Performance-Based Hydraulic Conductivity Models for Unbound Granular Materials

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Abstract

Specifications for unbound granular materials (UGM) must be based on the function of the unbound layer (drainable layer, high stiffness, or both). Using performance-based specifications that are based on laboratory performance of UGM (resilient modulus, permanent deformation, and permeability) provides durable and longer lasting unbound layers. This paper investigates the effect of fines content variation on the permeability (hydraulic conductivity) of two types of UGM, gravel and 100% crushed limestone. Hydraulic conductivity tests were conducted on compacted gravel UGM with 4.0% fines, 9.0% fines, and 14.5% fines. For 100% crushed limestone, hydraulic conductivity tests were conducted on compacted samples with 4.5% fines, 10.5% fines, and 16.0% fines. For gravel, the hydraulic conductivity decreased by 84% due to increasing fines content from 4.0% to 14.5%. For Limestone, the hydraulic conductivity decreased by 81% due to increasing fines content from 4.5% to 16.0%. For gradations with comparable fines content, limestone material showed higher hydraulic conductivity than that for gravel. The laboratory measured hydraulic conductivity was compared to Level 2 design inputs in the Mechanistic-Empirical Pavement Design Guide (Pavement ME). The calculated hydraulic conductivity using Pavement ME Level 2 equation was found to be higher than the laboratory measured values by 200% to 700% for gravels, and by 25% to 300% for limestones. The difference between the hydraulic conductivity computed using Pavement ME Level 2 equation and the laboratory measured values increased as the fines content increased. Overestimating the hydraulic conductivity of UGM layers may result in under designed pavement structures and consequently reduced pavement service life. The research recommends calibrating the performance based models with locally generated hydraulic conductivity data to improve the reliability of the models.

Introduction

Pavement materials are usually subjected to stress levels that exceed their elastic limits to accommodate the traffic loading with cost-effective design. Pavement structures fail due to gradual accumulation of permanent deformation, or degradation in materials during their service life, and not due to rapid collapse [1]. Physical and chemical properties of UGM determine the suitability of aggregate for different uses in pavement construction and govern aggregates durability and soundness [2]. Gradation is one of the main factors that influence the elastic and plastic behaviour of UGM [3]. For the same aggregate source, base materials with coarser gradations have higher resilient modulus than finer gradations [3,4,5]. In addition to mechanical properties, gradation has an influence on the permeability and frost susceptibility of unbound base materials [6].

Type (plastic or nonplastic) and amount of fines (passing No. 200 sieve) in base materials influence the response of base materials under traffic loading [2]. Several studies evaluated the optimum fines content that achieve maximum strength and increase stability of UGM. Based on laboratory testing of local UGM, Gandara et al. found that UGM with fines content ranging from 5% to 10% have higher resilient modulus and are less susceptible to moisture variation [7].

Gandara et al. recommended a fines content limit of 10% for better performance of base materials [7]. For dense-graded crushed limestone base material, Tutumluer and Seyhan recommended the optimum fines content to be 7% [8]. The optimum fines content varies based on aggregate physical properties and gradation.

The performance of UGM depends on the interaction between aggregate source, gradation, amount and plasticity of fines, degree of compaction, moisture content, and aggregate shape, texture and angularity [2,9,10,11,12]. Specifications for UGM aim to provide a range of locally available durable materials that meet design requirements and achieve the target design life. Specifications for UGM vary among transportation agencies based on the availability of materials, climatic conditions, and function. The effective use of locally-available material and targeting long service life are important aspects for design and construction of sustainable and cost-effective pavements [2].

A reliable analytical design of pavement structures requires laboratory measured values for resilient modulus of UGM [13]. For analytical pavement design, it is necessary to consider the effect of climatic conditions which includes variations in moisture content of UGM [14]. In addition to strength parameters, the drainability characteristics of UGM are required inputs to avoid premature failure of pavement structures [15].

The required design reliability and engineering effort shall be proportional to the significance of the project being designed, e.g., a low-volume secondary road doesn't require the same design reliability as a high-volume primary road [16]. Pavement ME has a hierarchical approach for determining the design input parameters based on the significance and the required design reliability for the project. According to this approach, three levels are available for the design input parameters [17]:

- Level 1: highest level of accuracy and reliability. Design input parameters are measured directly in the laboratory.
- Level 2: an intermediate level of accuracy and reliability. Basic material properties are measured in the laboratory (e.g. gradation, unconfined compressive strength, California bearing ratio,...). Design input parameters are estimated based on correlations between design inputs and the measured basic properties.
- Level 3: lowest level of accuracy and reliability. Design input parameters can be the default values provided by the design guide or typical values based on agency experience.

This paper investigates the effect of fines content variation on the permeability (hydraulic conductivity) of gravel and 100% crushed limestone UGM. To validate Pavement ME models, the laboratory measured hydraulic conductivity was compared to Level 2 design inputs in Pavement ME. This work is part of a project that aims to evaluate the performance parameters of UGM for design and analysis of pavement structures. The research provides laboratory test data in support of calibrating the performance based models with locally generated hydraulic conductivity data to improve the reliability of Pavement ME Level 2 models.

Test Materials

Two samples of UGM were collected by Manitoba Infrastructure and Transpiration (MIT) from different sources in the Province to represent two types of UGM: uncrushed gravel and 100% crushed limestone. Figures 1 and 2 show the shape of the coarse portion (retained on No. 4 sieve) of gravel and limestone materials, respectively. The UGM samples were sieved into individual particle sizes. The individual particle sizes were combined into three gradations with different fines content. For gravel, the fines contents for the three gradations were 4% (GA−4), 9% (GA−9), and 14.5% (GA−14.5). For limestone, the fines contents for the three gradations were 4.5% (LS−4.5), 10.5% (LS−10.5), and 16% (LS−16). The fines contents were selected based on the current specification of UGM in Manitoba to represent upper specification limit, lower specification limit, and a fines content below lower specification limit. The required material for each test specimen was mixed, bagged and stored separately to ensure a consistent gradation over all specimens. Figures 3 and 4 show the selected gradations for gravel and limestone materials, respectively.

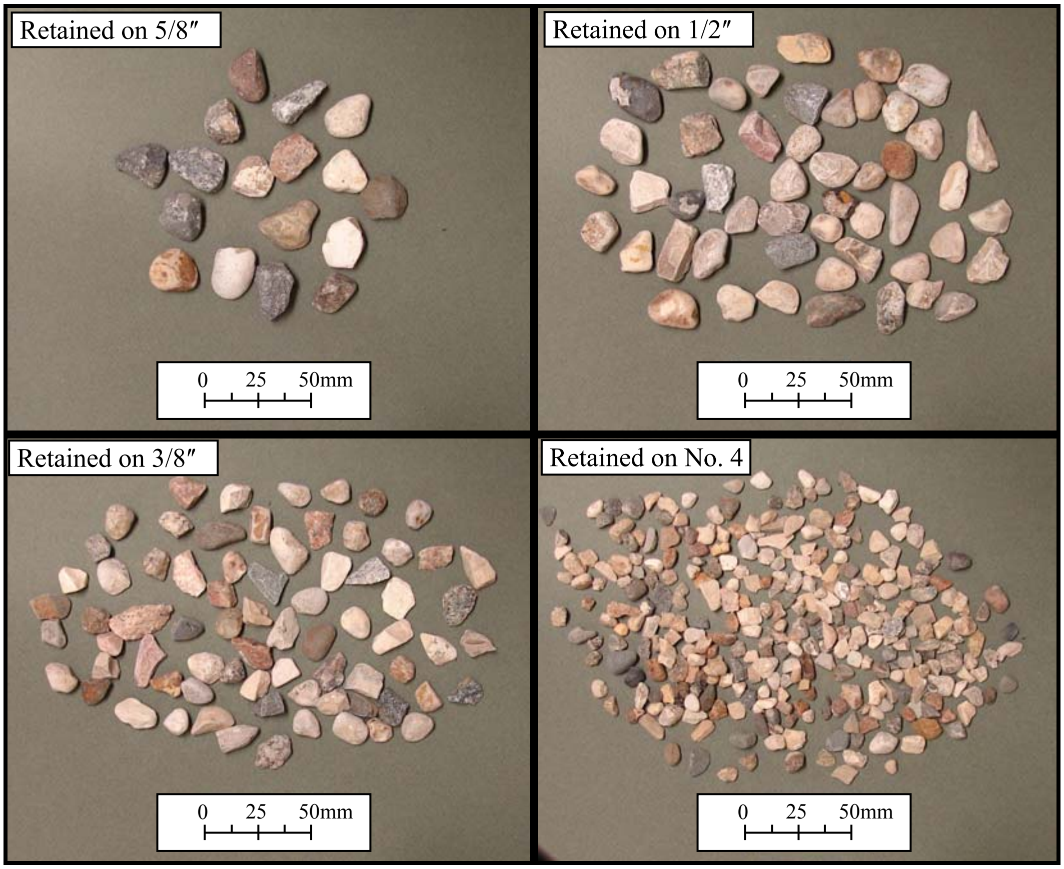

Figure 1: Shape of Coarse Portion (Retained on No. 4 Sieve) of Gravel UGM

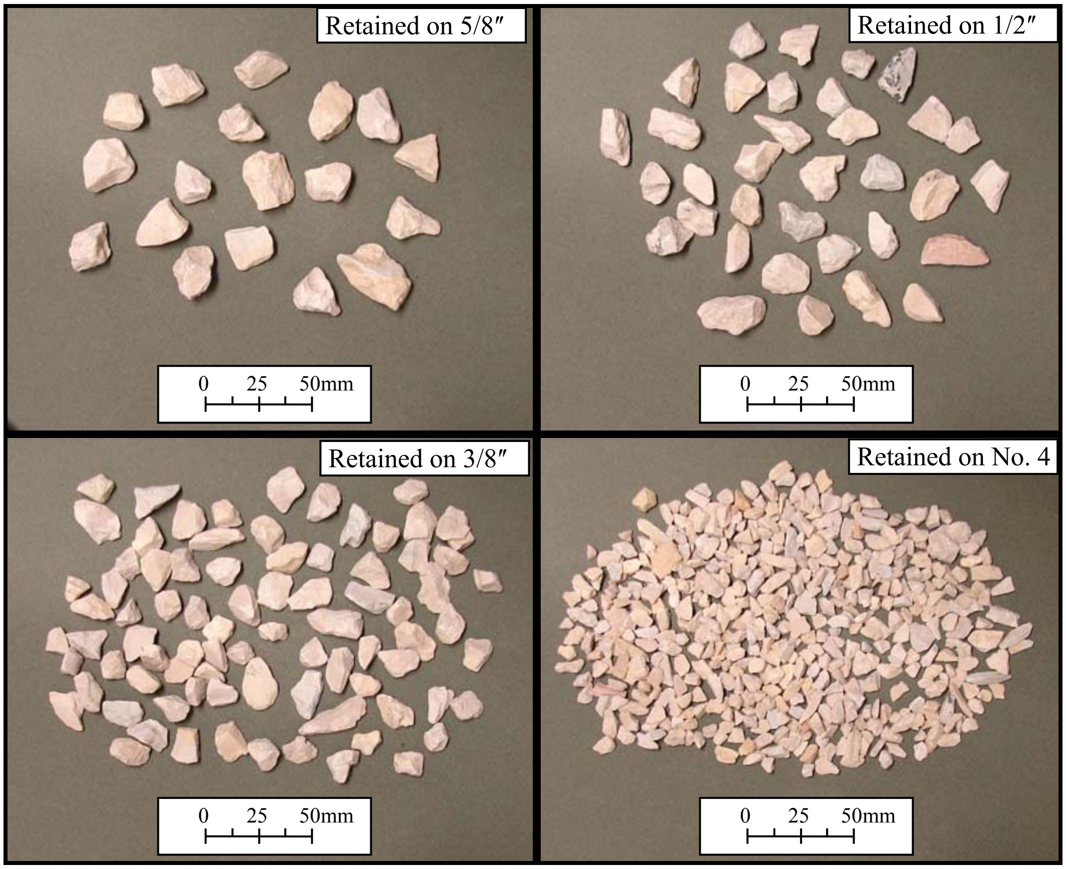

Figure 2: Shape of Coarse Portion (Retained on No. 4 Sieve) of Limestone UGM

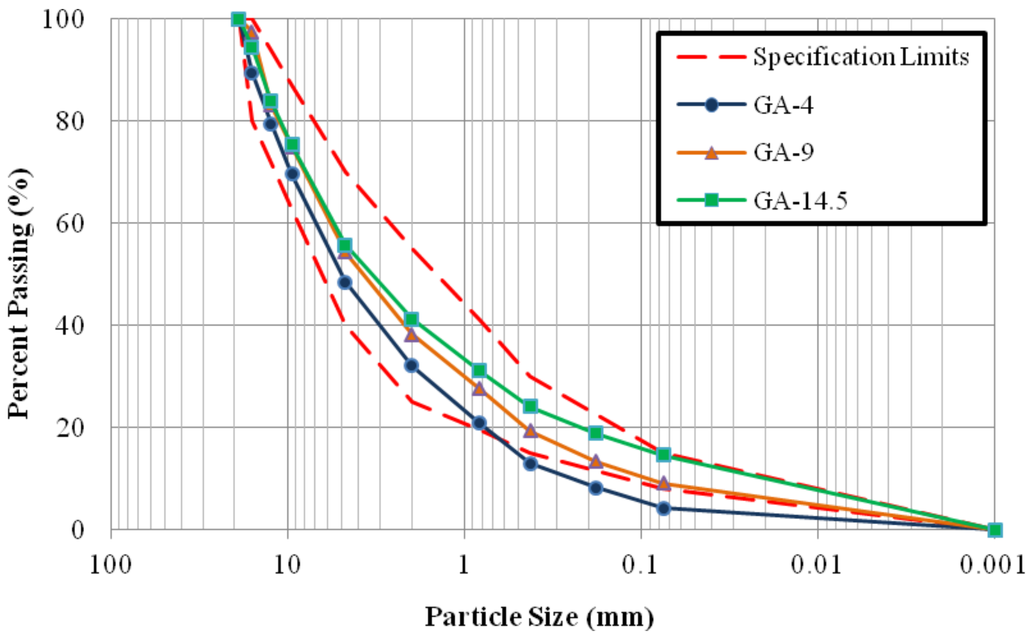

Figure 3: Particle Size Distribution for Gravel UGM Gradations

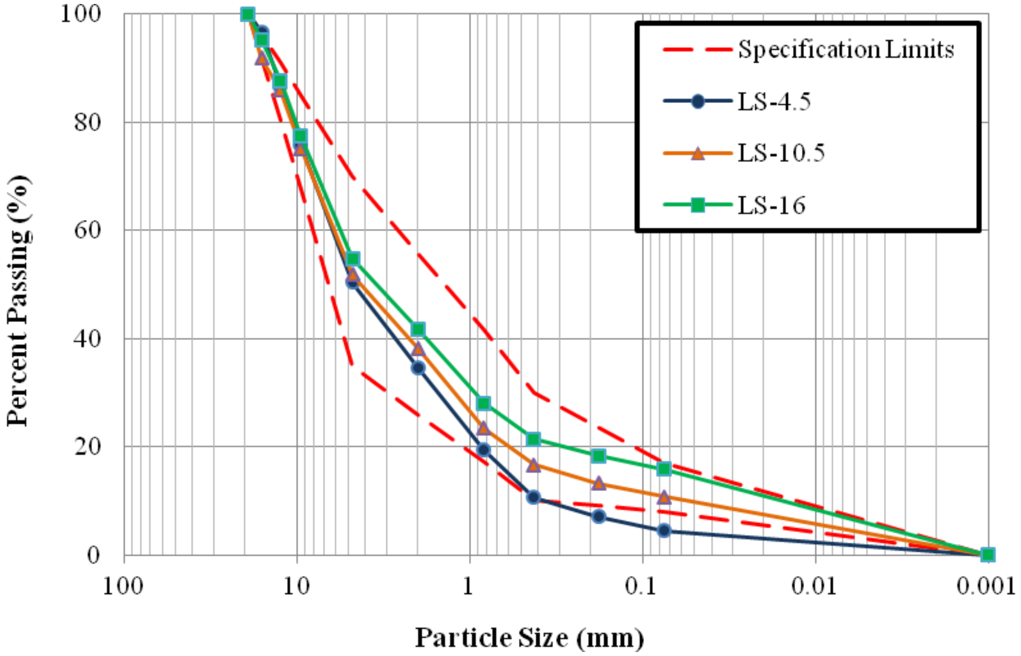

Figure 4: Particle Size Distribution for Limestone UGM Gradations

Standard Proctor and Atterberg Limits tests were conducted on all UGM gradations. Table 1 shows the maximum dry density and the OMC for all UGM gradations. All gradations had a plasticity index of zero. The fines portion (passing No. 200 sieve) was calcareous fines for limestone and clayey silt for gravel with an average silt/clay ratio of 1.75.

Table 1: Properties of Tested UGM Gradations

Material type	Gradation ID	Fines content (%)	OMC (%)	γ_{opt} (kg/m^3)	Plasticity index	Clay content (% of total)	Dust ratio
Gravel	GA−4	4.0	7.9	2170	NP*	1.7	0.33
	GA−9	9.0	7.0	2223	NP	3.5	0.47
	GA−14.5	14.5	8.3	2203	NP	4.7	0.61
Limestone	LS−4.5	4.5	7.5	2202	NP	-	0.42
	LS−10.5	10.5	7.0	2277	NP	-	0.65
	LS−16	16.0	6.5	2305	NP	-	0.74

* NP: no plasticity

Permeability Test Setup

A single ring rigid-wall permeameter was used to measure the hydraulic conductivity (permeability) of UGM. The procedures of ASTM D5856 "Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter" was followed [18]. The dimensions of the permeameter are 101.6 mm in diameter and 115.9 mm in height. Test specimen was compacted in three layers using a vibration compactor, Figure 5, on the permeameter mold at the OMC and with a minimum relative density of 98%. The total length of the compacted specimen slightly exceeded the length of the permeameter ring to allow trimming of the top of the specimen to a height uniform with the top of the compaction ring.

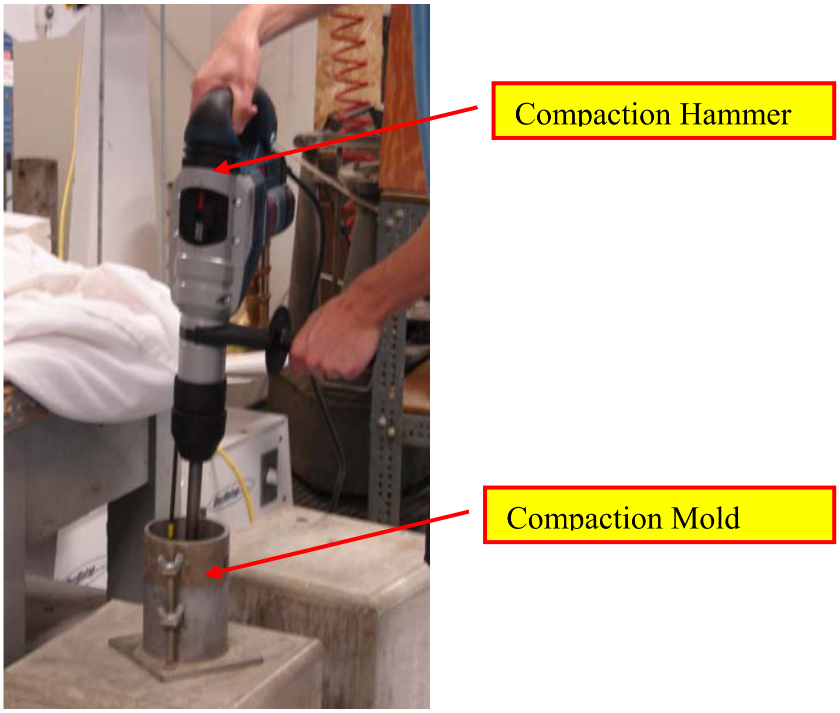

Figure 5: Vibratory Compaction (Compaction Time Varies Based on Material Type)

Saturation of the specimen was accomplished initially by connecting the effluent port of the permeameter to a vacuum pump. After approximately 5 minutes, the effluent port was slowly closed and the influent valve was then slowly opened allowing the negative pressure within the cell to be replaced with water. This procedure was repeated with increasing vacuum pressures until no air was drawn from the permeameter. After vacuum saturation, the specimen was connected to a constant water head to saturate overnight before testing.

The test setup consisted of a constant water level tank, a single ring rigid-wall permeameter, and a beaker to measure the water flow. The hydraulic head is measured as the difference in elevation between the inlet water level (top of the constant head tank) and the outlet water level (end of effluent tube). Figure 6 shows the permeability test setup.

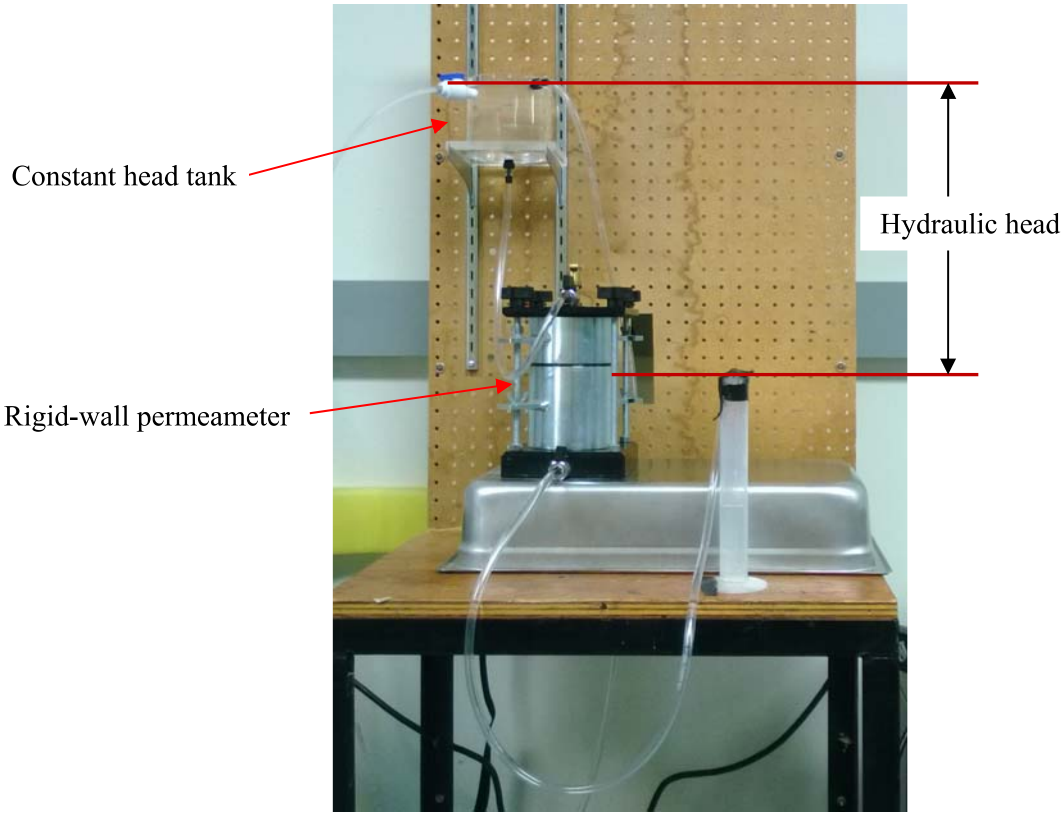

Figure 6: Permeability Test Setup

The permeameter was set up without a specimen, however all porous stones and filter papers used during the actual test were installed. The system was run at different hydraulic heads and the rate of flow was measured. The measured rate of flow for the empty permeameter, at different hydraulic heads, was more than 10 times the rate of flow when a specimen is compacted inside the permeameter. Therefore, the head losses in the test setup did not cause a significant effect on the measured hydraulic conductivity [18].

Validation of Darcy's Law

The governing equation of the constant head permeability test is Darcy's Law. According to Darcy's Law, the velocity of water flow through the specimen is directly proportional to the hydraulic gradient [18]. Darcy's law is valid when laminar flow condition exist which must be satisfied to ensure the validity of the test results. The validity of Darcy's law can be confirmed by measuring the hydraulic conductivity of UGM at various hydraulic gradients and observing whether a linear relationship exists between the hydraulic gradient and the velocity of water flow. Accordingly, the hydraulic conductivity of a specimen should not change with any change in the hydraulic head.

Hydraulic conductivity tests were conducted on a typical UGM specimen, representing an average gradation of the tested materials, over a range of hydraulic gradients to determine the validity of Darcy's Law. The hydraulic gradient ranged from 1.3 to 3.3. Figure 7 shows the relationship between hydraulic gradient and the velocity of water flow. A linear relationship existed between the tested range of hydraulic gradients and the velocity of water flow within the specimen with a coefficient of determination (R^2) equals to 0.98, as shown in Figure 7. Therefore, Darcy's Law was valid for UGM with hydraulic gradients ranging from 1.3 to 3.3. At the high end of the tested range of hydraulic gradients, there was no significant deviation of the velocity of flow from the observed linear relationship, therefore the linear relationship can be valid at higher gradients than the tested range.

ASTM D5856 recommends different ranges of hydraulic gradient to be used for permeability test based on the observed hydraulic conductivity [18]. Results of pilot tests indicated that the observed hydraulic conductivity for UGM should be ranging from 1×10^{-7} m/s to 1×10^{-5} m/s. According to ASTM D5856, a hydraulic gradient ranging from 2 to 5 shall be used for testing the permeability of UGM.

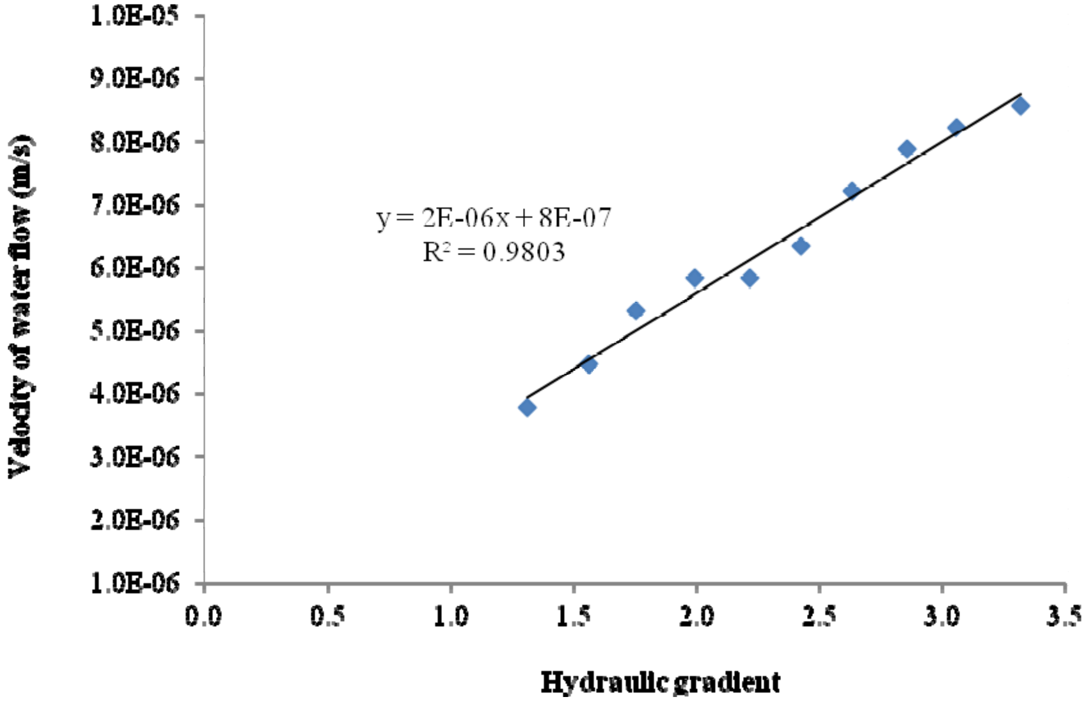

Figure 7: Relationship between Hydraulic Gradient and Velocity of Water Flow

Permeability Test Results

Figures 8 and 9 show the measured hydraulic conductivity (k) for gravel and limestone materials, respectively, at different fines content. The reported hydraulic conductivity values are at a water temperature of 20°C. For gravel gradations, the hydraulic conductivity decreased from 2.70×10^{-6} m/s to 0.85×10^{-6} m/s (-69%) due to increasing fines content from 4.0% to 9.0%. As the fines content increased further to 14.5%, the hydraulic conductivity decreased to 0.42×10^{-6} m/s (-84%). For Limestone gradations, the hydraulic conductivity decreased from 4.55×10^{-6} m/s to 1.75×10^{-6} m/s (-62%) due to increasing fines content from 4.5% to 10.5%. As the fines content increased further to 16.0%, the hydraulic conductivity decreased to 0.87×10^{-6} m/s (-81%).

The hydraulic conductivity for limestone gradations was higher than that for gravel gradations by 1.85×10^{-6} m/s at low fines content and by 0.45×10^{-6} m/s at high fines content. The difference in hydraulic conductivity can be due to the higher amount of total voids in the aggregate matrix of crushed limestone UGM than that of uncrushed gravel [19].

Table 2 provides a comparison between the hydraulic conductivity values for the tested UGM and the hydraulic conductivity values reported in the literature for limestone and sandstone UGM from different sources in Oklahoma [20]. The hydraulic conductivity for Oklahoma UGM was measured using a falling headed flexible wall permeability setup at saturation condition. The Oklahoma UGM were compacted using Modified Proctor method with gradations representing the specification limits of Oklahoma Department of Transportation specifications for dense-graded base material. Although some Oklahoma samples had coarser gradation, the hydraulic conductivity values for Manitoba samples were higher than that for Oklahoma samples, by more than two orders of magnitude for some samples. The difference in hydraulic conductivity between Manitoba samples and Oklahoma samples is due to using different compaction energy where Manitoba samples were compacted using Standard Proctor energy. Using a compaction energy of 600 kN.m/m^3 (Standard Proctor energy) instead of 2700 kN.m/m^3 (Modified Proctor energy) can result in the increase of hydraulic conductivity by multiple orders of magnitude [21].

Validation of Pavement ME Level 2 Models

For Level 2 design inputs in Pavement ME, the saturated hydraulic conductivity can be determined from fines content (P_{200}), plasticity index (PI), and the particle size corresponding to 60% passing (D_{60}) [16]. The PI for all the test gradations was zero. The saturated hydraulic conductivity (k_{sat}), in ft/hr, can be determined from the following equation:

$$k_{sat} = 118.11\times10^{\left[-1.1275\left(\log D_{60}+2\right)^2+7.2816\left(\log D_{60}+2\right)-11.2891\right]} \qquad \textbf{(1)}$$

Equation 1 is valid for the following conditions:

- $0 \leq P_{200}\times PI < 1$

- $D_{60} < 0.75$ in
- If $D_{60} > 0.75$ in, set $D_{60} = 0.75$ in

Table 3 shows the hydraulic conductivity values for the gravel and limestone gradations determined using Equation 1. For gravel gradations, the calculated hydraulic conductivity was higher than the laboratory measured value by 217%, 352% and 693% for GA-4, GA-9, and GA-14.5, respectively. For limestone gradations, the calculated hydraulic conductivity was higher than the laboratory measured value by 25%, 187% and 283% for LS-4.5, LS-10.5, and LS-16, respectively.

The deviation between the calculated hydraulic conductivity and the laboratory measured value increased as the fines content increase where Equation 1 depends on D_{60} and does not account for the change in fines content. Overestimating the hydraulic conductivity of base layer results in under designing the pavement structure and reducing the pavement service life.

Table 2: Comparison between Hydraulic Conductivity Values for Tested UGM and Values Reported in the Literature

Location	Material Type	D_{60} (mm)	Fines Content (%)	OMC (%)	γ_{max} (kg/m^3)	k* ($\times 10^{-6}$ m/s)
Manitoba	Gravel	7.3	4.0	7.9	2170	2.700
		6.0	9.0	7.0	2223	0.850
		5.8	14.5	8.3	2203	0.420
	Limestone	6.6	4.5	7.5	2202	4.550
		6.4	10.5	7.0	2277	1.750
		5.8	16.0	6.5	2305	0.870
Oklahoma	Limestone 1	17.0	7.3	5.0	2264	1.550
		4.2	15.5	6.6	2447	0.004
	Limestone 2	19.6	4.9	5.0	2305	1.000
		4.8	12.9	6.2	2335	0.400
	Sandstone	17.5	6.6	6.0	2192	0.700
		3.8	13.9	6.4	2182	0.004

[*] Hydraulic conductivity values are at saturation condition and a water temperature of 20°C. Manitoba samples were compacted using Standard Proctor energy and Oklahoma samples were compacted using Modified Proctor energy.

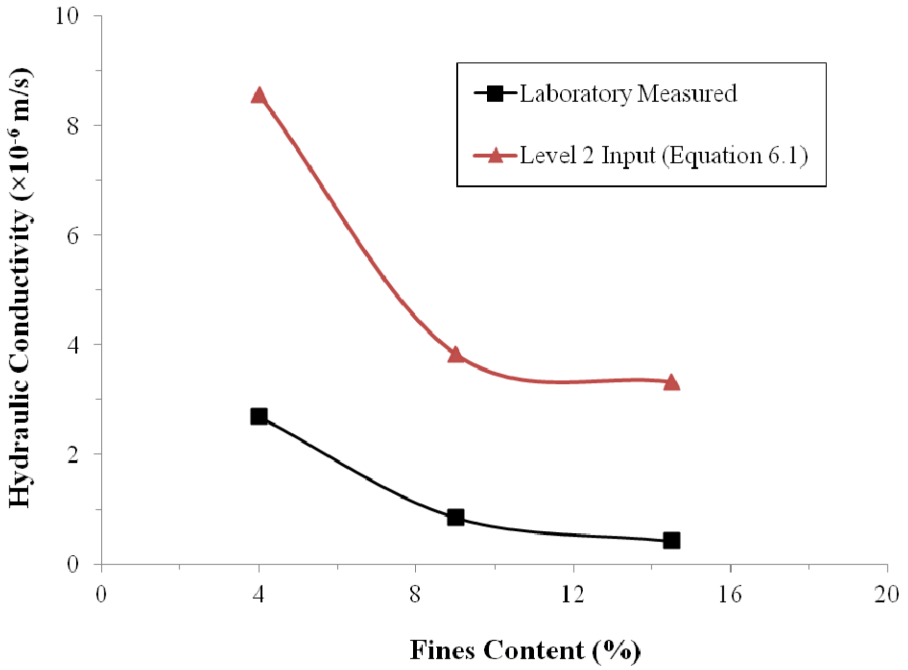

Figure 8: Measured Hydraulic Conductivity for Gravel UGM

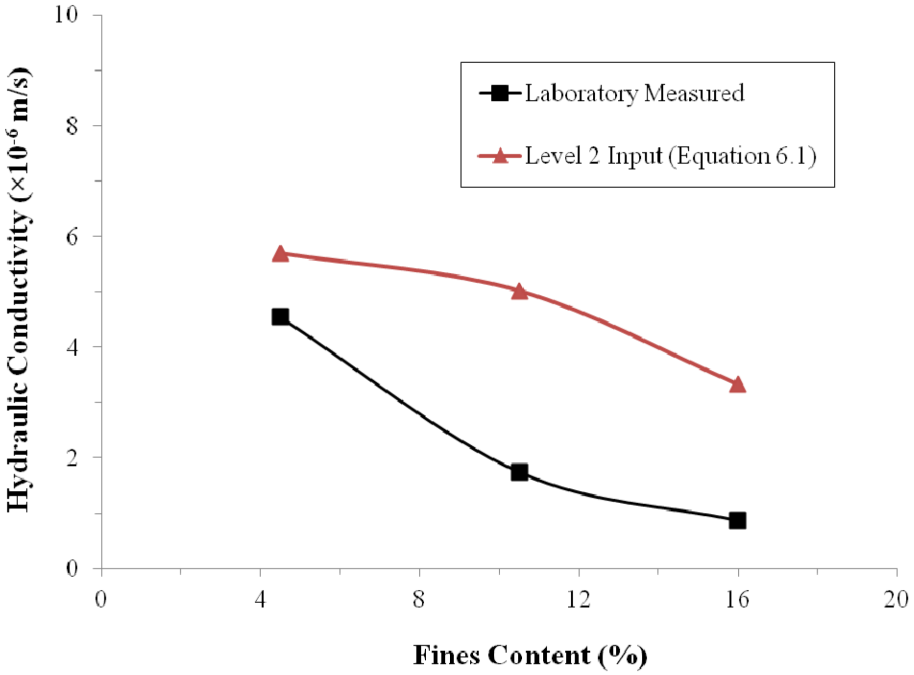

Figure 9: Measured Hydraulic Conductivity for Limestone UGM

Table 3: Hydraulic Conductivity of the Tested UGM Determined Using Equation 1, Level 2 Design Input

Gradation ID	D_{60} (mm)	Fines Content (%)	Laboratory Measured k ($\times10^{-6}$ m/s)	k_{sat} using Equation 1 ($\times10^{-6}$ m/s)	Difference (%)
GA-4	7.3	4.0	2.700	8.563	217
GA-9	6.0	9.0	0.850	3.840	352
GA-14.5	5.8	14.5	0.420	3.331	693
LS-4.5	6.6	4.5	4.550	5.697	25
LS-10.5	6.4	10.5	1.750	5.021	187
LS-16	5.8	16.0	0.870	3.331	283

Effect of Hydraulic Conductivity Variation on Quality of Drainage of Base Layers

AASHTO 1986 design guide was utilized to determine the effect of changing the hydraulic conductivity of UGM on the quality of drainage of base layers [22]. Assuming a two-lane road section with a slope of 2%, the time required to drain a base layer of 0.3 m thickness to 50% saturation and the quality of drainage were determined. Table 4 shows the time to drain the base layer and the quality of drainage using the laboratory measured hydraulic conductivity, Level 1 input, and the values obtained from Equation 1 for Level 2 input. For both gravel and limestone gradations, the time to drain the base layer decreased as the fines content decreased and the quality of drainage improved one category up. The improvement in quality of drainage extends the service life of pavement and reduces the required thickness of pavement layers. Table 4 shows that using Level 2 design input for hydraulic conductivity will over estimates the quality of drainage for GA-9, GA-14.5, and LS-16. Overestimating the quality of drainage can contribute to premature failure of a pavement structure due to under designing the required layer thicknesses.

Summary and Findings

Permeability of UGM was evaluated in the laboratory to develop Level 1 design inputs for Pavement ME. Two samples were collected to represent two types of UGM: gravel and 100% crushed limestone. For each UGM type, three gradations were tested with different fines content to evaluate the effect of fines on quality of drainage for base layers. Two gradations represent specification limits on allowable fines content and one gradation has less fines content than presently allowed by Manitoba specifications. Permeability of UGM gradations were tested at OMC and with a minimum relative density of 98%. For gravel gradations, the hydraulic conductivity decreased by 84% due to increasing fines content from 4.0% to 14.5%. For Limestone gradations, the hydraulic conductivity decreased by 81% due to increasing fines content from 4.5% to 16.0%.

To validate Pavement ME Level 2 models, the laboratory measured hydraulic conductivity was compared to Level 2 design inputs in Pavement ME. The calculated hydraulic conductivity from Pavement ME Level 2 equation was higher than the laboratory measured value (the difference was 693% for GA-14.5). Pavement ME equation does not account for the effect of fines content on the hydraulic conductivity for nonplastic fines.

AASHTO 1986 design guide was utilized to determine the effect of fines content variation on the quality of drainage for base layers. For both gravel and limestone gradations, the time to drain the base layer decreased as the fines content decreased. Reducing the fines content to 4.0% for gravel and 4.5% to 10.5% for limestone improved the quality of drainage for base layers from "poor" to "fair".

Transportation agencies must calibrate their own prediction models for hydraulic conductivity to determine Level 2 design input according to the typical UGM types available in their region. Using Pavement ME or other models available in the literature can result in over designing or under designing the pavement structure.

Table 4: Time to Drain and Quality of Drainage Based on the Hydraulic Conductivity Values for the Tested UGM

Gradation ID	Level 1 Design Input (Laboratory Measured)		Level 2 Design Input (Equation 1)	
	Time to drain base (day)	Quality of drainage	Time to drain base (day)	Quality of drainage
GA-4	4	Fair	2	Fair
GA-9	8	Poor	2	Fair
GA-14.5	9	Poor	2	Fair
LS-4.5	2	Fair	2	Fair
LS-10.5	5	Fair	2	Fair
LS-16	8	Poor	2	Fair

Acknowledgment

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