrid		
Source		12
Delivery		0
Total	**371**	**286**

4 DISCUSSION

The analysis of alternate pavement sections clearly demonstrates the importance of using a comprehensive systems approach with the appropriate scope of consideration when evaluating environmental impacts. If the alternatives with equivalent traffic capacity are evaluated solely based on the embodied carbon reflected on the EPD for the geogrid added to the design, the result would be an inaccurate comparison. Even if the environmental impacts of the entire project are correctly calculated separately, the failure to consider design alternatives on an equivalent basis will yield results which are not optimized.

The pavement section using an MSL design without a reduction in aggregate thickness demonstrates an additional aspect to be considered beyond the limited analysis presented here: depending on the density of the traffic loading for the road, the increase in traffic capacity will translate into an extension of the time period between maintenance events, such as resurfacing the road by milling the asphalt surface and installing a new overlay. Each maintenance event saved will result in additional environmental benefit, while the geogrid contributes no additional GWP (except for very small effects at end of life as discussed below). A more complete LCA for the project, with a cradle-to-grave system boundary, could quantify this benefit.

It should also be noted that the specific case of a flexible pavement section with a geogrid stabilized aggregate layer includes materials whose GWP and other impacts varies across the complete life cycle of the project. For example, asphalt cement concrete and aggregate base material are likely to be at least partially recycled at the end of the project’s life, while geogrid is more likely to be left in place or disposed of in a landfill. (The assumption used in the geogrid EPD in this case is that 20% of the geogrid would be disposed in a landfill, 10% would be reclaimed as part of reclaimed aggregate, and 70% would be left in place.) A properly designed asphalt pavement, i.e. one that does not experience base failure even at the end of its useful life, would not require recycling or disposal of geogrid used for aggregate stabilization, and therefore the geogrid would not contribute additional GWP at the end of life for the pavement. However, roads are sometimes reconfigured or expanded from their original design, which may necessitate the removal of the geogrid. The end of life fate of the geogrid would be extremely unlikely to change the design decision to use an MSL, due to the large difference between the GWP of the geogrid and that of the conventional materials, but a comprehensive LCA would quantify such considerations and allow a more precise analysis.

It should also be noted that civil engineering design and construction are categorically different from most areas where the analysis of GWP and other environmental impacts are applied, in that the consequences of a failure are potentially catastrophic. The incorporation of environmental analysis in design must include the proper understanding and assessment of the relative risks involved. The first responsibility in civil engineering and construction must be to the safety and well-being of the public who will be directly affected by the project. Consideration of more diffuse risks with lower levels of certainty must come on top of, not in lieu of, good engineering and construction practice.

When comparing the environmental impacts of alternative designs, the scope of consideration for the analysis should match the scope of the designs: in other words, the designer should conduct the environmental analysis such that the material and energy inputs encompass all the parameters which are included in the design analysis. There are many instances where the same design objective may be achieved using completely different approaches. Matching the scope of consideration for environmental impacts to the design scope and considering the entire system are necessary to ensure that all the complexities of the designs are fully captured.

5 CONCLUSIONS

The analysis presented herein demonstrates that the use of an MSL pavement design provides a significant sustainability benefit for pavements with equivalent traffic capacity.

In the first example scenario, the MSL design delivers a 16% increase in traffic capacity, while reducing GWP by 62 tonnes CO_2e per linear kilometer of the 10 meter wide section. Assuming 5 meter wide lanes, the savings would thus be 124 tonnes CO_2e per lane-kilometer.

In the second example scenario, the use of an MSL to provide increased traffic capacity compares favorably to increasing the thickness of the asphalt cement concrete layer. The MSL design is likely to be more cost efficient, but even where material costs are extremely low, the reduction in GWP as compared to the thicker conventional section is significant, delivering a reduction of approximately 30 percent through the completion of construction, with increased savings over the lifespan of the road.

The principle demonstrated here is broadly applicable to the analysis of alternative designs, materials, and products in all types of construction. As processes for the assessment of environmental impacts continue to evolve, it will be critical for both the engineering community and governing agencies to ensure that these analyses are conducted in a comprehensive and technically sound manner, including an appropriate scope of consideration. One of the most important challenges will be to create Product Category Rules for the EPDs of construction products and systems which support the use of a proper scope of consideration in Life Cycle Analysis.

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