# *Moisture Content Fluctuation in Minnesota Road Subgrades*

by Matthew Henderson

**Abstract**: Fluctuation in subgrade moisture content of road subgrades is known to reduce the quality and lifespan of the driving surface. This paper examines possible specific sources of moisture fluctuation in subgrade soils. Groundwater, precipitation, and seasonal cycles are all investigated to determine their influence on long term and continuous moisture fluctuations. While precipitation's impact is minimal and probably only affects small continuous water variations, groundwater can greatly change subgrade moisture. The freezing and thawing experienced in cold climates appear to have the most destructive impact on driving surfaces. Minnesota offers an environment where all the possible factors discussed in this paper are abundant. Additionally, Minnesota's soil makes it particularly vulnerable to subgrade moisture problems. Minnesota's roads are in desperate need of renovation and developing a method to account for subgrade moisture variations could save time and money. Future testing is recommended to determine if a thicker road section would be worth the additional cost to protect roads against subgrade moisture variation.

## Introduction

*Overview of the Problem*

There are several likely sources of moisture underneath roadways. Each potential source manifests as a possible design challenge for civil engineers because subgrade moisture is detrimental to the long-term performance of the driving surface. The degree to which a subgrade's water content changes dictates the level of importance that design consideration should receive. However, there is some disagreement in the industry over which possible sources of subgrade moisture are important and which possible sources can be neglected. The importance of subgrade moisture design considerations will change depending upon the road's location. In the state of Minnesota, the volatility of many potential subgrade water sources makes uncovering their importance in design a priority. If the source of fluctuation in subgrade moisture content can be determined, it could increase the life of Minnesota roads. Additionally, if a cost-effective solution to premature road deterioration could be found, time and money could be saved while Minnesota struggles to renovate its crumbling transportation network.

*Background Information*

Underneath every road's driving surface are several layers of soil, each with specific properties that contribute to the desired overall performance. The Minnesota Department of Transportation (MnDOT) Pavement Design Manual breaks these sheets of soil into three main categories: the aggregate base layer, the subbase layer, and the subgrade layer. Figure 1, taken from the pavement design manual, depicts the general structure of a road section [1].

The aggregate base is the soil immediately underneath the asphalt or concrete driving surface. Typically, the aggregate base consists of class 5 or class 6 densely-graded gravels with large aggregates. Desired properties of the aggregate base include

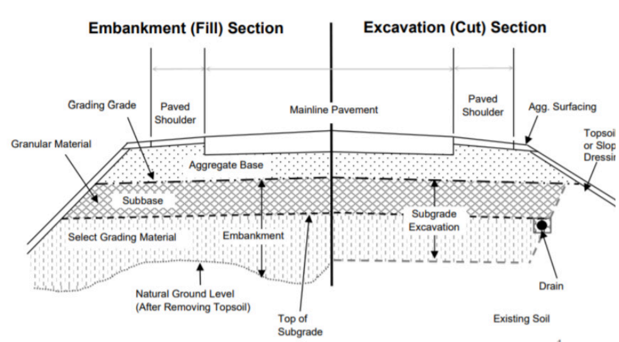


**Figure 1.** MnDOT Typical Road Section [1]

a construction platform for paving, a filter layer, resistance to frost heave, and resistance to the effects of moisture. The same design manual describes a road subbase as the layer of granular, sand or gravel, material beneath the aggregate base. The subbase is usually made of granular or select granular material. Its primary purpose is to help resist frost heave and improve moisture properties [1]. The subgrade layer is the bottommost sheet of soil in a road section. 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 sometimes a tendency to only study pavement performance in terms of pavement mix design and road section, the subgrade can have great influence on how well a pavement performs [2].

Because compacted soil in a road subgrade is often sensitive to moisture, moisture in the subgrade has long been considered important in pavement design [3]. 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 soil and can be calculated as the ratio of weight of water to weight of soils in a sample [4]. Optimum moisture content (OMC) is the water content at which the soil can be compacted to its densest state [4]. Subgrade soil is compacted during construction at 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 [5].

The moisture of a soil is directly related to the density of a soil. 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 reaches its OMC. Figure 2 displays the common shape of soil compaction curves [6].

From Figure 2, it can be easily seen that a change in moisture will affect the density of a soil. The American Association of State Highway and

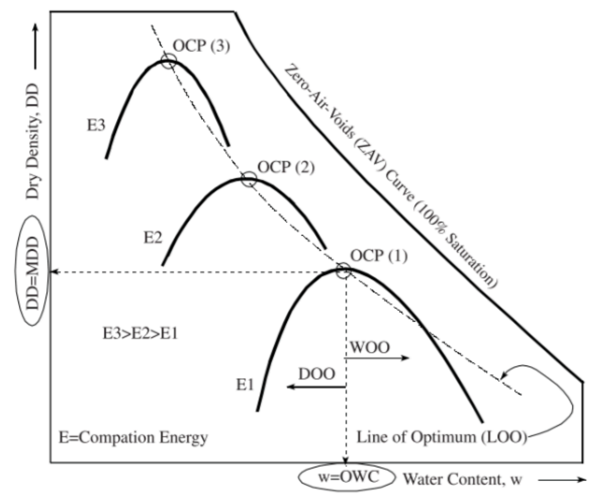


**Figure 2.** Typical Soil Compaction Curves [6]

Transportation Officials (AASHTO) Guide for Design of Pavement Structures recommends that any set of specifications for compaction of roadbed soils should include a density requirement and soil density should be monitored during construction [7]. 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].

*Effects of Subgrade Moisture Issues*

The moisture content and density of a subgrade are crucial factors in the lifetime performance of a road. Moisture underneath pavement sections can be measured to estimate the mechanistic properties of unbound soil layers, which affect pavement performances during the service period [5]. Excess subsurface water reduces the strength of the soil which may cause pavement cracking, rutting, deterioration of existing pavement cracks and joints, and frost heave [1].

The detrimental effects of excess subgrade moisture are universal and well documented. Many studies have been performed to test the correlation between a soil's strength and its water content. Lab tests have concluded that the resilient modulus of all classes of unsaturated granular materials decreased to some extent with an increase in moisture content [8]. However, the extent to which moisture can influence a soil depends on its classification. Edris and Lytton concluded that the dynamic properties of fine-grained subgrade materials, silts and clays, depend strongly on factors that control moisture such as climate [9]. Bayomy and Salem agreed that the magnitude of the increase in resilient modulus in compacted subgrade materials depends on composition, the amount of silt and clay-sized particles in the soil, as well as the water content [8]. Hicks and Monismith concurred even in coarse-grained gravels and sand, clean materials (e.g., well-graded gravel, poorly-graded gravel, well-graded sand, poorly-graded sand) are not likely to exhibit the same degree of moisture sensitivity as a soil with more fines [10]. By definition, fines are soils that pass through a #200 sieve [4]. Clay and silt particles are often small enough to pass as fines while coarse soils like sand and gravel are usually larger. The problem of moisture prematurely deteriorating roadways in not uncommon. The AASHTO Guide for Design of Pavement Structures states that distress in pavements is often caused or accelerated by the presence of moisture in the pavement section [7].

Since the numerous problems associated with subgrade moisture are so well researched, it would be reasonable to assume that it is a primary consideration during road section design. However, this is not always the case. Bae et al. claim that even though it has been agreed that environmental factors such as moisture content in the subgrade greatly affect pavement performance, the quantitative effects on pavement performance have not been well documented [3]. 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]. The AASHTO Guide for Design of Pavement Structures also offers an ambiguous stance on the topic. It suggests design thickness for pavement thickness and aggregate base depth but does not specify how the design thickness of each layer should depend on subgrade conditions. In fact, the guide suggests that local knowledge and experience should take precedence over the outlined requirements [7]. The vague and imprecise language surrounding the importance of subgrade moisture can be a source of disagreement on a construction site which can cause delays in the building process.

If factors that affect subgrade moisture were better understood, they could be considered in the design process and subsequently help engineer better roads. Currently, during subgrade construction, soil is compacted at OMC to approximately the maximum dry density [5]. However, questions abound as to whether that standard process is enough to ensure moisture issues will not arise. As Bayomy and Salem remind us, it is well known that certain environmental changes accelerate pavement deterioration [8]. If these specific environmental changes could be quantitatively accounted for, roads could last longer and perform better over their lifetime. This research would be particularly important in Minnesota, given that the American Society of Civil Engineers recently gave its roads a D+ grade [11]. In this paper, several important factors that could influence subgrade moisture will be addressed to quantify how each one contributes to driving surface failure in Minnesota.

**Factors That Influence Subgrade Moisture Content**

*Deviation in Moisture from OMC to Equilibrium Moisture*

After a road has been built, the moisture in the subgrade does not remain at the OMC that it was compacted at. On the contrary, the water content will migrate towards equilibrium moisture [3], [5], [8], [12]. In a previous study by Bae and Stoffels, equilibrium moisture content (EMC) varied from 20 percent wetter to 15 percent dryer than the soil's OMC [5]. Bayomy and Salem concluded that although fluctuations in subgrade moisture continue over time, the EMC is usually reached within five years of construction [8]. The subsequent water variations occur on a smaller scale. While some argue continual moisture changes only fluctuate by 1 percent, others claim fluctuations can vary up to 10 percent [5], [8]. It is possible that any change in moisture in the subgrade could have consequences for the road. These two different categories of moisture variation, the initial change from OMC to EMC and the smaller continuous changes that last indefinitely, will both be examined in this paper. Unfortunately, no comprehensive consensus currently exists regarding how much moisture content variation is enough to compromise the road's condition. Groundwater, precipitation, and seasonal cycles are three of the possible causes of moisture fluctuation.

*Groundwater*

Groundwater level has long been considered a major factor in determining subgrade moisture [5]. Water can easily enter a road section as groundwater from an interrupted aquifer, high water table, or a localized spring [7]. However, groundwater can affect soil that is not in direct contact with the moisture through capillarity. Capillarity is the upward movement of water in soil due to surface tension and it can allow groundwater to rise well above the groundwater table [4]. To account for this, there must be a safe distance from the top of a road subgrade to the water table. Studies conducted by Russam as well as Yoder and Witczak reported that the effects of the groundwater table on soil saturation are significant when the water table is roughly less than 6 m below the top of the subgrade [13], [14]. Since groundwater levels remain relatively stable over time, it is likely that groundwater contributes minimally to the continuous moisture fluctuation that go on indefinitely in subgrades. However, there is general agreement that groundwater could be a key source that directs a subgrade's change from OMC to EMC after construction.

*Precipitation*

In addition to groundwater, precipitation is frequently viewed as a potential source of moisture for subgrade soils [5]. While precipitation seems like an obvious contributor to water fluctuation, there are many studies that argue the contrary. Many studies have found the correlation between precipitation and subgrade moisture to be minimal or non-existent [12], [15], [16], [17]. One study by Rainwater et al. interestingly found that precipitation affects the unbound aggregate base layer, but the excess moisture dissipated before reaching the subgrade level [17]. Another experiment found that when average rainfall increased, the moisture content also rose but when the rainfall dropped, the moisture did not drop suddenly. These findings point more towards seasonal factors than towards precipitation's influence [8]. Since the bottom of a road section is deep beneath the ground, it makes sense that factors like groundwater would have more of an effect on subgrade water content [5]. If precipitation did influence moisture content, it is likely that it would only affect the smaller continuous fluctuations and not the trend towards an EMC.

*Seasonal Cycles*

Like groundwater and precipitation, seasonal conditions have been studied as possible influencers of subgrade conditions. Studies have been able to make many connections between seasonal cycles and subgrade moisture content. The most significant factors are the freeze/thaw cycles that can affect soil. According to Bayomy and Salem, the freezing of soil moisture can transform a soft subgrade into a rigid material while thawing the material can produce a softening effect such that for some time after thawing, the material has a resilient modulus that is only a fraction of its pre-freezing value [8]. This point is reinforced in a study by Bae et al. that concluded the moisture value decreased when frost action occurred in winter while nonfreezing sites showed less seasonal variation [3]. When spring thaw occurs, moisture moves back into the subgrade and can cause failure. In a study, White and Coree discovered that 60% of AASHTO road test failures occurred during the spring season [18]. Bayomy and Salem looked into the specific issues caused by spring thawing and found that structural ruts in roads were the result of permanent deformation occurring in the section layers and subgrade. The study concluded these ruts evolve rapidly during spring when the pavement structure is weakened by excessive moisture released from thawing soils [8].

Fine soils, while often experiencing less change in moisture due to lower hydraulic conductivity values, are more affected by freeze/thaw cycles. Frost susceptible soils have pore sizes that promote capillary rise which facilitates the growth of frost lenses. Therefore, the amount of fines in a subgrade is an important factor in determining its frost susceptibility [1]. One study by Bergen and Monismith focused on observing freezing and thawing in a clay subgrade to discern how fine soils handle the seasonal cycles. In the clay subgrades, they found the variation in resilient modulus of the clay after one freeze/thaw cycle to be 52 to 60 percent of the initial value [19]. From these studies, it can be determined that much of the fluctuation in subgrade moisture is attributed to seasonal changes. Bae et al. claim that seasonal variation of moisture can be the dominant factor in evaluating pavement roughness progression for sites that experience freezing [3]. Bayomy and Salem even claim that the combination of freezing/thawing temperatures in moist pavement subgrade soils can cause more severe effects than the effects of any other water content change [8]. Seasonal cycles might contribute to the subgrade's transition to EMC and it can be concluded that they are a driving force behind the continuous moisture fluctuations.

**Subgrade Moisture Fluctuation Implications for Minnesota**

*Groundwater in Minnesota*

All of the aforementioned factors that can influence subgrade moisture should especially be considered in Minnesota. For starters, the "Land of 10,000 Lakes" not only has access to an abundance of surface water, but also an adequate amount of groundwater. Figure 3 from the Minnesota Pollution Control Agency illustrates that groundwater is present in most of the state [20]. Additionally, for about half of the state, groundwater is either readily available or available near the surface from glacial sands.

The typical depth of groundwater in Minnesota also makes it an important factor to consider. The MnDOT Pavement Design Manual calls for a minimum pavement section of 30 inches for roads with less than 7 million 20-year Bituminous Equivalent Single Axle Loads (BESALs) and 36 inches for roads with more than 7 million 20-year BESALs

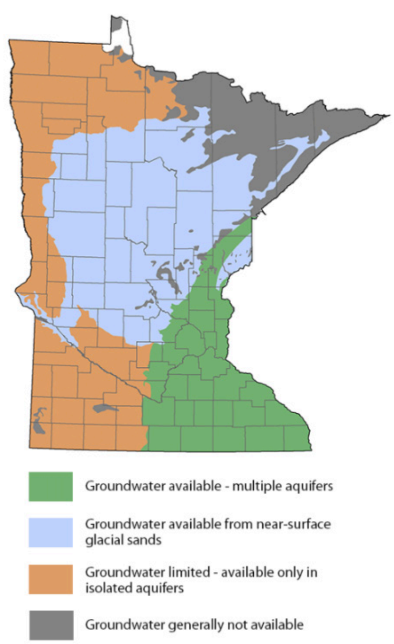


**Figure 3.** Groundwater Availability in Minnesota [20]

for new pavements [1]. A Minnesota Department of Natural Resources study found the water table elevation in the state is commonly within 10 to 30 feet of the land surface [21]. Figure 4 displays the water table elevation throughout Minnesota. In the figure, lower water table elevations are represented by dark blue colors while higher water table elevations are represented by orange. [21].

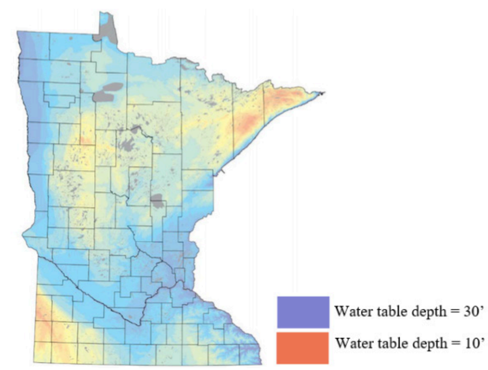


**Figure 4.** Water Table Elevation in Minnesota [21]

While 10 to 30 feet is sufficiently deep to avoid penetrating groundwater with a road section, it is important to remember that capillary action can draw moisture up great distances in fine soils. Additionally, thicker road sections than the minimum 30 to 36 inches bring the top of the subgrade even closer to the groundwater table.

*Precipitation in Minnesota*

Minnesota experiences a wide spectrum precipitation across the state. The Minnesota Department of Natural Resources map shown in Figure 5 displays this variability in annual precipitation [22].

This data confirms that there is an adequate amount of moisture precipitation to consider it a factor in road section design. Also, since annual precipitation varies greatly across the state, its importance in section design could also change depending on a road's location.

*Seasonal Cycles*

Minnesota experiences some of the most extreme seasonal cycles in the United States. Temperature range from an average low of about 0o F across the state in January to an average high of about 80o F across the state in July [23]. These extreme temperature swings are accompanied by freezes that

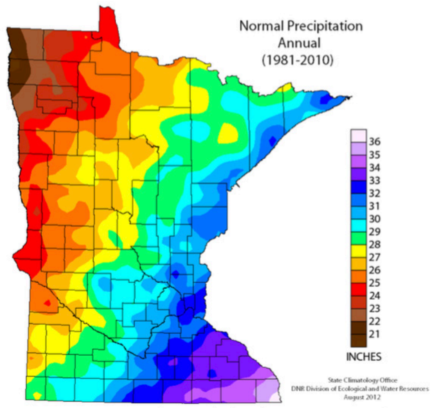


**Figure 5.** Average Annual Precipitation Across Minnesota [22]

penetrate deep underneath roads and intense thaws that produce abundant moisture. Figure 6 from the Minnesota Department of Transportation compares frost depth measurements underneath two paved roads on opposite ends of Minnesota [24].

The data shows that frost penetrates deeper and lasts longer in northern Minnesota compared to Southern Minnesota. While effects of frost might be more severe in the northern portion of the state, the maximum depth of frost achieved in the 2017-2018 winter in the southern part of the state easily surpasses the minimum depth requirements for subgrades outlined by the MnDOT Pavement Design Manual [1]. This is a real concern and indicates that seasonal variations should be considered in Minnesota road section design.

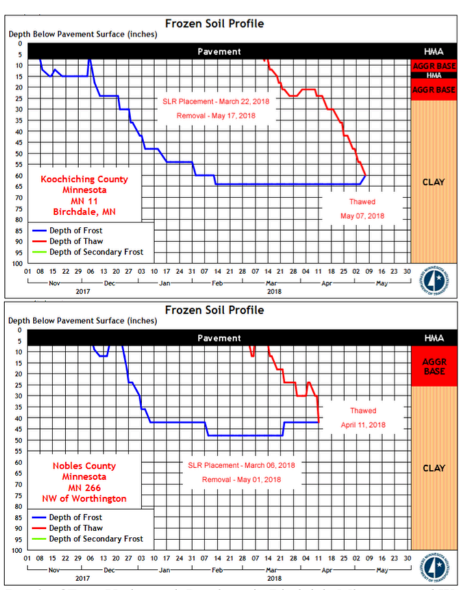


**Figure 6.** Depth of Frost Underneath Roadway in Birchdale Minnesota and Worthington Minnesota During the 2017-2018 Freeze Cycle [24]

*Typical Minnesota Subgrade Soils*

Minnesota's topsoil classifications vary considerably throughout the state. From organic material ideal for farming to permeable sandy soils, there is a lot of variety. Some engineers use topsoil surveys to examine the type of soils that will be encountered during a road construction project if excavation does not exceed five feet. At that depth, the soil is fairly homogenous to the topsoil. However, the top of soil subgrades is recommended to be a minimum of 30" below the surface and thicker sections can be even deeper [1]. Because the subgrade layer carries the loads of the road section below a depth of five feet, understanding the soils encountered at deeper depths could be crucial to better understanding how moisture fluctuations correlate to road performance.

As part of this investigation, soil boring logs were examined for all 87 counties in Minnesota. Boring soil classifications were recorded at a depth of five feet at five locations for each county. The boring locations were selected at sites throughout each county to give a survey of the county's soil. That representative data was then used to record a single generalized classification of soil at a depth of five feet for each county. It is important to note that soil conditions can vary greatly across a construction site and even more so across an area as large as a county. This study does not claim that a single soil classification is representative of an entire county but rather attempts to acquire a representative sample of soils encountered throughout the state. The soil boring data was collected from the MnDOT Electric Geotechnical Database [25]. Out of 87 counties in Minnesota, only six had generalized soil classifications at five feet deep that did not categorize the material as peat, clay, silt, or loam. This means it is likely almost all of Minnesota's roads are built on a soil that contains at least 10% fines. These widespread conclusions that implicate such a large area are made based on methods that involve imprecise qualitative assumptions. However, many counties have subgrade depth soils that contain much more than 10% fines so the argument for considering soil classification when designing a road section remains strong. As mentioned earlier, fines, such as clays and silts, retain moisture better than coarse soils and are more susceptible to the negative effects of moisture fluctuations.

**Recommendations**

While research suggests that certain factors have been more influential than others on subgrade moisture changes, they should all be considered in road section design. The conditions in Minnesota make groundwater, precipitation, and seasonal cycles all relevant design considerations. Additionally, many of the soils found in Minnesota are conducive to causing moisture issues. One way the longevity and performance of Minnesota roads could be improved is by forcing these conditions to be considered by design engineers. The current language in highway design literature is vague and might not account for all the factors related to excessive moisture damage. Thicker road sections are a proven solution to deal with problematic subgrades [3], [7]. However, these improvements come with a cost. While the specific additional costs of building a more moisture resistant road depend on many factors such as the additional depth required and project location, any added costs must always be properly justified on public infrastructure projects. More research should be conducted to see if the added costs of reducing subgrade moisture related failures would be worth it. The relationship between subgrade moisture effects and road section thickness should be further researched in hopes of providing more answers to this question.

**Conclusion**

Excessive subgrade moisture and subgrade moisture fluctuations are detrimental to the performance of a road's driving surface. Cracking, rutting, swelling, and roadway deterioration are all results of reduced strength in a road section caused by subgrade moisture. There are several factors that can contribute to a soil's change from OMC to EMC or to continuous moisture fluctuations that occur over the lifetime of a road. Groundwater level, precipitation, and seasonal freeze/thaw behavior are some of the most influential forces. Groundwater can cause changes from OMC to EMC and precipitation can influence continuous smaller changes in moisture content. Seasonal freezing and thawing are likely the biggest culprit in causing moisture related subgrade problems due to the extreme changes it produces each year. While groundwater level, precipitation, and seasonal variation are variables that should be considered throughout the United States, they are particularly relevant in the state of Minnesota. The state has many aquifers capable of influencing subgrades through capillary action. It also experiences significant annual precipitation and extreme seasonal variation. Additionally, the soils at subgrade depth throughout the state could promote the entrapment of moisture which amplifies the importance of considering how a subgrade could behave in the road section design process. Based on these findings, more research should be done to reveal if increasing the thickness of road sections would be an effective way to neutralize the problems associated with inevitable subgrade moisture fluctuations in Minnesota. Future research should examine possible solutions to help transportation and geotechnical engineers deal with the complex issue of subgrade moisture fluctuations in Minnesota.

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