EFFECTS OF SUBGRADE-COMPACTION MOISTURE CONTENT ON PERFORMANCE OF THE ASPHALT ROADS IN MINNESOTA

Undergraduate Research Opportunity Program Final Report

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Introduction

Roadway pavements consist of several layers, each with specific properties that contribute to the overall performance. According to the Minnesota Department of Transportation (MnDOT) Pavement Design Manual, a pavement structure consists of different layer categories: the surface layer, aggregate base layer, subbase layer, and subgrade layer. Figure 1, taken from the pavement design manual, depicts the general structure of a road section [1].

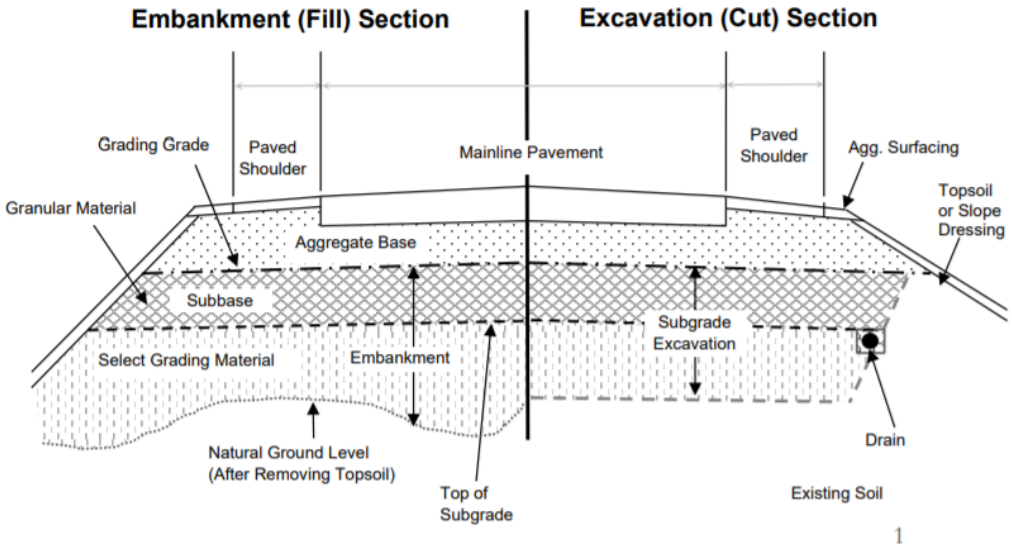

Figure 1. MnDOT Typical Pavement Section [1]

The subgrade layer is the bottommost layer in a road section and consists of natural soil. The subgrade is the in-situ material upon which the entire pavement structure rests [2]. Unlike the aggregate base and subbase, the subgrade is the existing natural soil, often compacted or treated with stabilizers. Although there is a tendency to only study pavement performance in terms of pavement mix design and pavement layers closer to the surface, the subgrade can also have influence on how well a pavement performs [2].

Subgrade load bearing capacity and volume changes are important parameters that can be compromised by the presence of excess moisture in a soil [2]. Moisture Content, sometimes referred to as water content, is one of the most common soil parameters. It is a measure of how much moisture is in a soil and can be calculated as the ratio of weight of water to weight of soils in a sample [3]. Optimum Moisture Content (OMC) is the water content at which the soil can be compacted to its densest state [3]. Subgrade soil is compacted during construction at or near the OMC. However, the moisture content changes over time and eventually reaches a certain equilibrium moisture level. This new water content can be greater or less than the OMC [4].

The moisture in the soil directly influences the subgrade density. Density measurements are an effective way to measure how well a sample is compacted and therefore how well it will support loads. For a given amount of energy applied through compaction, the maximum dry unit weight of a soil can only be attained when the soil is compacted at its OMC. Figure 2 displays the common shape of soil compaction curves at different compaction energy [5].

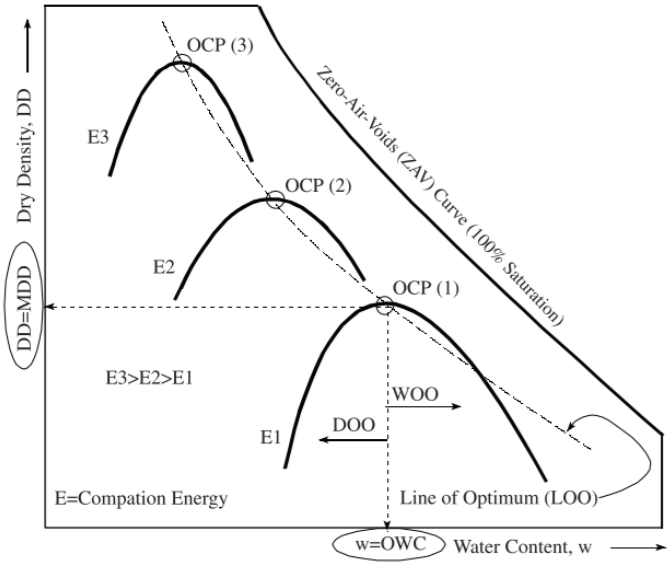

Figure 2. Typical Soil Compaction Curves [5]

From Figure 2, it can also be easily seen that a change in moisture will affect the density of a soil. The American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures insists that any set of specifications for compaction of roadbed soils should include a density requirement and soil density should be monitored during construction [6]. Compaction is necessary to improve a material's engineering properties such as load-bearing capacity, stability, stiffness, volume change characteristics, resistance to settlement, and frost damage [1].

In this work, the influence of subgrade-compaction moisture content was studied on a variety of typical road cross-sections that are seen in Minnesota. Using the pavement design software used by the MnDOT, MnPave [7], and a mechanistic empirical pavement modeling software known as KENPAVE [8], an experiment was devised to determine if changes in subgrade moisture content have an influence on the design life of roads. The following sections include a description of the methodology of the study, results, and an interpretation of the results.

Methodology

To test the influence of subgrade moisture content on the performance of asphalt roads, six different hypothetical road cross-sections were designed based on the types of roads commonly seen in Minnesota. Road 1 was modeled after metropolitan interstates and state highways, Road 2 was designed to simulate rural interstates, Road 3 is an example of rural state and county highways, Road 4 exemplifies community streets, Road 5 was designed after lightly traveled city streets, and Road 6 was designed to be an average cross-section so it could be used as a representation of standard Minnesota roads. Traffic data from the MnDOT's traffic and forecasting maps was used to determine the Annual Average Daily Traffic (AADT) for each hypothetical road [9]. The MnDOT's Equivalent Standard Axle Load (ESAL) calculator was used to derive the volume of 20-year design ESALs each cross-section would experience [10]. Table 1 summarizes the data used to model the six cross-sections designed.

Table 1. Designed Cross-Sections

Road Design	AADT	Example	20 Year Design ESALs
Road #1	100,000	Urban Interstates/State Highways	13,000,000
Road #2	10,000	Rural Interstates	3,500,000
Road #3	1,000	Rural State Highways/County Highways	334,000
Road #4	100	Community Streets	11,000
Road #5	10	Lightly Traveled City Streets	1,000
Road #6	8,000	Representative Average Road	1,500,000

The MnDOT has its own software to create road cross-sections to meet design criteria. For flexible pavements, the MnDOT utilizes its MnPAVE software. That same software was used to create realistic cross-sections for each road. Figure 3 displays the design output for Road #1.

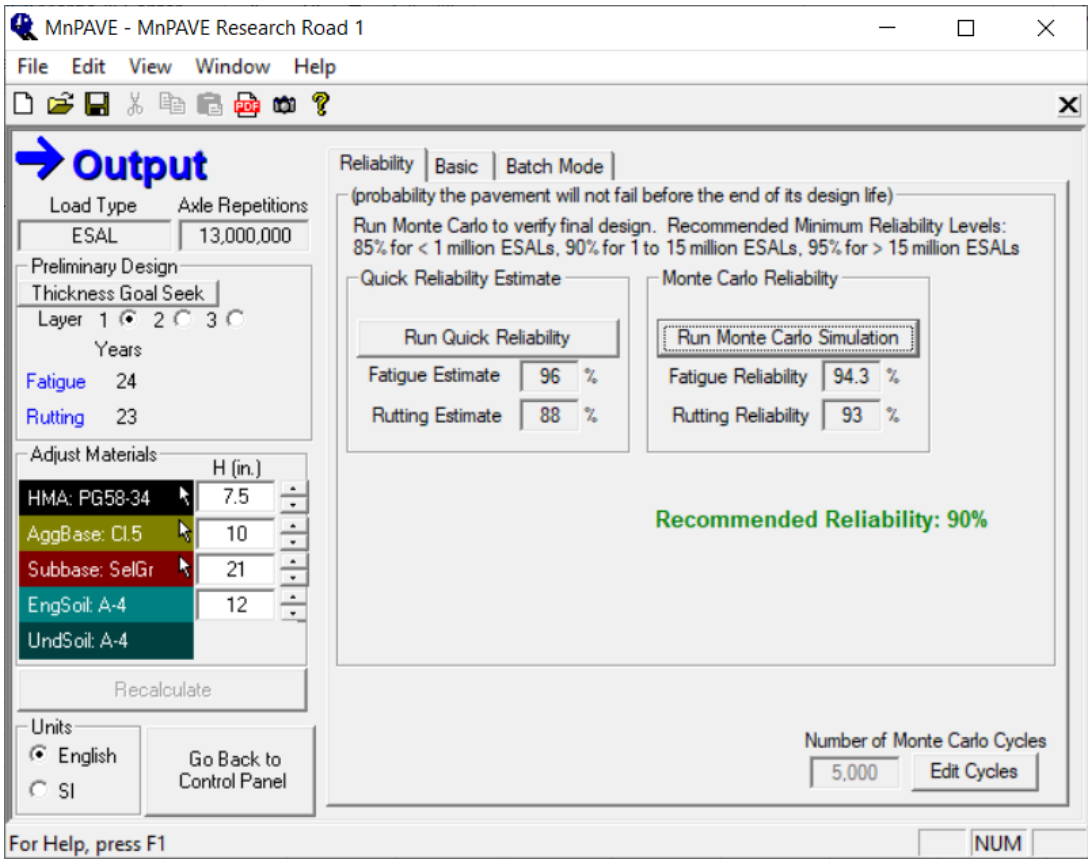

Figure 3. Design Output Cross-Section for Road #1 [7]

The MnPAVE design for each road cross-section resulted in the layer thicknesses shown in Table 2. The surface layer utilizes the PG58-34 binder that is used on most Minnesota roads. The base and subbase layers were designed using the MnDOT's Class 5 gravel and Select Granular sand respectively since these are typical materials used in Minnesota roads. The AASHTO soil classification of A-4 was selected for subgrade soil because this class can include some sandy, clayey, and silty soils [11]. Subgrade soil in Minnesota is inconsistent so a classification that includes a variety of soil types is appropriate [12]. The top 12 inches of subgrade was designed to be compacted where needed. The subgrade layer does not have a layer thickness because the layer is considered to extend to bedrock. The MnDOT has requirements for minimum layer thicknesses that were followed in the design [7].

Table 2. Road Cross-Section Designs

Road Design	Pavement (HMA PG58-34)	Base (Class 5)	Subbase (Select Granular)	Compacted Subgrade (A-4 soil)	Subgrade (A-4 soil)
Road #1	7.5"	10.0"	21.0"	12.0"	infinite
Road #2	5.0"	8.0"	15.0"	12.0"	infinite
Road #3	4.2"	4.0"	4.0"	12.0"	infinite
Road #4	3.1"	3.0"	-	-	infinite
Road #5	3.1"	3.0"	-	-	infinite
Road #6	4.5"	5.5"	10.5"	12.0"	infinite

After the cross-sections were designed, they were analyzed using KENPAVE simulations. KENPAVE is a mechanistic empirical pavement modeling software that provides the design life of a road based on the properties of each pavement layer and the traffic load. Three simulations were carried out on each road. The first test represented a subgrade at optimum moisture content and therefore maximum strength. The second and third test represent a 2.5% and 5.0% increase in moisture content in the subgrade layer respectively. The Li and Selig Model for fine grained subgrade soil shown in Equation 1 was used to adjust the strength of the subgrade layer appropriately based on these changes in moisture content [13].

$\frac{M_R}{M_{R(opt)}} = 0.98 - 0.28 \cdot (w - w_{opt}) + 0.029 \cdot (w - w_{opt})^2$	Equation 1. [13]

The layer property inputs and the traffic inputs for the simulations are provided in Table 3. The selected resilient modulus for each layer was approximated based on representative materials similar to the MnDOT design materials during the middle of their design life [11]. The traffic inputs are based on a standard ESAL.

Table 3. Layer Property Inputs

Hot Mix Asphalt Pavement Resilient Modulus	300,000 psi
Base Resilient Modulus	50,000 psi
Subbase Resilient Modulus	25,000 psi
Optimum Compacted Subgrade Resilient Modulus	17,500 psi
2.5% Moisture Increase Compacted Subgrade Resilient Modulus	8,071 psi
5.0% Moisture Increase Compacted Subgrade Resilient Modulus	5,337 psi
Optimum Subgrade Resilient Modulus	9,000 psi
2.5% Moisture Increase Subgrade Resilient Modulus	4,151 psi
5.0% Moisture Increase Subgrade Resilient Modulus	2,745 psi
Poisson's Ratio for HMA and Granular Layers	0.35
Poisson's Ratio for Subgrade Layers	0.45
Load per Axle	18,000 lb
Load per Tire	4,500 lb
Contact Pressure per Tire	95 psi
Center to Center Spacing Between Dual Tires	13.25 in

Results

KENPAVE testing resulted in an outputs damage ratio and design life for each hypothetical cross-section. Figure 4 shows the KENPAVE output from the test of Cross-Section #1 with the subgrade at optimum moisture content.

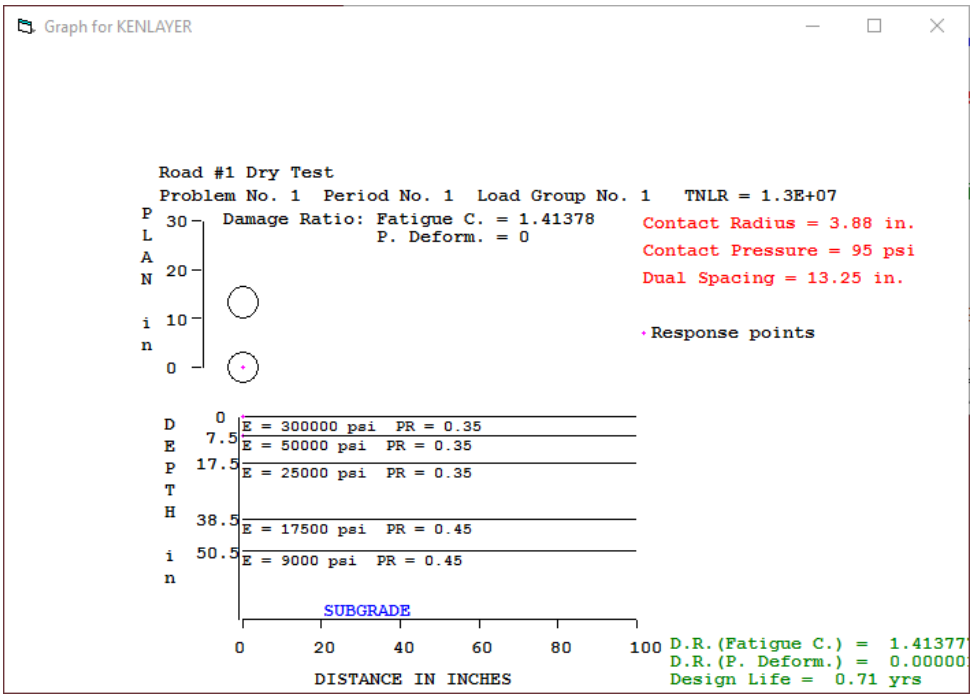

Figure 4. Example KENPAVE Output

After running the series of three simulations for each designed road, the data was plotted on figures for interpretation. Since the quality of subgrade preparation on construction sites is typically measured by relative compaction, the increase in moisture content was converted to a corresponding decrease in relative compaction using the Indiana Department of Transportation typical moisture density curves [14]. The optimum moisture content subgrades correspond to a 100% relative compaction, the 2.5% increase in moisture content corresponds to a relative compaction of 98%, and the 5.0% increase in moisture content corresponds to a relative compaction of 96% [14]. Plots were made for each road that show damage and design life as a function of the increase in moisture or decrease in relative compaction. It is important to note the road cross-sections designed by the MnDOT were created based on a 20-year design life that includes the harsh Minnesota climate. However, KENPAVE does not factor climate into damage and design life calculations. For this reason, cross-sections that were designed to have light traffic in MnPAVE will yield unrealistic design lives since climate was the limiting factor in their design. By contrast, cross-sections that were designed in MnPAVE to experience a lot of traffic will display more realistic KENPAVE design lives since traffic is the factor that limits the design. The results for each road cross-section except for Road #2 are included below. The data from Road #2 is an outlier and non-representative of the data set.

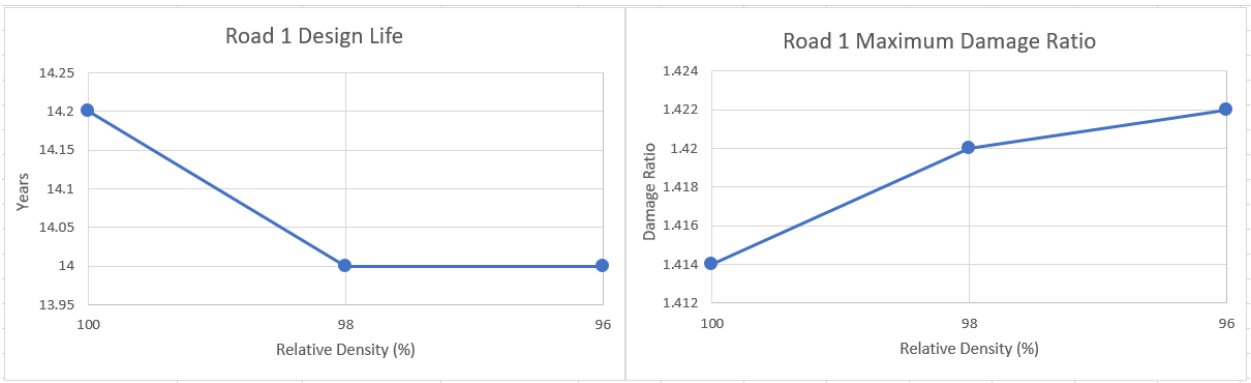

Figure 5. Predicted Pavement Life and Damage Ratio for Cross-Section #1

Figure 6. Predicted Pavement Life and Damage Ratio for Cross-Section #3

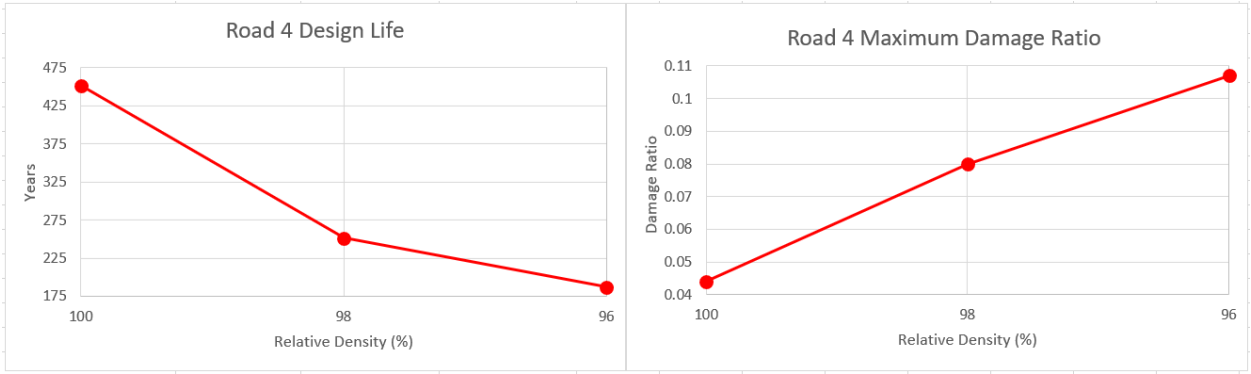

Figure 7. Predicted Pavement Life and Damage Ratio for Cross-Section #4

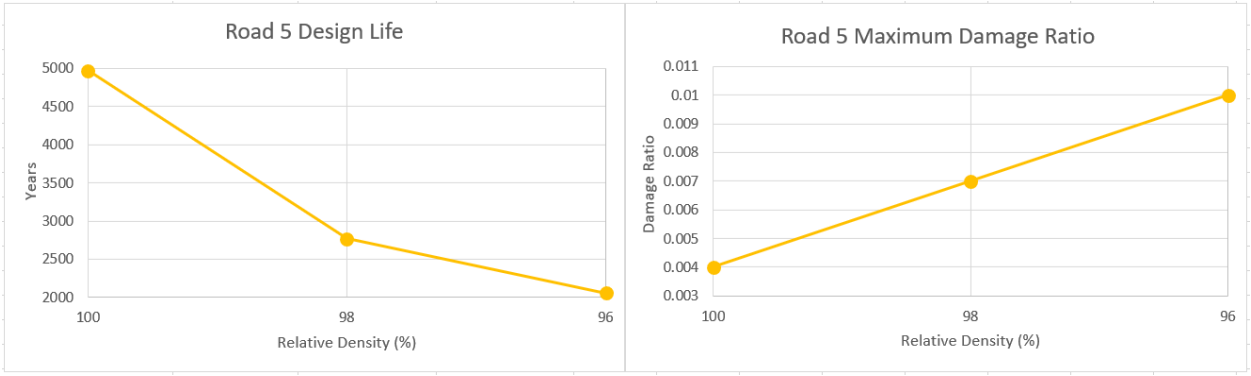

Figure 8. Predicted Pavement Life and Damage Ratio for Cross-Section #5

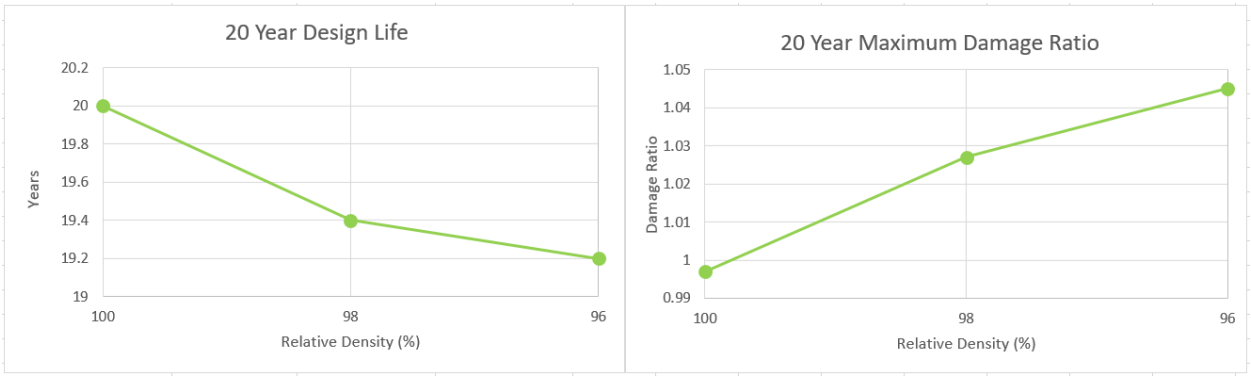

Figure 9. Predicted Pavement Life and Damage Ratio for Cross-Section #6

While the change in design life and damage ratio varies greatly depending on the type of road, the general trend is constant across all cross-sections. Design life appears to drop as subgrade moisture increases, even by a few percentage points. As the subgrade moisture content continues to increase, so does the design life, albeit by a slower rate. This same trend can be seen in the pavement damage ratio. As moisture increases, so too does the damage ratio. While the Li and Selig model only allows for moisture adjustments covered in the scope of this study, it is reasonable to assume that a moisture increase of larger than 5% would have an even more damaging effect on road performance [13]. For Cross-Section #6 which was designed to be an average of the other five roads examined and was created to have a KENPAVE design life of exactly 20 years at optimum moisture content, a 5% increase in moisture content of the subgrade soil decreases the road design life by nearly the same 5%.

This experiment does not examine the potential effects of Minnesota's harsh climate on the additional moisture beyond the optimum amount in the subgrade. Excess moisture in the subgrade could induce a more rapid decline in design life due to freeze-thaw cycles that can cause the road to expand and contract. Even without the inclusion of weather in this model, it is clear an increase in moisture content or a decrease in relative density negatively impacts the performance of roads in Minnesota.

Interpretation of Results

The state of Minnesota, like most of the United States is dealing with aging infrastructure that is long overdue for renovation. Minnesota's roads are no exception to this growing issue. The American Society of Civil Engineers recently gave Minnesota roads a D+ grade [14]. To compound this problem, funding for road construction is often limited and designing pavement cross-sections that can handle the harsh Minnesota climate is difficult. To maximize return on highway project investments and to make sure roads achieve their target design lives, every factor that influences driving surface performance must be fully understood. While research on pavement is common, projects that seek to understand how the existing subgrade soil influence pavement design life are less common. The lack of quantitative knowledge on this topic is evident in the road design literature used in the industry. The MnDOT Pavement Design Manual states, "Any construction beneath the aggregate base and subbase is at the discretion of the District Materials/Soil Engineer [1]." This research that identifies moisture in the subgrade as a factor in determining pavement design life proves that subgrade moisture during and after construction is influential. This means that pavement design programs that assume the strength of the subgrade layer remains constant during a road's lifetime must also assume that the layer's moisture content remains constant. Those assumptions are unlikely in Minnesota where groundwater, precipitation, and seasonal cycles vary dramatically [12]. In the future, Minnesota should ensure in depth subgrade investigations occur on all road reconstruction and new construction projects. Additionally, design programs should be sure to model how the moisture level in the subgrade at construction and during the life of the road will influence the pavement's performance.

Conclusion

To study the importance of excess moisture in the subgrade layer of Minnesota roads, a series of simulations was implemented. Six example road cross-sections were designed using MnPAVE to exemplify the variety of roads built in Minnesota. Each cross-section was subject to a set of three KENPAVE simulations. The first test featured the subgrade layer at optimum moisture content, the second test was implemented with an increase in subgrade moisture content of 2.5% and the final test included a 5.0% increase in subgrade moisture content. The Li and Selig model was used to predict the resilient modulus values for each moisture adjustment for each KENPAVE simulation. A similar pattern of increasing damage and decreasing design life developed for all test road cross-sections. While the nature of this experiment cannot quantify the decrease in pavement life due to an increase in moisture content, it can definitively say that driving surface performance decreases as a result of a subgrade moisture increase. Moving forward, Minnesota design agencies that are not considering subgrade moisture when specifying construction standards should look to do so. Additionally, research should be implemented to identify if subgrade moisture is changing over time in road subgrades. This issue should be considered in all new construction and reconstruction road projects in Minnesota to maximize investment in Minnesota transportation.

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