Drainability of Base Aggregate and Sand Project TPF 5(341)

Final Project Presentation

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Statement of Problem

- Lack of proper pore water drainage is one of the main causes of geosystem failure (e.g., roadway base course, retaining wall backfills).
- Proper drainage required to minimize elevated pore pressure, minimize freeze-thaw damage.
- Simple and reliable tools capable of estimating drainability parameters for common aggregate types will aid in material selection and design.
  - Saturated hydraulic conductivity, K_{sat}
  - SWCC parameters, n & α
  - Drainable porosity (n_d), field capacity (θ_f), minimum saturation (S_{min})

Project Objectives

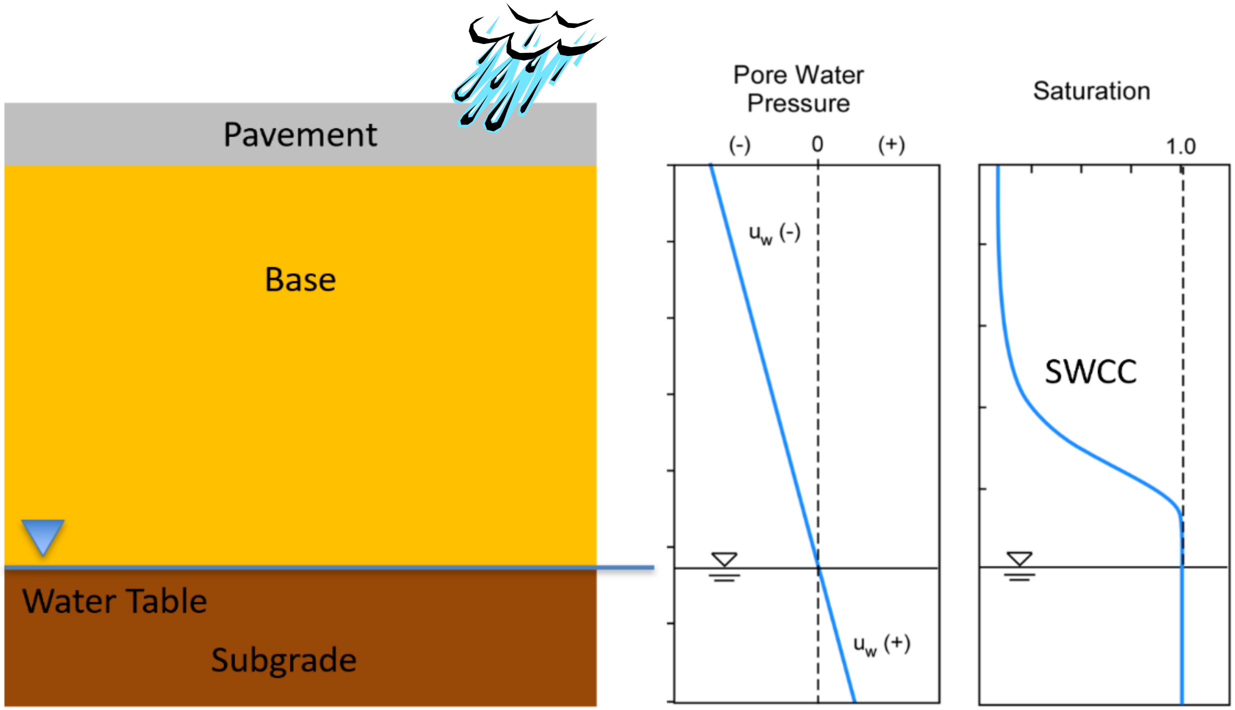
- Conduct laboratory permeability and water retention tests on materials used in or considered for use in pavement base systems.
- Evaluate general and specific empirical correlations for estimating drainability properties (K_{sat} and SWCC).
- Develop simple predictive tools that may be used to assess drainability from other properties (e.g., gradation, fines content, etc.)

Drainability: An Unsaturated Soils Problem

1) Material Properties (Permeability, Water Retention Characteristics)

2) Pavement System Design (Layering, Slope, Drainage Boundaries)

3) Environmental Conditions (Precipitation, Temperature)



Samples Obtained

Sample Number	Sample
1	3149 Super Sand (MnDOT)
2	MN Class 5 (MnDOT)
3	1007 Type 5 DGB (MoDOT)
4	1007 Type 7 DGB (MoDOT)
5	1010 Man. Sand (MoDOT)
6	MCC Freeborn West Quarry Crushed Stone (WisDOT)
7	Lannon Lisbon Pit (North Ave.) Structural Backfill (WisDOT)
8	Lannon Lisbon Pit (Mukwonago) Structural Backfill (WisDOT)
9	Lannon Stone Product Chips (WisDOT)
10	Super Aggregate Pit Granular Backfill (WisDOT)
15	Bryan Redrock Class 5, MnDOT Pit 70006
16	Bryan Redrock Ball Diamond material, MnDOT Pit 70006
A1	1¼'' Base (WisDOT)
A2	¾'' Washed (WisDOT)
A3	Manufactured Sand (WisDOT)
A4	¾'' Base Cs. (WisDOT)
A5	Breaker Run (limestone/dolomite) (WisDOT)

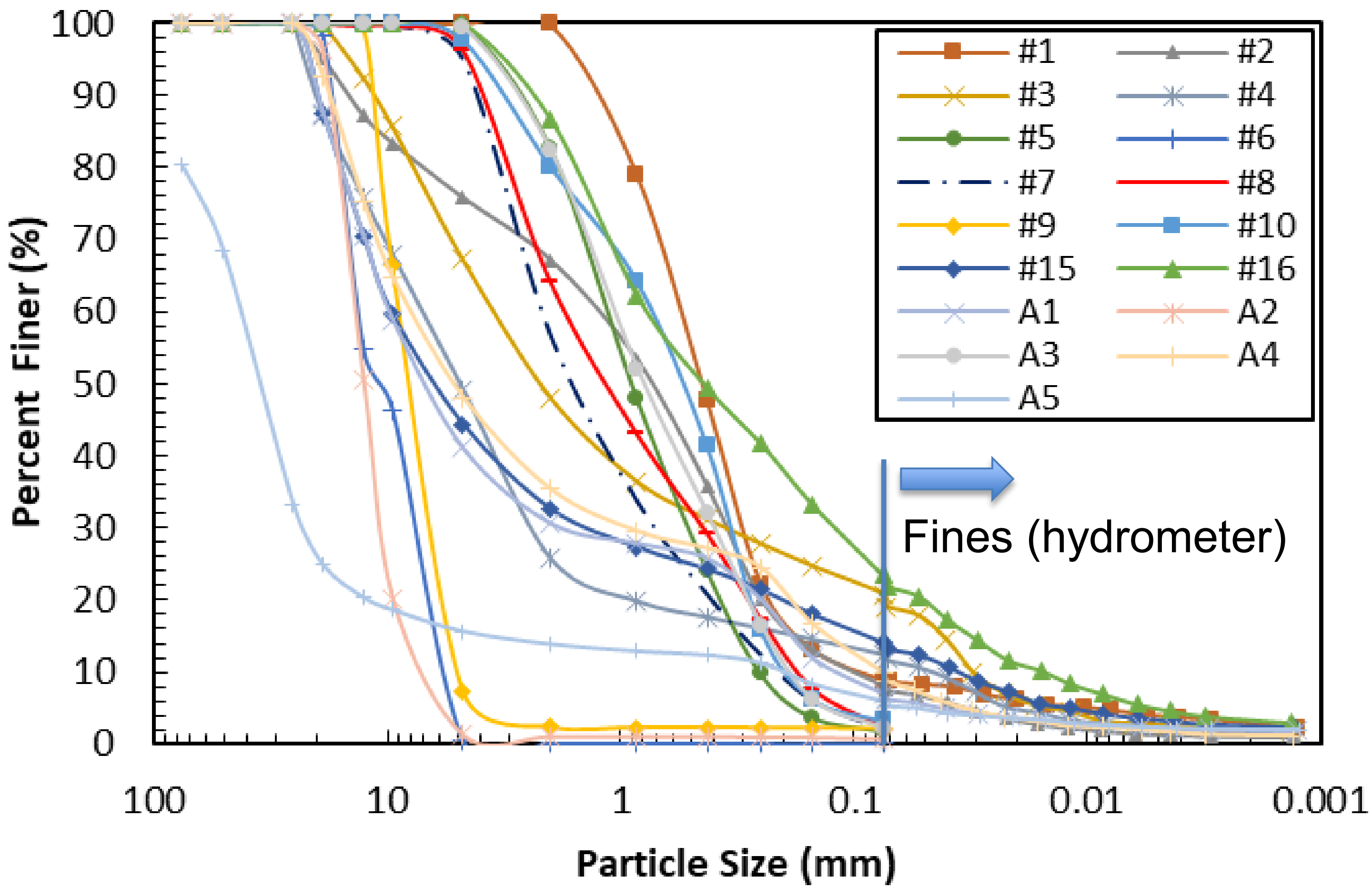
(1) 3149 Super Sand

(2) Mn Class 5

(3) 1007 Type 5 DGB

(4) 1007 Type 7 DGB

Particle Size Distributions



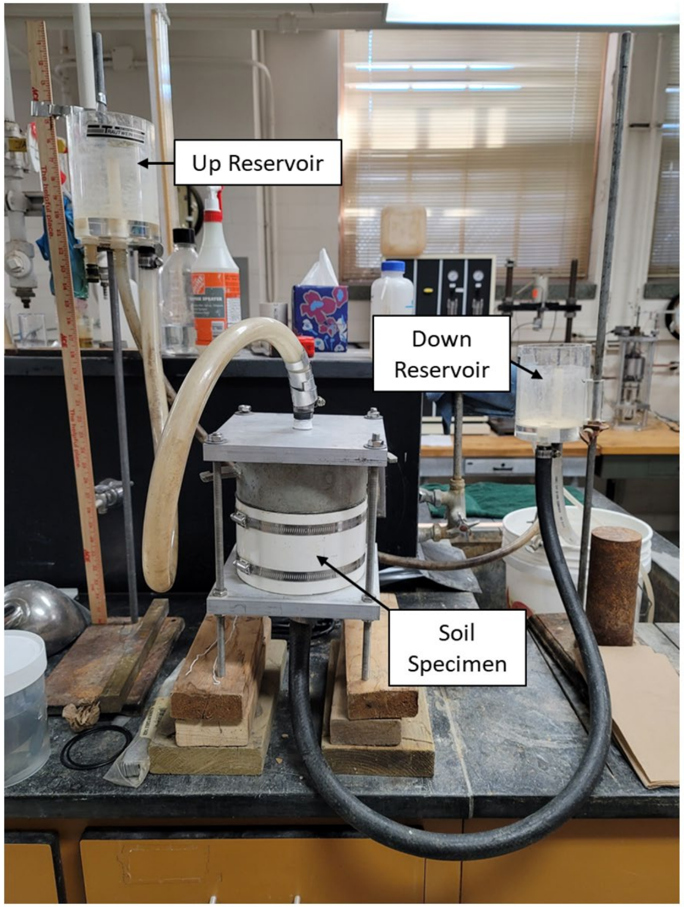
Indices and Classification

9 sands & 7 gravels; fines from ~0% to ~23%

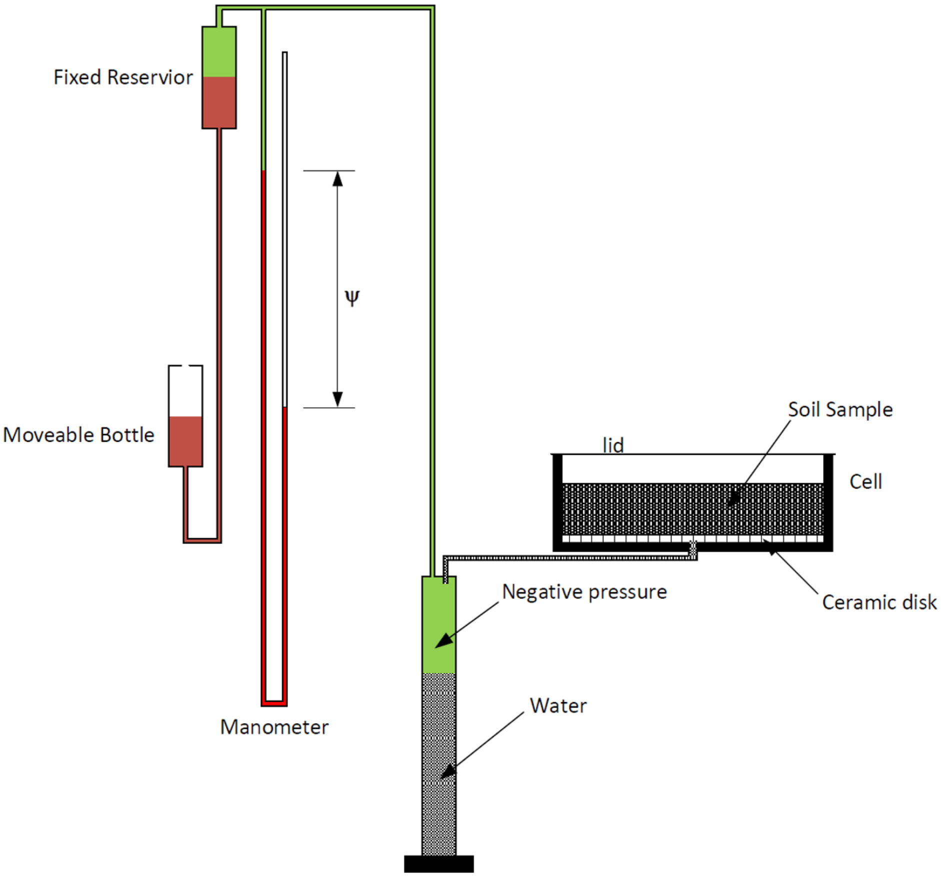
Sample	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	% Fines	% Gravels	γ_d (kN/m^3)	USCS
#1	0.09	0.30	0.46	0.55	5.91	8.82	100.00	18.57	SP-SM
#2	0.10	0.36	0.72	1.38	13.53	8.18	75.73	19.63	SW-SM
#3	0.03	0.36	2.28	3.65	114.78	20.8	67.18	17.76	SM
#4	0.05	2.50	4.90	7.09	154.13	12.5	49.24	17.80	GM
#5	0.27	0.52	0.90	1.26	4.75	1.89	99.75	15.91	SP
#6	5.85	7.70	10.9	14.0	2.39	0.19	0.59	16.22	GP
#7	0.22	0.72	1.70	2.20	10.09	2.03	95.17	18.65	SW
#8	0.18	0.45	1.30	1.82	10.11	2.39	96.40	20.10	SP
#9	5.00	6.60	8.05	8.95	1.79	2.17	7.37	16.57	GP
#10	0.20	0.33	0.53	0.72	3.60	3.24	97.72	18.26	SP
#15	0.04	1.58	6.35	9.50	256.76	14.1	44.37	18.66	GM
#16	0.02	0.13	0.44	0.79	46.90	23.4	99.88	17.69	SM
A1	0.13	1.82	7.00	9.92	76.31	7.05	41.03	18.63	GW-GM
A2	7.19	11.2	12.8	14.4	2.00	0.84	1.39	15.94	GP
A3	0.19	0.40	0.80	1.10	5.73	2.27	99.33	17.27	SP
A4	0.08	0.93	5.20	7.99	102.44	9.89	48.06	19.18	GW-GM

Note: D_{10}, D_{30}, D_{50}, D_{60} = particle sizes corresponding to 10%, 30%, 50%, 60% finer, respectively, in particle-size distribution curve; C_u = coefficient of uniformity; C_c = coefficient of curvature; USCS = unified soil classification system

K_{sat} and SWCC Testing

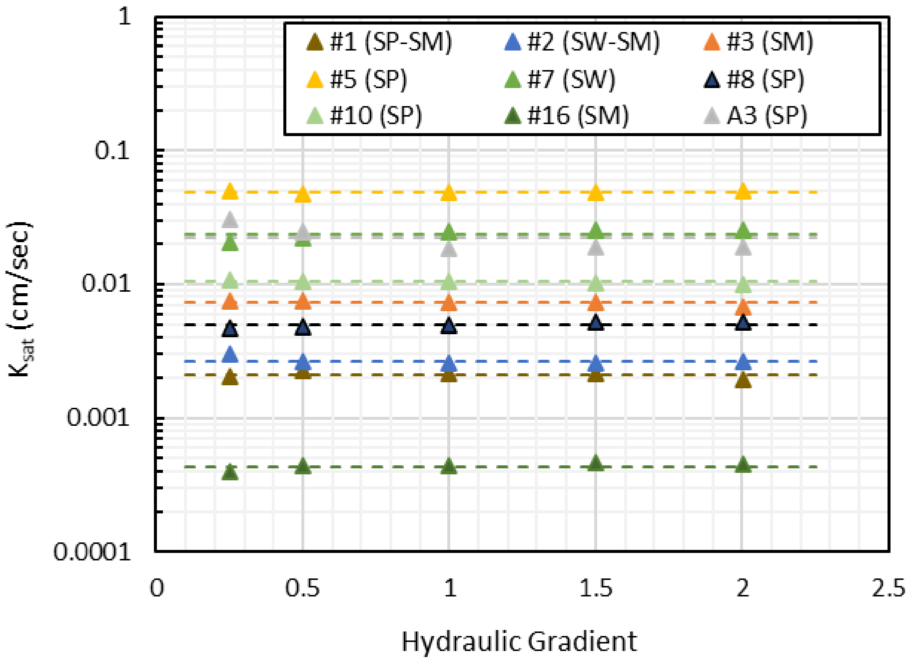


Constant Head Apparatus (K_{sat})

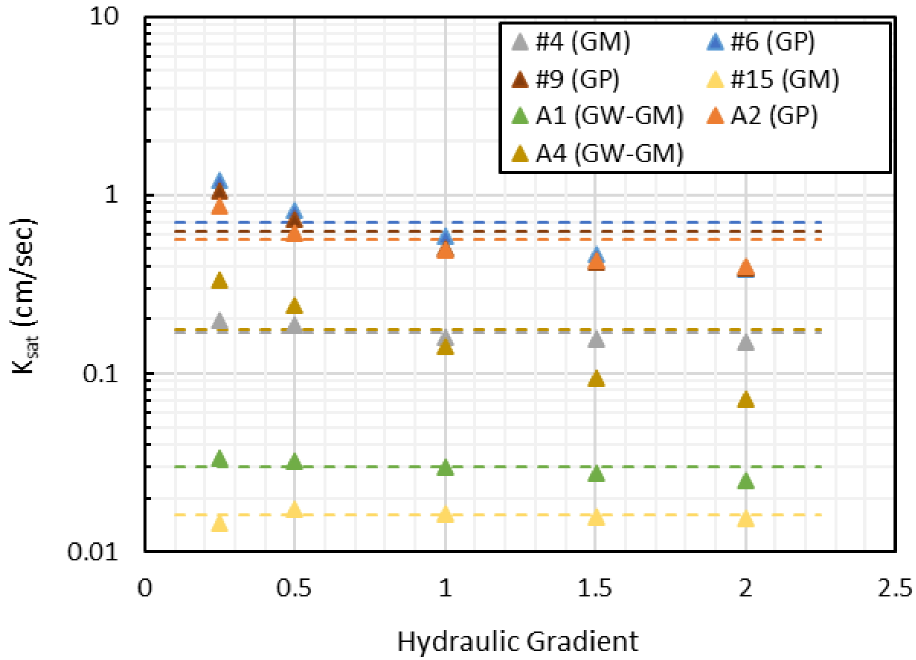


Hanging Column Apparatus (SWCC)

K_{sat}: Effect of Hydraulic Gradient



(Sands)



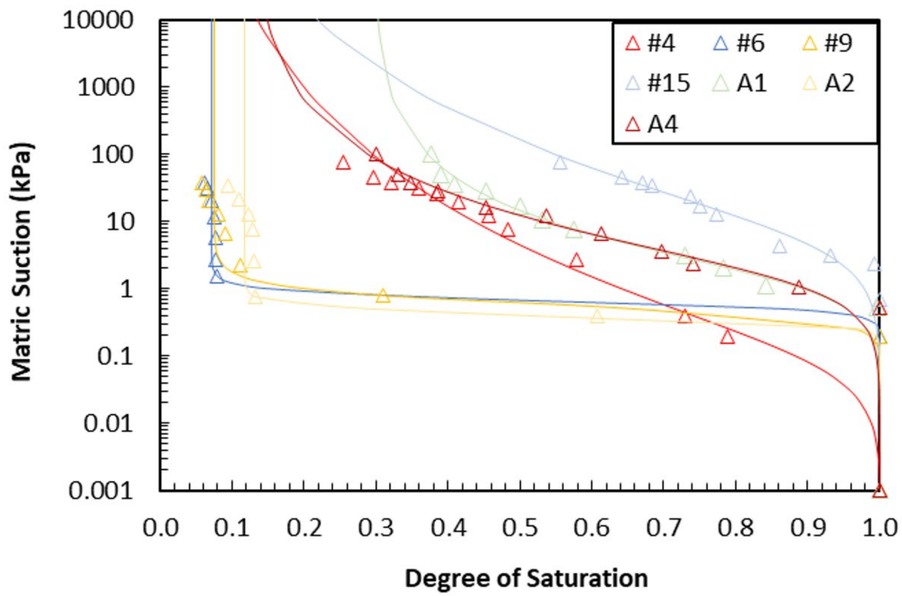
(Gravels)

- Potential fines migration
- Turbulent flow regime (gravels?)

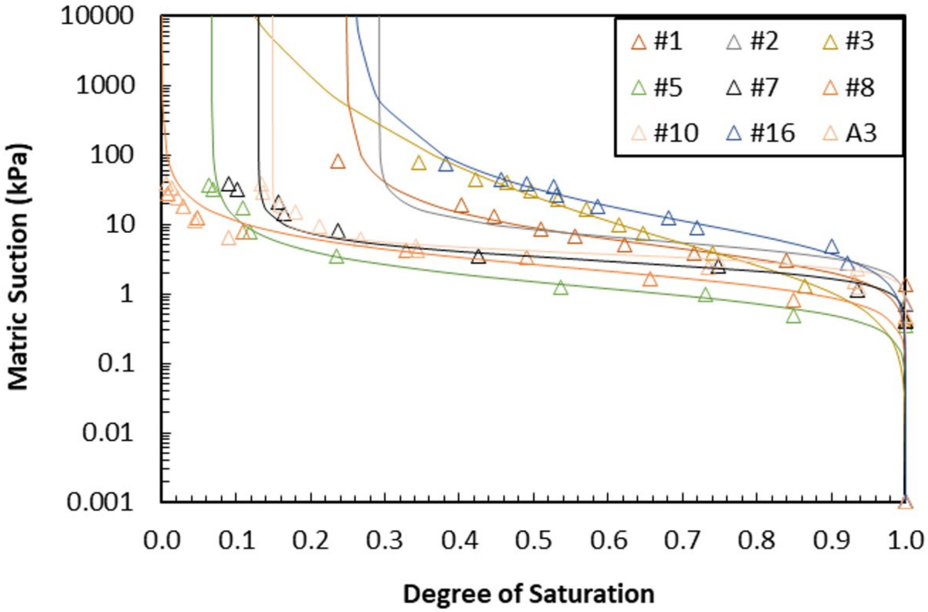
$$Q = kiA$$

Soil-Water Characteristic Curves

(Gravels)



(Sands)



$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1+(\alpha\psi)^n}\right]^{1-1/n}$$

Van Genuchten (1980) Model

K_{sat} and SWCCs

Sample	Hydraulic Conductivity Testing					Soil-Water Characteristic Curve Testing					
	γ_d (kN/m^3)	Min. K_{sat} (cm/s)	Max. K_{sat} (cm/s)	Avg. K_{sat} (cm/s)	Standard Deviation	γ_d (kN/m^3)	Air-Entry Pressure (kPa)	van Genuchten (1980) Parameters (*13*)			
								θ_r	θ_s	α	n
#1 (SP-SM)	18.6	0.002	0.002	0.002	0	18.5	1.80	0.07	0.29	0.29	2.09
#2 (SW-SM)	19.6	0.003	0.003	0.003	0	19.6	2.90	0.07	0.24	0.20	3.16
#3 (SM)	17.8	0.007	0.008	0.007	0	17.8	0.59	0.00	0.32	0.77	1.23
#4 (GM)	17.8	0.150	0.196	0.169	0.02	17.8	0.04	0.00	0.32	13.26	1.17
#5 (SP)	15.9	0.048	0.050	0.049	0.001	16.0	0.45	0.03	0.38	1.07	2.31
#6 (GP)	16.2	0.387	1.207	0.696	0.3	16.3	0.46	0.03	0.37	1.57	6.48
#7 (SW)	18.7	0.021	0.025	0.024	0.002	18.6	1.70	0.04	0.28	0.38	3.45
#8 (SP)	20.1	0.005	0.005	0.005	0	20.1	0.80	0.00	0.23	0.57	2.24
#9 (GP)	16.6	0.389	1.050	0.620	0.25	16.6	0.30	0.03	0.36	1.93	3.97
#10 (SP)	18.3	0.015	0.017	0.016	0	18.3	2.10	0.04	0.30	0.29	4.62
#11 (GW-GM)	18.6	0.025	0.034	0.030	0.003	18.7	0.51	0.08	0.28	0.74	1.52
#12 (GP)	15.9	0.396	0.874	0.562	0.17	16.0	0.23	0.05	0.39	2.54	7.18
#13 (SP)	17.3	0.019	0.030	0.022	0.005	17.3	1.90	0.00	0.34	0.34	3.74
#14 (GW-GM)	19.2	0.072	0.333	0.176	0.10	19.2	0.60	0.03	0.26	0.65	1.40
#15 (GM)	18.7	0.015	0.017	0.016	0.001	18.7	2.10	0.00	0.28	0.20	1.20
#16 (SM)	17.7	0.0004	0.0005	0.0004	0	17.7	2.60	0.08	0.32	0.16	1.65

Gravel average K_{sat} = 0.324 cm/s
Sand average K_{sat} = 0.014 cm/s

Empirical Equations for K_{sat}

Literature search was conducted to summarize equations for predicting saturated hydraulic conductivity from grain size, compaction indices, ad fluid properties (e.g., d10, porosity, viscosity)

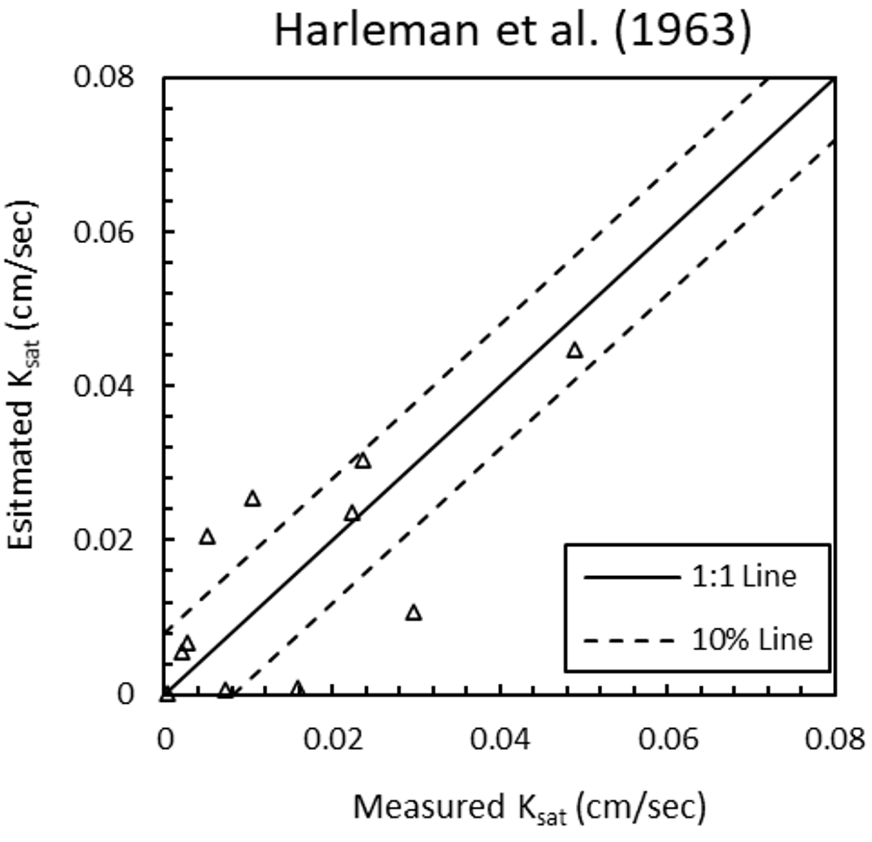
The equations used in this study were as follows:
Alyamani and Sen (Equation C.21)
Beyer (Equation C.12)
Harleman et al. (Equation C.11)
Original Hazen (Equation C.1a)
Modified Hazen (Equation C.1b)
Kozeny (Equation C.9)
Kozeny-Carman (Equation C.10)
Sauerbrei (Equation C.19)
Slichter (Equation C.3)
Terzaghi (Equation C.5)
U.S. Bureau of Reclamation (Equation C.20)
Salarashayeri and Siosemarde (Equation C.25)
Chapuis (Equation C.28)

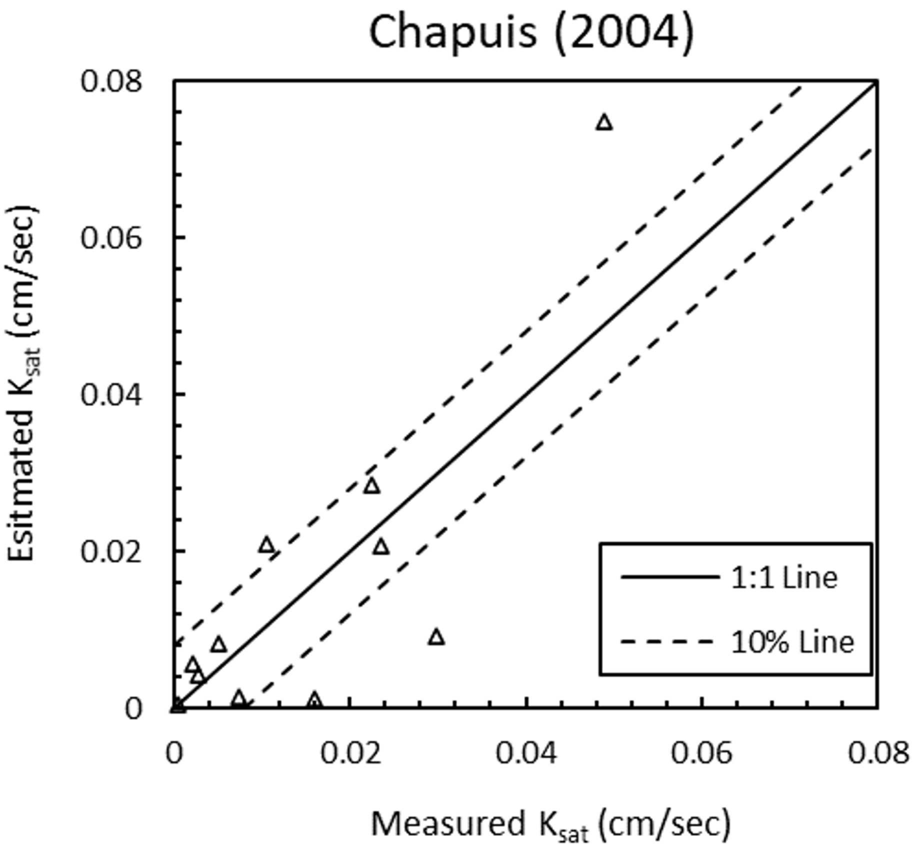
$$K[m/s] = \beta \frac{g}{v} \log \frac{500}{C_u} d_{10}^2$$

(Beyer, 1964)

Empirical Equation Performance

(Gravels excluded)

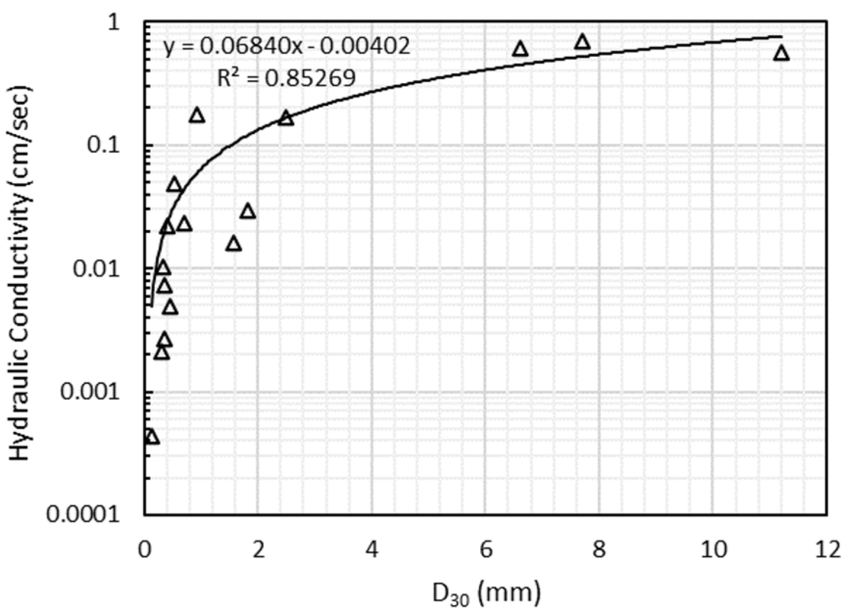


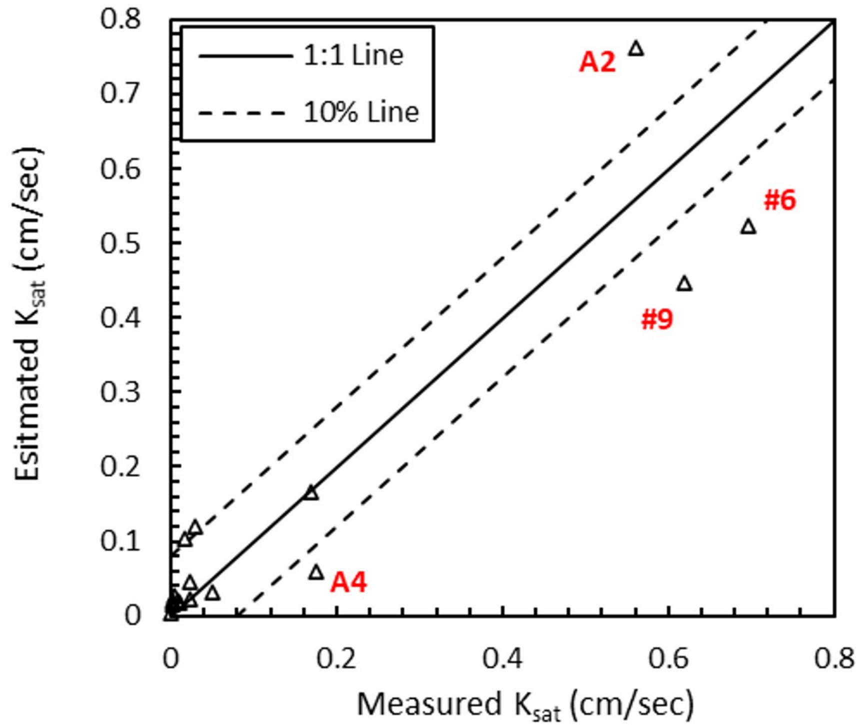


Dataset Specific Correlations

(Example using D30)

$$K_{sat} = 0.0684 \times D_{30} - 0.004 \; (R^2 = 0.85)$$





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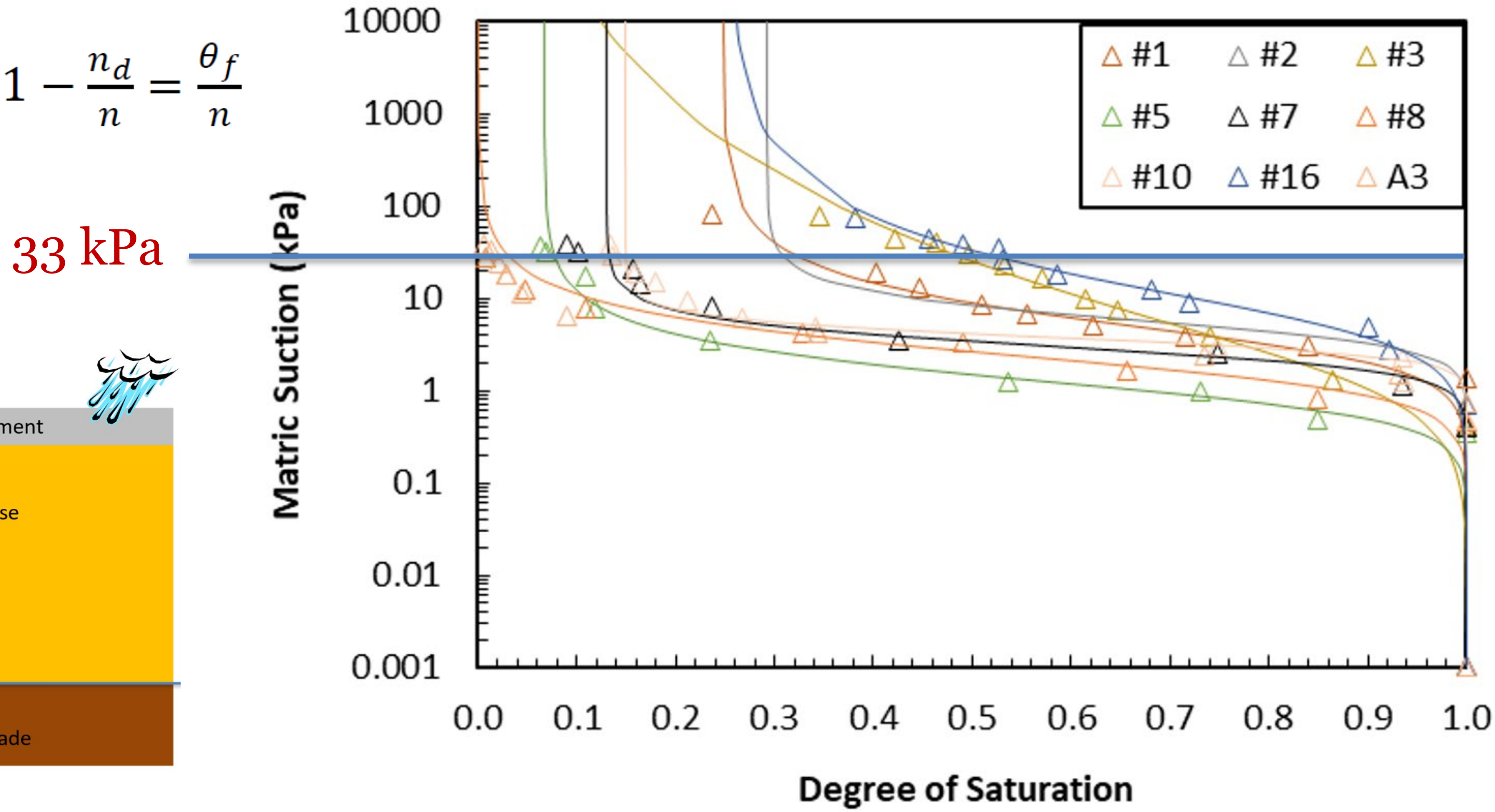
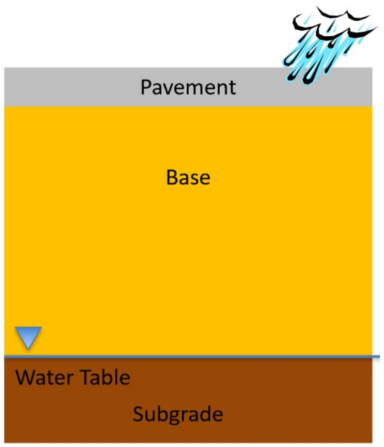
Field Capacity, Drainable Porosity, & Minimum Saturation

$$n_d = n - \theta_f$$

$$S_{min} = 1 - \frac{n_d}{n} = \frac{\theta_f}{n}$$





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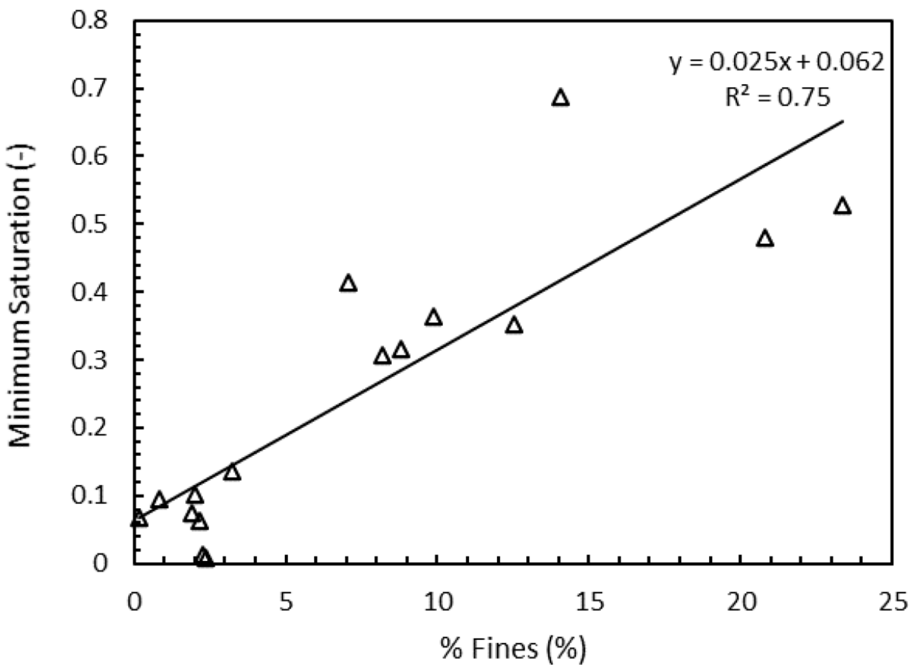
Sample	Total Porosity ($n = \theta_s$)	Field Capacity (θ_f)	Effective Porosity (n_d)	Minimum Saturation (S_{min})
#1 (SP-SM)	0.29	0.09	0.2	0.32
#2 (SW-SM)	0.24	0.08	0.17	0.31
#3 (SM)	0.32	0.15	0.16	0.48
#4 (GM)	0.32	0.11	0.2	0.35
#5 (SP)	0.38	0.03	0.36	0.08
#6 (GP)	0.37	0.03	0.35	0.07
#7 (SW)	0.28	0.03	0.25	0.10
#8 (SP)	0.23	0.002	0.22	0.01
#9 (GP)	0.36	0.02	0.34	0.06
#10 (SP)	0.3	0.04	0.26	0.14
#15 (GM)	0.28	0.19	0.09	0.69
#16 (SM)	0.32	0.17	0.15	0.53
A1 (GW-GM)	0.28	0.12	0.16	0.41
A2 (GP)	0.39	0.04	0.35	0.09
A3 (SP)	0.34	0.005	0.33	0.01
A4 (GW-GM)	0.26	0.10	0.17	0.36

$$S_{min} = 0.025(\%F) + 0.062 \; (R^2 = 0.75)$$



Estimating van Genuchten SWCC parameters (Benson et al., 2014)

$$\alpha = \alpha_1 N_\alpha$$

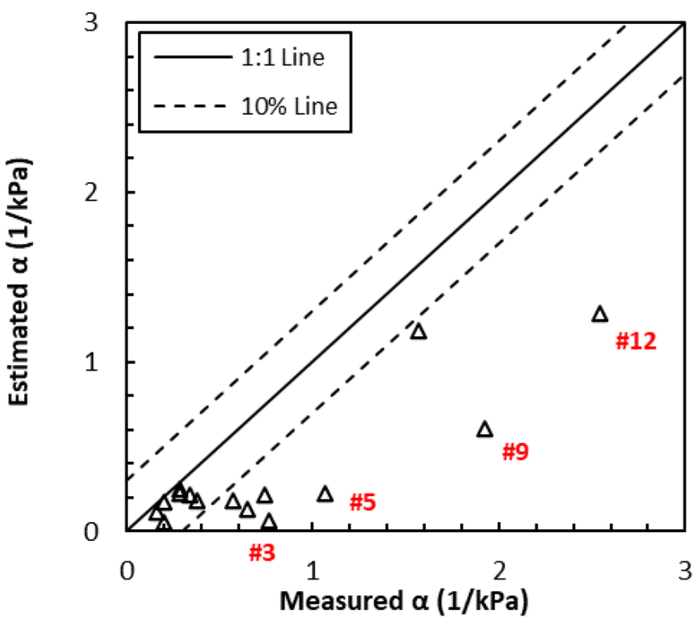
$$n = n_1 N_n$$

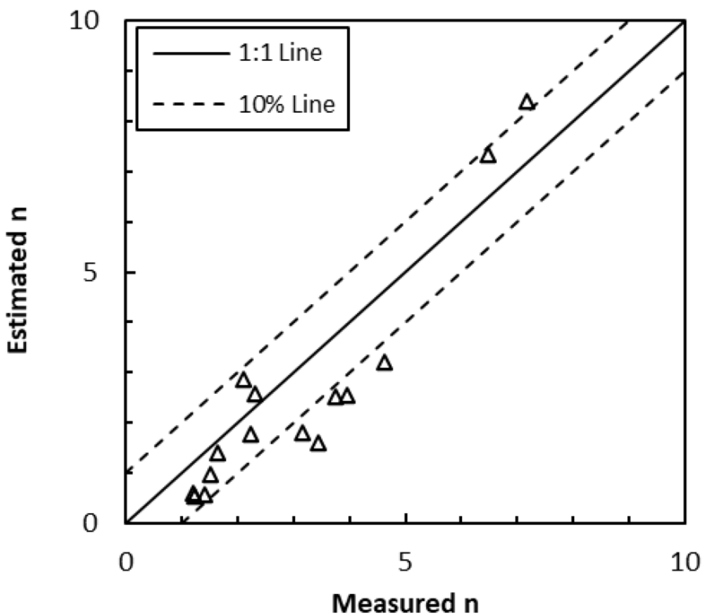
$$\alpha_1 = 0.0008 \times {D_{30}}^2 + 0.1843 \times D_{30} + 0.3567 \; (R^2 = 0.85)$$

$$N_\alpha = -0.12 \ln(C_u) + 0.7155$$

$$n_1 = 0.0419 \times {D_{30}}^2 + 0.0073 \times D_{30} + 2.4052 \; (R^2 = 0.65)$$

$$N_n = 1.5107 \times {C_u}^{-0.3187}$$





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Proposed Drainability Rating System

Qualitative Drainability	K_{sat} (cm/s)	Minimum Saturation
Excellent	$K_{sat} \geq 0.35$	$S_{min} \leq 0.10$
Marginal	$0.02 \leq K_{sat} < 0.35$	$0.10 < S_{min} \leq 0.30$
Poor	$K_{sat} < 0.02$	$S_{min} > 0.30$

Approach 1: Direct measurement of K_{sat} and S_{min}

Approach 2: Estimation of K_{sat} and S_{min} from grain size (D_{30}, C_u)

Approach 3: Estimation of K_{sat} and S_{min} from % fines

Based on Direct Measurements

Sample	K_{sat} (cm/s)	Minimum Saturation	K_{sat} Criterion	S_{min} Criterion	Overall Rating
#1 (SP-SM)	0.0021	0.32	Poor	Marginal	Poor-Marginal
#2 (SW-SM)	0.0027	0.31	Poor	Marginal	Poor-Marginal
#3 (SM)	0.0073	0.48	Poor	Poor	Poor
#4 (GM)	0.1693	0.35	Marginal	Poor	Marginal
#5 (SP)	0.0489	0.08	Marginal	Excellent	Marg - Excellent
#6 (GP)	0.6957	0.07	Excellent	Excellent	Excellent
#7 (SW)	0.0236	0.10	Marginal	Excellent	Marginal
#8 (SP)	0.0050	0.01	Poor	Excellent	Marginal
#9 (GP)	0.6196	0.06	Excellent	Excellent	Excellent
#10 (SP)	0.0104	0.14	Poor	Marginal	Poor-Marginal
#15 (GM)	0.0159	0.69	Poor	Poor	Poor
#16 (SM)	0.0004	0.53	Poor	Poor	Poor
A1 (GW-GM)	0.0298	0.41	Marginal	Poor	Poor-Marginal
A2 (GP)	0.5618	0.09	Excellent	Excellent	Excellent
A3 (SP)	0.0224	0.01	Marginal	Excellent	Marg - Excellent
A4 (GW-GM)	0.1759	0.36	Poor	Marginal	Poor-Marginal

#6 (GP)

#15 (GM)

Based on Grain Size

$$K_{sat} = 0.0684 \times D_{30} - 0.004 \; (R^2 = 0.85)$$

$$\alpha_1 = 0.0008 \times {D_{30}}^2 + 0.1843 \times D_{30} + 0.3567 \; (R^2 = 0.85)$$

$$N_\alpha = -0.12 \ln(C_u) + 0.7155$$

$$n_1 = 0.0419 \times {D_{30}}^2 + 0.0073 \times D_{30} + 2.4052 \; (R^2 = 0.65)$$

$$N_n = 1.5107 \times {C_u}^{-0.3187}$$

$$\alpha = \alpha_1 N_\alpha$$

$$n = n_1 N_n$$

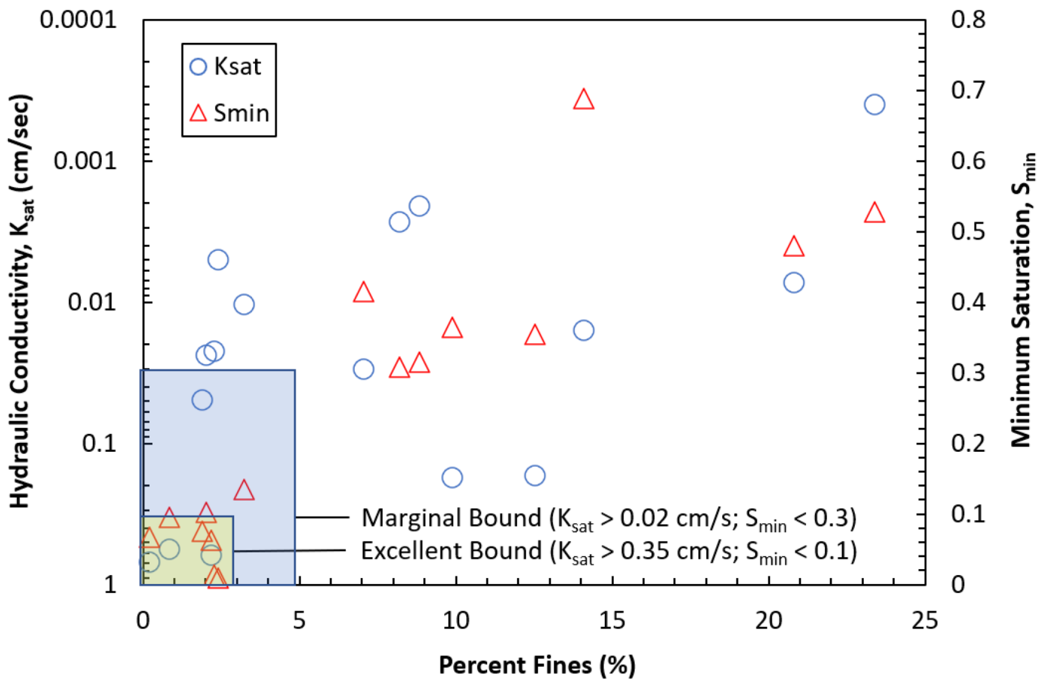
$$S_{min} = \left[\frac{1}{1+(\alpha 33)^n}\right]^{1-\frac{1}{n}} \leq 1.0$$

Sample	K_{sat} (cm/s)	Minimum Saturation	K_{sat} Criterion	S_{min} Criterion	Overall Rating
#1 (SP-SM)	0.017	0.13	Poor	Excellent	Marginal
#2 (SW-SM)	0.021	0.35	Marginal	Excellent	Marginal
#3 (SM)	0.021	*(1.0)*	Marginal	Poor	Poor-Marginal
#4 (GM)	0.167	*(1.0)*	Marginal	Poor	Poor-Marginal
#5 (SP)	0.032	0.08	Poor	Excellent	Marginal
#6 (GP)	0.523	0.00	Excellent	Excellent	Excellent
#7 (SW)	0.045	0.22	Marginal	Excellent	Marg - Excellent
#8 (SP)	0.027	0.25	Marginal	Excellent	Marg - Excellent
#9 (GP)	0.447	0.00	Excellent	Excellent	Excellent
#10 (SP)	0.019	0.05	Marginal	Excellent	Marg - Excellent
#15 (GM)	0.005	*(1.0)*	Poor	Poor	Poor
#16 (SM)	0.120	0.78	Marginal	Marginal	Marginal
A1 (GW-GM)	0.023	*(1.0)*	Marginal	Marginal	Marginal
A2 (GP)	0.060	0.01	Marginal	Excellent	Marg - Excellent
A3 (SP)	0.017	0.12	Poor	Excellent	Marginal
A4 (GW-GM)	0.021	*(1.0)*	Marginal	Marginal	Marginal

Based on % Fines

$$K_{sat} = 0.0684 \times D_{30} - 0.004 \ (R^2 = 0.85)$$

$$S_{min} = 0.025(\%F) + 0.062 \ (R^2 = 0.75)$$



Sample	% Fines	Overall Rating
#1 (SP-SM)	8.8	Poor
#2 (SW-SM)	8.2	Poor
#3 (SM)	20.8	Poor
#4 (GM)	12.5	Poor
#5 (SP)	1.9	Excellent
#6 (GP)	0.2	Excellent
#7 (SW)	2	Excellent
#8 (SP)	2.4	Excellent
#9 (GP)	2.2	Excellent
#10 (SP)	3.2	Marginal
#15 (GM)	14.1	Poor
#16 (SM)	23.4	Poor
A1 (GW-GM)	7.1	Poor
A2 (GP)	0.8	Excellent
A3 (SP)	2.3	Excellent
A4 (GW-GM)	9.9	Poor

Comparison of 3 Approaches

	Overall Rating		
Sample	Direct Measurement	Estimation from Grain Size	Estimation from Percent Fines
#1 (SP-SM)	Poor-Marginal	Marginal	Poor
#2 (SW-SM)	Poor-Marginal	Marginal	Poor
#3 (SM)	Poor	Poor-Marginal	Poor
#4 (GM)	Marginal	Poor-Marginal	Poor
#5 (SP)	Marg - Excellent	Marginal	Excellent
#6 (GP)	Excellent	Excellent	Excellent
#7 (SW)	Marginal	Marg - Excellent	Excellent
#8 (SP)	Marginal	Marg - Excellent	Excellent
#9 (GP)	Excellent	Excellent	Excellent
#10 (SP)	Poor-Marginal	Marg - Excellent	Marginal
#15 (GM)	Poor	Poor	Poor
#16 (SM)	Poor	Marginal	Poor
A1 (GW-GM)	Poor-Marginal	Marginal	Poor
A2 (GP)	Excellent	Marg - Excellent	Excellent
A3 (SP)	Marg - Excellent	Marginal	Excellent
A4 (GW-GM)	Poor-Marginal	Marginal	Poor

#6 (GP)

#15 (GM)

Project Reports and Papers

- Oh, H., Likos, W.J., Edil, T.B. 2021, "Drainability of base aggregate and sand," NRRA Final project report, TPF-5(341).
- Oh, H., Likos, W.J., Edil, T.B. 2021, "Qualitative rating system for drainability of roadway base materials," *Transportation Research Record*, in review.
- Likos, W.J., 2021, "Applying unsaturated soil mechanics to improve pavement geomaterial performance," TRB Webinar, August 3, 2021.