Effects of Unbound Granular Materials Gradation Parameters on the Drainage Quality of Pavement Structures

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Abstract

Drainage quality, as defined by AASHTO 1993, is affected by parameters related to subsurface materials properties as well as parameters related to roadway geometry. Hydraulic conductivity (permeability) of unbound granular materials (UGM) used in base and subbase layers construction is one of the major properties that influence drainage quality. This study investigates the variations in hydraulic conductivity and drainage quality resulting from modifying UGM gradation parameters. The considered UGM gradation parameters were porosity, fines content, and effective size of the blend. Field and laboratory testing of hydraulic conductivity were performed in order to quantify the benefits gained from basing UGM blends on performance related parameters. The test results were also used to investigate the reliability of the estimated hydraulic conductivity from the Moulton prediction model.

Several dense-graded UGM gradations of gravel were evaluated in this study. Permeability field testing was carried out on those gradations in multiple highway construction projects throughout Manitoba. The field testing utilized the double ring infiltrometer test for measuring the in-situ hydraulic conductivity of compacted base layers. In addition, UGM samples from each construction project were collected for further laboratory testing of hydraulic conductivity using the rigid-wall permeameter. Results from field and laboratory testing were used to provide performance-based range of values for drainage quality corresponding to the range of UGM gradation parameters investigated in this study. The measured hydraulic conductivity values were compared to values and prediction models reported in the literature for dense-graded UGM. Moulton's hydraulic conductivity prediction model was found to provide an approximation of hydraulic conductivity values of the studied materials.

Introduction

A typical pavement structure consists of three layers being subgrade, base/subbase, and pavement surface [1, 2]. The base/subbase layer is usually constructed of unbound granular materials (UGM) for the purpose of providing structural support through load distribution, and providing sufficient drainage of water that infiltrates the pavement system from different environmental events [3]. AASHTO pavement design guide accounts for layer drainage through the drainage quality which has a direct effect on the pavement structural number and pavement performance through the drainage coefficient (Cd) for rigid pavements, and the drainage modifier (m) for flexible pavements [10]. Therefore, sub surface drainage influences layer thicknesses in design.

In pavement structures, it is well recognized that many surface distresses are related to the presence of moisture either directly or indirectly [4, 5]. For instance, if water is trapped in a pavement system, it will cause significant reduction in the shear strength of the supporting base and subgrade layers,[6, 7]. Based on Cedergren (1974), it was concluded that applying traffic loads on pavements with saturated sublayers would decrease their service life up to 10 times faster than if the same loads are applied on a pavement with well drained sublayers [8]. The effect moisture presence on pavement would be even more severe when freeze/thaw cycles are considered [9]. Therefore, decreasing maintenance costs and efforts would require more attention to drainage as a design parameter for pavement structures.

A complete pavement subsurface drainage system consists of:

- Permeable aggregate base/subbase
- Longitudinal drains
- Transverse outlets or daylighting

This study focuses on the effect of UGM properties on the quality of subsurface drainage in pavement structures.

Quantifying Subsurface Drainage

One way of enhancing pavement drainage quality is to improve the characteristics of base materials by using engineered UGM blends. The engineered UGM blends shall provide good drainage through interconnected voids, while maintaining proper structural stability through stone-on-stone contact. According to AASHTO 1993 design guide, the drainage quality of a layer is determined using the drainage time parameter (t) which is defined as the time required to drain 50% of the free moisture in a given pavement system at saturation conditions, [10]. The drainage time parameter is influenced by the geometrics of the pavement structure as well as the material properties of the layer of interest.

Table 1 Quantification of drainage quality [10]**.**

Quality of Drainage	Time to Drain
Excellent	2 hrs
Good	1 day
Fair	7 days
Poor	1 month
Very poor	Does not drain

Drainage time in days can be calculated by using equation (1), where $\boldsymbol{T}$ is a time factor that accounts for the structure's geometry and $\boldsymbol{m}$ is a material factor that accounts for base/subbase material and gradation.

$$\boldsymbol{t = T * m * 24} \qquad (1)$$

The time factor T is determined based on the slope factor from the nomograph in Figure 1. The slope factor in the nomograph is calculated from equation (2), where S_R and L_R are the resultant slope and resultant flow path respectively and **H** is the base thickness in feet.

$$S_1 = \frac{L_R * S_R}{H} \quad (2)$$

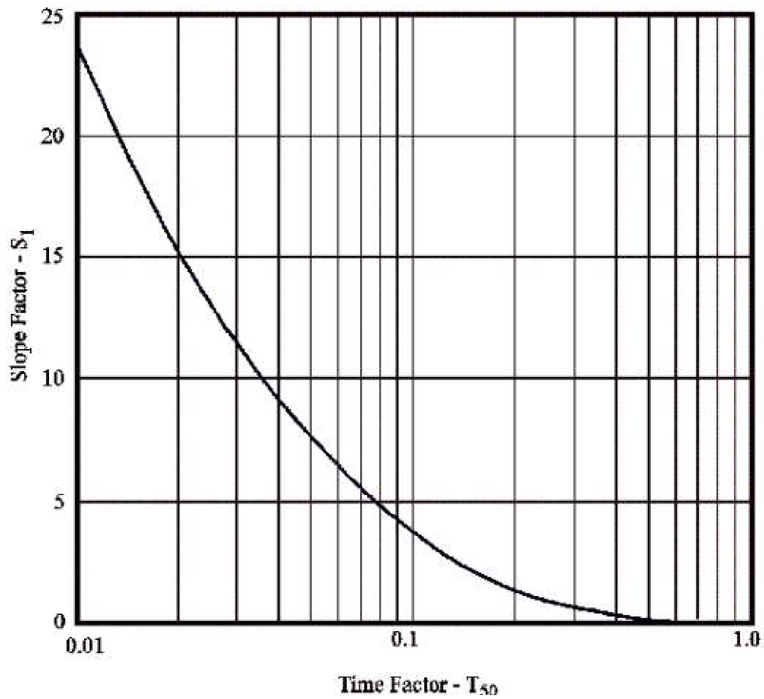

Figure 1 Time factor for %50 drainage [14]

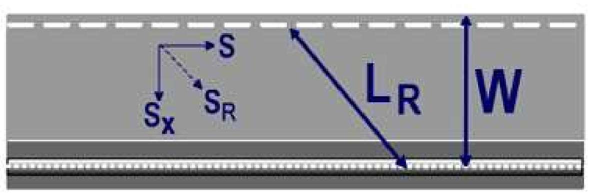

Figure 2 Pavement geometry parameters, (Plan view of a typical pavement surface)

The material factor m is calculated from equation (3), where N_e is the effective porosity, and K is the hydraulic conductivity of the base layer. The effective porosity is a measure of the pores ability to drain water. In other words, a granular material with high effective porosity is more capable of storing water than of draining it under the effect of gravity. The effective porosity is influenced by material properties including void ratio, gradation, and type of coarse and fine materials.

$$m = \frac{N_e * L_R^2}{K * H} \quad (3)$$

Hydraulic Conductivity Prediction Models

Since drainage is a significant factor in pavement performance, it is beneficial to be included in the design process. However, measuring the hydraulic conductivity of UGM for a specific project after the UGM is crushed and produced can not be considered as an effective design practice. Therefore, relying on a reliable prediction model for hydraulic conductivity is a better design practice.

The Moulton model was developed in 1980 and was based on a statistical analysis of material properties on a large sample size [15]. The result of such analysis showed that effective size (D_{10}), porosity (N), and fines content (P_{200}) explained over %91 in the variation in hydraulic conductivity. The model that best fit that data was presented by Moulton as shown in equation (4), where **K** is in units of ft/day, and $\mathbf{D_{10}}$ in units of mm. The Moulton model is used in the FHWA drainage design computer program, DRIP2.0, which is recommended by NCHRP's guide for mechanistic empirical design [11].

$$\boldsymbol{K = \left[\left(6.214\ x\ 10^5\right) D_{10}{}^{1.478} * N^{6.654}\right] / P_{200}^{0.597}} \tag{4}$$

Materials and Methodology

Eight different gravel gradations were collected from different areas in Yukon and Manitoba to be used in this study. The samples represented typical road base materials in the regions where collected with fines content ranging from 3.3% to 12.3%, and maximum size ranging from 19mm to 37mm, as shown in Table 2. Also, the effective sizes D_{60} and D_{10} of the samples ranged from 4.65 mm to 12.07mm and 0.05mm to 0.42mm, respectively. Standard proctor testing, sieve analysis, and sample portioning were done in preparation for laboratory hydraulic conductivity testing.

Table 2 Materials properties

Sample ID	Fines content (%)	Maximum dry density (Kg/m³)	Optimum moisture content (%)	D_{10} (mm)	D_{60} (mm)	Coefficient of uniformity "Cu"	Crush count (%)
M12.3	12.3	2156	8.7	0.05	4.65	98.3	55
M6.9	6.9	2053	10.1	0.23	8.03	35.1	62.6
M3.3	3.3	2220	7.8	0.42	12.07	28.7	73.8
Y3.5	3.5	2206	9	0.22	5.67	24.6	67
Y3.9	3.9	2221	9.2	0.41	7.52	18.6	76
Y4.9	4.9	2237	8.6	0.40	7.59	19.1	64
Y6.4	6.4	2287	8.5	0.23	6.79	29.9	83
Y9.7	9.7	2362	6.4	0.10	7.37	71.7	64

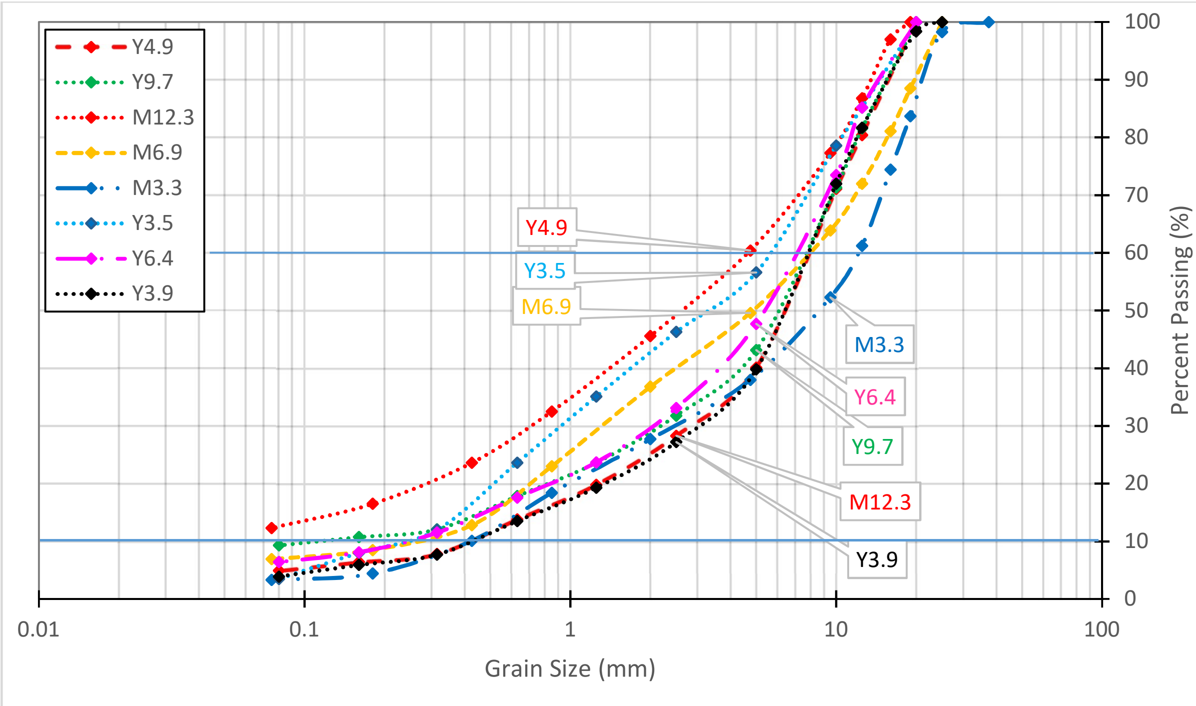

Figure 3 Aggregate gradation

Table 3 Aggregate gradation

Sample ID	Passing 37.5 mm (%)	Passing 25 mm (%)	Passing 19 mm (%)	Passing* 16 mm (%)	Passing 12.5 mm (%)	Passing 9.5 mm (%)	Passing 4.75 mm (%)	Passing 2 mm (%)	Passing 0.425 mm (%)	Passing 0.075 mm (%)
M12.3	100	100	100	97	86.8	77.3	60.4	45.6	23.7	12.3
M6.9	100	100	88.5	81.1	72	63.9	49.6	36.8	12.8	6.9
M3.3	100	98.3	83.7	74.4	61.2	52.3	38	27.7	10.1	3.3
Y3.5	100	100	100	N/A	85.2	78.6	56.6	46.3	12	3.5
Y3.9	100	100	98.4	N/A	81.7	72	39.8	27.2	7.8	3.9
Y4.9	100	100	100	N/A	80.4	71.1	40.1	28.3	7.8	4.9
Y6.4	100	100	100	N/A	85.2	73.5	47.7	33.1	11.5	6.4
Y9.7	100	100	100	N/A	81.5	71.2	43	31.6	11.8	9.7

* N/A = sieve size was not included in sieve analysis

Materials were oven dried prior to testing for more control on moisture content. The studied UGMs were tested for their hydraulic conductivity in accordance with AASTM-D5856 [12]. At least two replicates were conducted for each sample as a quality control measure. In preparation, materials were compacted in three lifts in a steel permeameter mold (dia=101.6mm) using a vibratory compactor adjusted at about 2000 blows per minute. A vacuum pump connected to the effluent of the permeameter was used to saturate the sample prior to starting the test. Then the assembly was connected to a constant head source and recordings of time, discharged volume and temperature were made. The hydraulic conductivity was calculated and temperature corrected using equations (5) and (6).

$$K_T = \frac{Q*L}{t*A*\Delta h*10^6} \qquad \textbf{(5)}$$

$$K_{20} = K_T * \frac{\eta_T}{\eta_{20}} \qquad \textbf{(6)}$$

K_T = Hydraulic conductivity in (m/s) at temperature **T** in (C°)
Q = Discharged volume (mL)
L = Sample height (m)
t = Time required to discharge Q (s)
Δh = Difference in head between inlet and outlet (m)
η_T = Viscosity of water at temperature **T**

The field testing for hydraulic conductivity was done using the double ring apparatus according to ASTM D3385 [13]. For test preparation, the two steel rings were driven 50mm into the compacted base layer. That was achieved by using a sledge hammer on the driving plate. A paste mix of bentonite and water was used to seal the soil near the rings' edges. This paste mix keeps water drainage restricted to a path in the base layer only. Once preparation was complete, the test was started by filling the two rings to the same level with clean water and installing the measuring rod and float. Caution was used during this step to prevent soil disruption resulting from pouring water in the rings.

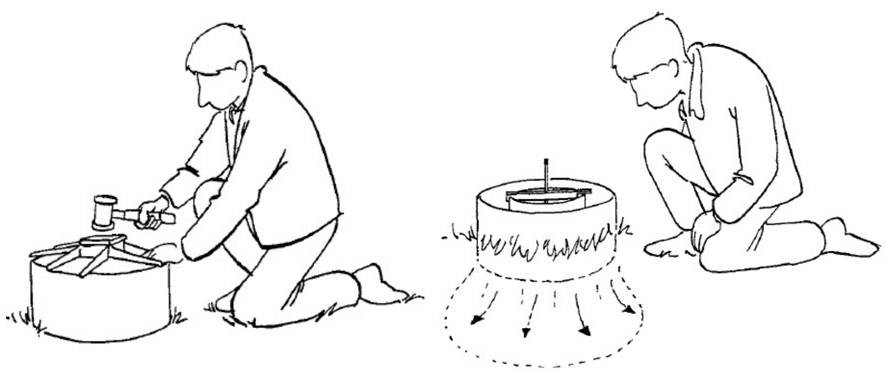

Figure 4 Setup and operation of the double ring infiltrometer [16]

Readings of elapsed time, water level, and water temperature were recorded periodically. The recorded readings were used to calculate the infiltration rate of the tested material. However, under steady state infiltration which is achieved at saturation, it can be assumed that the infiltration rate is equal to the hydraulic conductivity. Such assumption is based on a hydraulic gradient of 1 which results from the equilibrium between the difference in ponded water level and the difference in the wetting front depth when the base layer is saturated. The field hydraulic conductivity is then calculated using equation (7), where **I** is the infiltration rate, **Q** is the infiltration volume, **i** is the hydraulic gradient, **A** is the area of the inner ring, and **t** is the time required for the infiltration of volume **Q**.

$$K = I = \frac{Q}{i* A*t} \qquad \textbf{(7)}$$

Results and Discussion

The lab and field measured hydraulic conductivity values were used as an input parameter to calculate the time required to drain a given pavement section for each UGM blend according to AASHTO 1993 design guide. To facilitate comparison, all calculations for time to drain were made using an arbitrary pavement geometry consisting of 2x3.65m lanes and 2% crown slope sitting on 300mm thick base layer.

Table 4 Average hydraulic conductivity and drainage results

Sample ID	Fines content (%)	D10 (mm)	D60 (mm)	Porosity	Lab "K" (m/s) x10^{-7}	Drainage Time (days)	Quality of drainage
M12.3	12.3	0.05	4.65	0.186	0.012	8141	Clogged
M6.9	6.9	0.23	8.03	0.225	15.50	5	Fair
M3.3	3.3	0.42	12.07	0.162	21.20	4	Fair
Y3.5	3.5	0.22	5.67	0.192	17.60	5	Fair
Y3.9	3.9	0.41	7.52	0.173	14.02	6	Fair
Y4.9	4.9	0.40	7.59	0.161	7.47	10	Poor
Y6.4	6.4	0.23	6.79	0.183	1.36	48	Poor
Y9.7	9.7	0.10	7.37	0.1	1.56	21	Poor

Table 5 Field drainage test results

Material ID	Field "K" (m/s)	Field drainage time (days)	Field Quality of drainage
M12.3	5.1E-7	74	Poor
M3.3	87.5E-7	1	Good

It can be observed from Table 4 and Figure 6 that the increase in fine content has a negative effect on the UGM permeability and drainage quality. In addition to its high correlation with fines content, the hydraulic conductivity is also affected by the **D10** and **D60** of the material as well as the coefficient of uniformity (**Cu**). The smaller the value of (**Cu**) the more uniformly graded a material is, which allows for more interconnected voids that water can drain through. However, **Cu** is also an indicator of the material workability. A review of Table 2 and Table 4 shows that an increase in both **D10** and **D60** combined with a decrease in **Cu** would positively affect the drainage capacity of the material. A large effective size (**D10**) combined with a low coefficient of uniformity provides higher coefficient of permeability [14].

The field measurements of hydraulic conductivity varied from lab measurements due to possible leakage on the sides of the rings. The variation seemed to increase as the soil became less permeable. This variation is explained by the flow of water seeking the easier path through the sides of the rings in the case of a clogged soil layer. Even though drainage data retrieved from the field were over estimating the hydraulic conductivity, the data confirm the improvement in drainage quality due to reducing fines content and increasing grain size.

The Moulton prediction model for hydraulic conductivity provided a good approximation of the results of the laboratory tested hydraulic conductivity as can be seen from Figure 6 and Figure 6. The model is most sensitive to the fines content as this parameter had the highest correlation with hydraulic conductivity.

However, Figure 7 shows the improvement in drainage gained by increasing the effective size, **D10**, of a UGM from 0.21 to 0.43mm. Such increase in **D10** was achieved mainly by increasing the maximum aggregate size from 19mm to 37mm. According to the established model, the hydraulic conductivity increased 35% which translate to an upgrade of drainage quality from poor to fair.

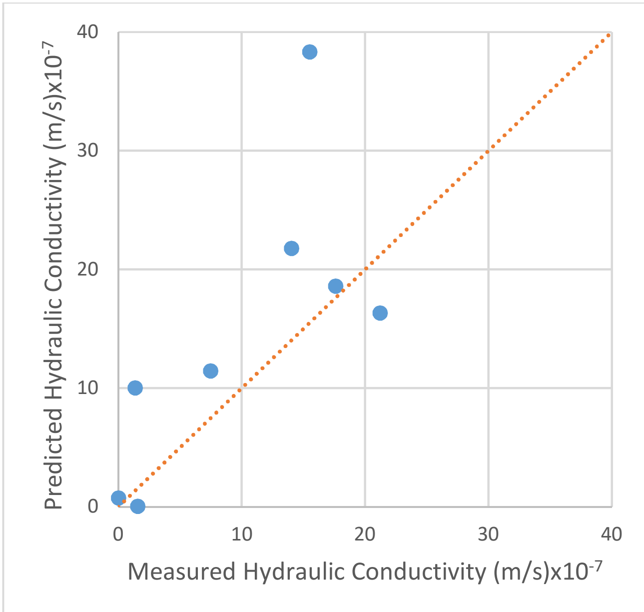

Figure 5 Measured and predicted hydraulic conductivity using Moulton-1980 equation

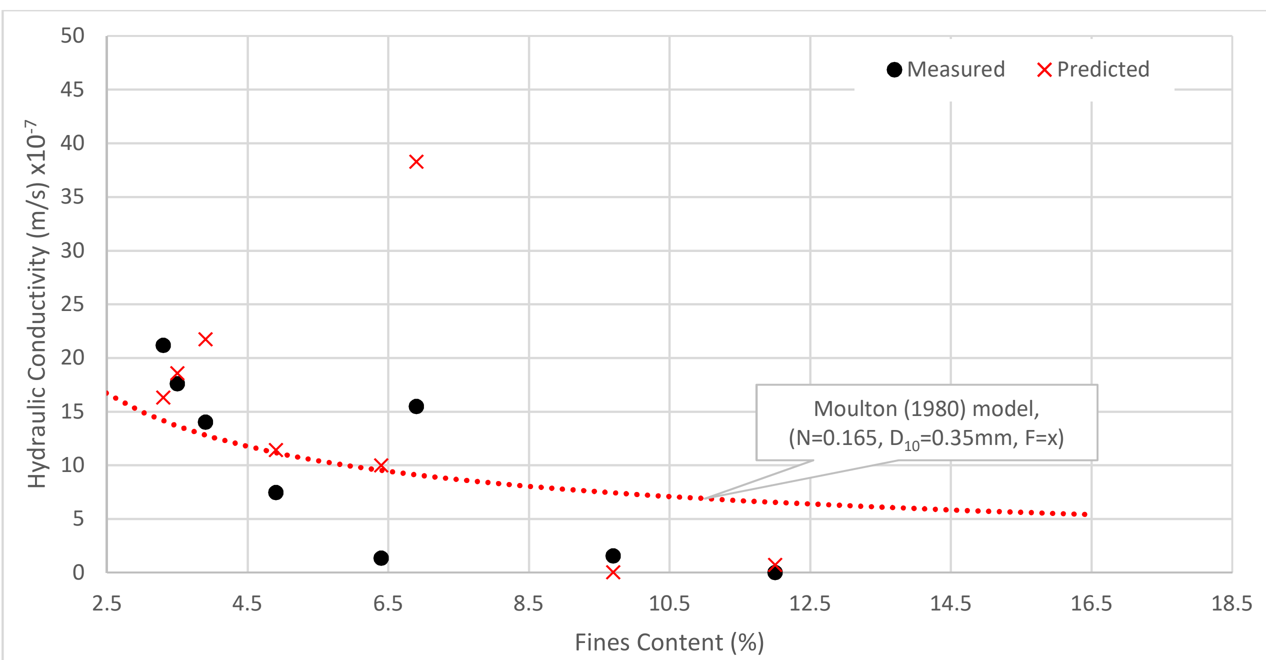

Figure 6 Effect of fines on the hydraulic conductivity of the tested unbound granular materials

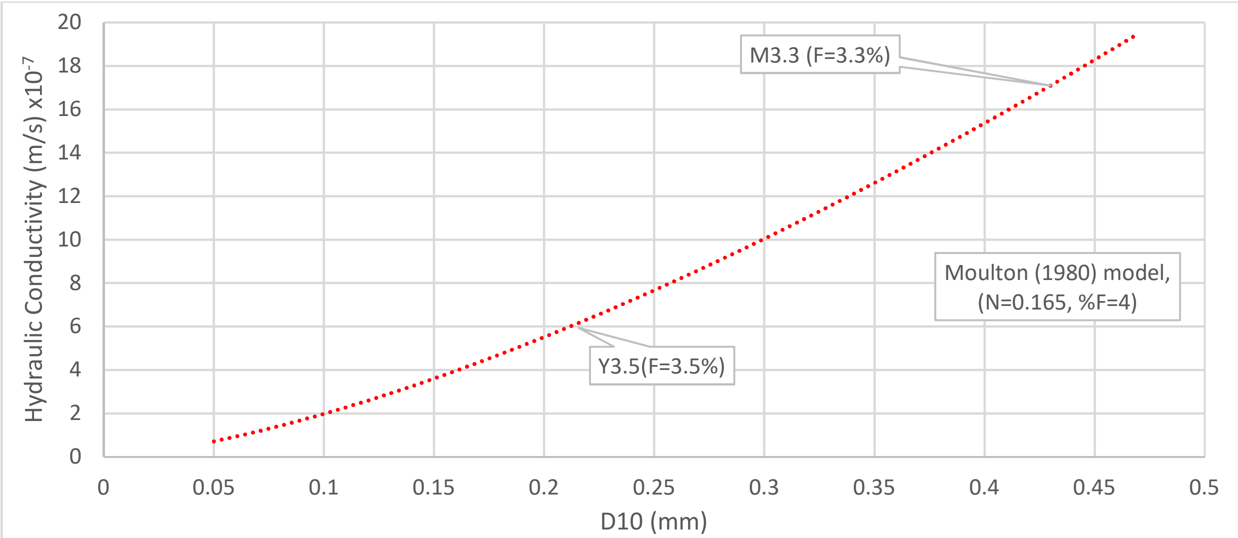

Figure 7 Sensitivity of Moulton prediction model to the effective size of the blend (D_{10})

Since base thickness affects drainage and in order to compare the benefits gained by enhancing the drainage of the pavement structure, Figure 8 shows the relationship between the time to drain and the thickness of the base layer for the tested UGM. Figure 8 also shows the detrimental effects on the drainage capacity of the base layer from an increase in fines content. It can also be noticed that changing the UGM properties is a much efficient approach to enhancing subsurface drainage than changing the layer thickness.

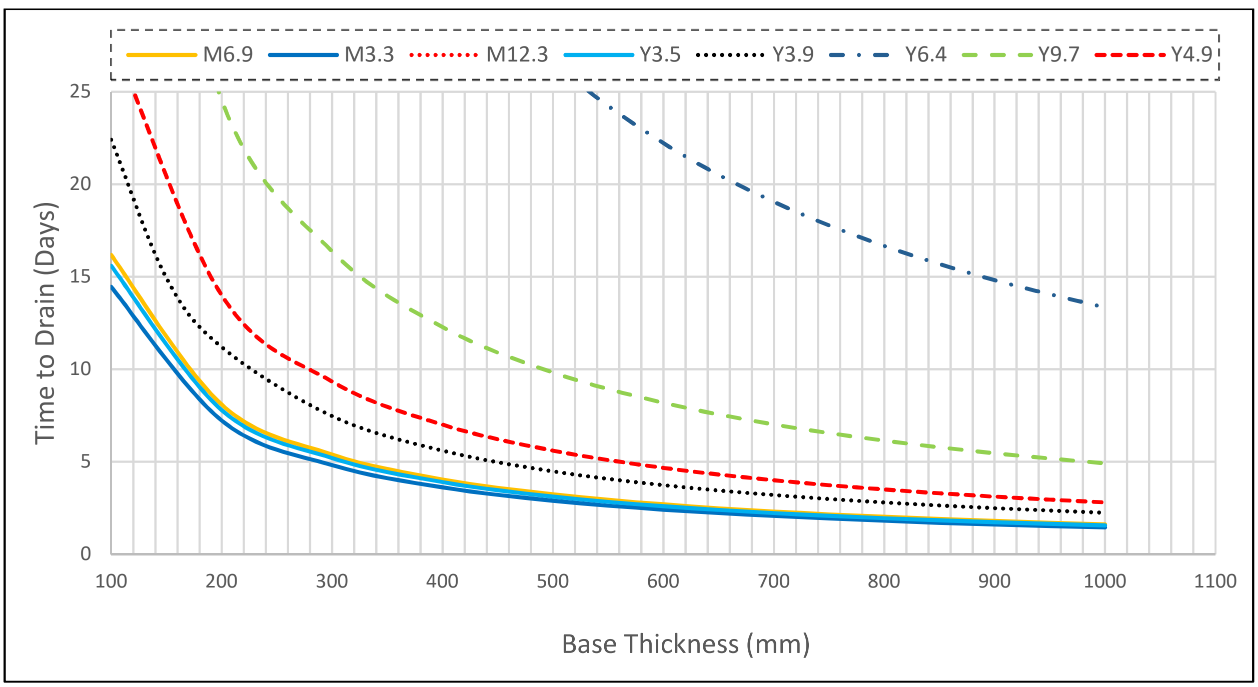

Figure 8 Relationship between the base thickness and the time required to drain for the tested blends

Key Findings

Eight UGM samples were tested in the laboratory for their hydraulic conductivity which is a key input for obtaining the drainage quality of a pavement structure. The results showed that the drainage quality of a typical pavement structure based on the tested materials ranged from very poor to fair. These values were estimated under typical structural and material conditions and in a controlled laboratory environment. The hydraulic conductivity measured in the field yielded higher values than that of the lab test. However, it still confirmed the improvement in drainage performance gained by reducing fines and increasing grain size in UGM.

Hydraulic conductivity is directly influenced by material parameters, such as gradation, grain shape, and grain size. Hydraulic conductivity is inversely proportional and is most sensitive to the fines content. The Moulton prediction model combined the three material parameters that explained %91 of the variation in hydraulic conductivity, which are effective size, porosity, and fines content. The Moulton equation provided a good approximation of the measured hydraulic conductivity of the tested samples in this study, and it can be used in estimating hydraulic conductivity for design purposes. Drainage quality is affected by material properties and by structural parameters, including layer thickness. It was found that increasing hydraulic conductivity through better gradation controls is a more efficient approach in enhancing drainage quality than through increasing sub layer thickness.

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