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16. Abstract (Limit: 200 words)

Soil water retention refers to the relationship between the amount of soil water and the energy with which it is held. This relationship is important for characterizing water movement through granular materials. In this project, we generated soil moisture retention data of 18 non-recycled and 7 recycled materials used in pavement construction. The results showed that water retention of non-recycled materials was nearly similar. The major differences among the curves were in the inflection points (air entry values) and in the water contents either near saturation or at 15,300 cm of suction. Using this database, we also developed Pedo-transfer functions that can predict (1) water retention or (2) the parameters of functions that describe water retention from easily measurable properties of the pavement materials. Water retention of concrete with and without shingles was only slightly different. This is partially because shingle chips imbedded in the concrete were large. Traditionally, the influence of matric suction has not been directly considered in pavement design. The water retention data in this report will be helpful in developing resistance factors for Minnesota Flexible Pavement Design Program either through physical modeling or through statistical relationships between design criteria and the water contents.

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Moisture Retention Characteristics of Base and Sub-base Materials

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EXECUTIVE SUMMARY

Soil water retention refers to the relationship between the amount of soil water and the energy with which it is held. This relationship is not only an indicator of the pore size distribution but also the volume occupied by various pore classes. The relationship is important for characterizing the rate at which water moves through a granular material under both saturated and unsaturated conditions. Important consequences of this relationship are the amount of drainage that occurs through soils, how deep the frost penetrates, and how strength properties vary seasonally. Although there is substantial information in the literature on soil water retention characteristics, most of this information is for relatively loose agricultural soils. The goal of the project was to generate soil moisture retention data for compacted aggregate base, sub-base, and subgrade materials used in pavement construction. Since there is an increasing emphasis on the use of recycled materials in roadbed preparation, the secondary goal of this project was to characterize the water retention properties of aggregate base materials that contained recycled material.

In this study, we characterized the physical and chemical properties and wetting and drying water retention characteristics of 18 samples of non-recycled base and sub-base materials. These samples included thirteen samples of Select Granular (SG), one sample of class-4 (CL-4), four samples of class-5 (CL-5). In addition, we characterized the above properties in 7 recycled materials used in roadbed construction. These materials include one sample each of concrete, crushed concrete, crushed concrete with shingles, and 4 samples of bottom ash. The results showed that most base and sub-base materials used for roadbed construction in Minnesota are nearly similar in terms of traditional sand, silt, and clay contents. In general, drying curves of these materials were nearly similar (within a narrow range of water contents). The main differences among these curves were in the inflection points (air entry values) and in the water contents either near saturation or at 15,300 cm of suction. This is expected considering that particle size distribution of most samples were nearly similar. In this study, we also developed Pedo-transfer function models that predict water retention properties of roadbed materials from easily measurable properties such sand % and dry bulk density or the water retention function parameters of van Genuchten, Brook and Corey, Fredlund and Xing equations from particle size distribution, percent particles passing #200, D10, D60, or the grading numbers. We also tested the empirical and physico-empirical models in the literature for predicting water retention of roadbed materials. In general, these models did not predict well the water retention properties of roadbed materials because of high densities (up to 1.95 Mg m^{-3}) or low clay content.

There was only a slight difference in water retention of concrete with and without shingles. This is partially because shingle chips imbedded in the concrete were large and thus did not alter the properties of the concrete. However, orientation of imbedded shingles can have significant effect on pathways for water flow in base and sub-base materials.

The influence of matric suction has traditionally not been directly considered in pavement design. The water retention data in this report will be helpful in developing resistance factors for Minnesota Flexible Pavement Design Program (MnPAVE) either through physical modeling or through statistical relationships between design criteria and the water contents.

Chapter 1: INTRODUCTION

Soil water retention refers to the relationship between the amount water in soil and the energy with which it is held. This relationship is not only an indicator of the pore size distribution but also the volume occupied by various pore classes. The relationship is important for characterizing the rate at which water moves through a granular material and its strength and stiffness under both saturated and unsaturated conditions. Important consequences of this relationship are the amount of drainage that occurs through soils, how deep the frost penetrates, and how strength properties vary seasonally. Since soil particle packing leads to formation of many different size pore necks and pore bodies, water retention of granular material also varies depending upon the size distribution of the granular material, the shape of the particles, and how they are packed. Furthermore, since different pore neck sizes and pore bodies are joined together in a sequence, this leads to different soil water retention characteristics depending on whether soil is wetting or drying.

Before 1979, there was substantial information in the literature on water retention characteristics of different soils but there was no easy way to predict these properties for other unknown soils and soil materials. Gupta and Larson (1979) were among the first who developed Pedo-transfer functions for predicting water retention characteristics of soils. Since that time, there have been significant efforts toward building of soil hydraulic properties databases as well as in improving Pedo-transfer functions. Notable among those are the works of Rawls and Brakensiek (1981) and Rawls et al. (1982). Since the mid 1960's there have been other efforts made to develop new methods of predicting hydraulic properties based on material characterization (Mualem, 1976; Arya and Paris, 1981) and thus, better representation of the hydraulic functions (Brook and Corey, 1964; Campbell, 1974; and van Genuchten, 1980).

In 1989, an international conference was held to summarize the existing knowledge on soil water retention characteristics and to present method of estimating these properties for unsaturated soils (van Genuchten et al., 1992). One product of this conference was a collection of all databases that were available in the literature. Since that time, these databases have grown and are now routinely used in many modeling efforts. In 1997, a second international conference was held on characterization and measurement of the hydraulic properties of unsaturated porous media" (van Genuchten et al., 1999). In this conference, besides improving the existing methodologies for determining hydraulic properties and Pedo-transfer functions, research was also summarized on additional artifacts in water flow such as preferential flow and water retention characteristics of multi-phase systems.

Although there is a large amount of data available on soil water retention characteristics a limitation of existing databases is that moisture characterization is for relatively loose agricultural soils at or below natural field bulk densities. Water retention data for low clay highly compacted soils, as is the case for pavement base and sub-base, is limited. Also, there is no single transfer function model available for predicting water retention characteristics of aggregate base or granular subgrade materials from easily measurable soil properties. Most numerical simulations of water flow and drainage under pavements in the literature have been made with water retention characteristics estimated using loose agricultural soils databases

(Roberson et al., 2004). However, there is no confirmation of predictions relative to the measured values.

Minnesota Department of Transportation (Mn/DOT) is currently using a relatively small database (SoilVision®) which includes the work by Fredlund and Xing (1994) in the field of geotechnical engineering. This project was started with the idea of generating soil moisture retention database for compacted aggregate base, granular, sub-base and subgrade soils typically used in pavement construction and then using this database to develop methods for predicting these properties for unknown materials. The long-term goal is to incorporate this database in the Soil Vision software so that soil water retention properties for unbound pavement materials can be generated from easily measurable properties such as particle size distribution.

Since there is an increasing use of recycled materials in roadbed construction, there is also a potential for change in water retention properties and thus soil water flow when recycled materials are mixed with aggregate base and sub-base materials. Alteration in the water retention properties of the materials due to mixing of recycled materials may be due to differences in physical properties such as grain size and shape (small chips in case of shingles) or due to chemical properties such as wettability (in case of shredded tires and shingles) or due to cementation (with ash fly).

Specifically, the goal of this project was to characterize water retention characteristics of aggregate base and sub-base materials during both drying and wetting cycles and then develop procedures that can be used to predict these properties from relatively simple measurements such as particle size distribution and packing density.

Chapter 2: OBJECTIVES

Specific objectives of the study were:

- Develop wetting and drying water retention characteristics of aggregate base, sub-base, and subgrade materials including select granular materials used in roadbed construction.
- Develop best-fit parameters of Brooks and Corey (1966), Van Genuchten (1980), and Fredlund and Xing (1994) functions that describe water retention characteristics.
- Quantify the gradation of these base materials in terms of parameters such as particle size distribution, % passing #200, D10, D60, or grading numbers.
- Develop Pedo-transfer functions of water retention at a given suction to material gradation properties.
- Develop regression relationships between Van Genuchten, Brook and Corey and Fredlund and Xing function parameters to material gradation properties.
- Run moisture retention characteristics on 5-10 aggregate base materials that contain recycled material.
- Identify the impact of recycled material on hydraulic properties.

Chapter 3: SCOPE

The study characterized water retention characteristics of 18 aggregate base and sub-base materials that bracket the extremes of gradation bands. These samples were classified according to Mn/DOT specifications and include thirteen samples of Select Granular (SG), one sample of class-4 (CL-4), four samples of class-5 (CL-5). These samples include aggregates that are believed to provide good pavement drainage. Six of the thirteen select granular samples were also used in another study by the Civil Engineering department at the University of Minnesota to characterize their resilient modulus (Davich et al., 2004). Samples of these specified gradations were generated by Mn/DOT laboratory through mixing or were collected from field sites by the Mn/DOT personnel. The study also characterized the water retention characteristics of 7 recycled materials used in roadbed construction. These materials were selected in consultation with the Recycled Materials Resource Center at the University of New Hampshire. These materials include one sample each of concrete, crushed concrete, crushed concrete with shingles, and 4 samples of bottom ash.

Chapter 4: METHODOLOGY

Particle Size Distribution and Chemical and Mineralogical Properties

The particle size distribution of the roadbed materials was estimated using dry sieve apparatus for particles sizes >0.075 inches (0.19 mm) and Horiba LA-910 Laser Analyzer for finer particles. The gradation was done at the Mn/DOT Soil Laboratory. This particle size analysis was used to calculate the grading number (GN) of each sample.

$$GN(\%) = \frac{25mm + 19mm + 9.5mm + 4.75mm + 2.0mm + 0.425mm + 0.075mm}{100} \qquad \text{Eq. [1]}$$

where all numbers are in percent passing a given sieve size. Maximum value of GN is 7.0 and represents the extremely fine gradation whereas minimum value of GN is 0.0 and represents the very coarse gradation. Grading number for both the coarse and the fine fractions were calculated. Coarse grading number (CGN) accounted for particles between 4.75 to 25 mm diameter whereas fine grading number (FGN) accounted for particles between 0.075 and 2.0 mm diameter particles (Table 1). Kremer and Dai (2004) showed that strength measurements with the Dynamic Cone Penetrometer were related to grading numbers.

Base and sub-base materials were also tested for dissolved heavy metals and other basic elements. The procedure involved mixing soil and water in 1:10 ratio, shaking the suspension for 24 hours and then centrifuging the suspension for 20 minutes at 6000 rpm. The dissolved chemicals were analyzed in the supernatant on the Inductive Coupled Plasma (ICP).

The Soil Geomorphology Laboratory at the University of Nebraska analyzed the samples for clay mineralogy. The procedure involved separating the clay particles and running the x-ray diffraction of clay particles mounted on a glass slide. Peaks in diffraction patterns are then used to separate out various clay minerals present in the sample.

Water Retention

Drying and wetting water retention characteristics were measured on all samples. At a given suction, the amount of water held in soil during drying is greater than that during wetting. In other words, it takes more force to desorb than to sorb water from a soil material at a given water content. This hysteretic effect is mainly due to elliptical nature of the soil pores (Gupta and Wang, 2002).

The procedure for water retention curves involved preparing the soil sample to optimum water content identified by the Standard Proctor test and then packing the soil in metal cores to a maximum density also identified in the Standard Proctor test. Both optimum water content and density values were provided by Mn/DOT (Table 1). For drying curves, soil cores were saturated and then desorbed by applying a given air pressure in a pressure chamber. The soil drains the excess water over and above its retention capacity at that pressure. Once equilibrium was reached, the soil was subjected to the next air pressure and the outflow was measured. This process was repeated until the air pressure equivalent to the air entry value of the ceramic plate was reached. Finally, the soil core was taken out of the pressure chamber, weighed, and then oven dried at 105 ^oC. Water content at a given pressure was then calculated from the final water content of the soil core and the volume of outflow between pressure steps. Details of the procedure are given in Appendix A1 and A2.

Drying curves for the roadbed material covered a pressure head range of 10.2 cm to 15,300 cm H_2O. Several different apparatuses were used to cover the full range:

- Tempe cell apparatus: pressure range from 10.2 to 1,020 cm H_2O,
- 5-bar pressure plate apparatus: pressure range from 102 to 3,060 cm H_2O,
- 15-bar pressure plate apparatus: pressure range from 1,020 to 15,300 cm H_2O.

The pressure ranges overlapped and thus helped verify the accuracy of the results obtained from three different soil cores in three different pressure apparatuses.

Sorption curves were measured in a Tempe cell and covered the pressure range from 10.2 to 1020 cm H_2O head. The procedures for the wetting curve involved subjecting the soil core packed at the optimum water content to an air pressure corresponding to the suction desired. This was done while the soil core was in contact with a reservoir of water that is at atmospheric pressure. Atmospheric pressure at the base of the ceramic plate was maintained with a Marriott bottle set-up. The drop in water level in the Marriott bottle then corresponds to the volume of water that is adsorbed by the soil at a given air pressure. Details of the procedures for wetting curve are also given in the Appendix A3.

Development of Pedo-transfer functions

Drying soil water retention curves were used to develop Pedo-transfer functions. The procedure involved running stepwise regression of water retention at a given suction to easily measurable soil properties such as sand, silt, and clay contents, and the bulk density. Multiple regressions were done using the SAS (SAS, 2004) or SYSTAT version 6.0 (1996) statistical package.

Estimation of van Genuchten, Brooks-Corey, and Fredlund-Xing Parameters

Analytical formulations have been proposed to describe the water retention of soil materials over the whole suction range. Two of the well-known relationships are by van Genuchten (1980) and Brooks and Corey (1966). van Genuchten parameters (Eq. [2]) were calculated using the RETC (van Genuchten et al., 1980) program.

$$\Theta(h) = \left[1 + \alpha(-h)^n\right]^{-m} \qquad \text{Eq. [2]}$$

$$K(\theta) = K(\theta_s)\Theta^{0.5}\left[1\left(1-\Theta^{\frac{1}{m}}\right)^m\right]^2 \qquad \text{Eq. [3]}$$

$$\Theta = \frac{q - q_r}{q_s - q_r}$$ Eq. [4]

where h is matric potential (cm), α is inverse of the air-entry value, m and n are constants that describe the shape of the water retention curve (m=1-1/n), K(θ_s) is saturated hydraulic conductivity, Θ is the relative water content, θ_s is the saturated water content, and θ_r is the residual water content.

Brooks and Corey formulations can be described as:

$$\Theta = \left(\frac{h_a}{h}\right)^{n_c}$$ Eq. [5]

$$K(q) = K(q_s)\Theta^{3+2n_c}$$ Eq. [6]

where h_a is the air entry suction and n_c is the pore size distribution index. Brooks and Corey parameters were obtained by fitting Eq. [5] to the measured data in a Soil Vision program.

Fredlund and Xing (1994) presented a more generalized equation (Eq. [7]) for describing the water retention characteristic of the soil materials.

$$q = q_s \left[1 - \frac{\ln\left(1 + \frac{h}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\ln[\exp(1)] = \left[\frac{h}{a_f}\right]^{nf}}\right]^{mf}$$ Eq. [7]

where h_r is the suction at which residual water content occurs, a_f is a soil parameter (kPa) which is a function of air entry value of the soil, n_f is a soil parameter which is function of the rate of water extraction once the air entry value has been exceeded, and m_f is a soil parameter which is a function of the residual water content. Equation [7] was fitted to the experimental data in a Soil Vision program to obtain the fitted parameters.

Statistical Analysis

Step-wise multiple regression between van Genuchten, Brook-Corey, or Fredlund-Xing parameters and particle size analysis was run using the SAS (SAS, 2004) or SYSTAT version 6.0 (1996) statistical packages.

Chapter 5: RESULTS

Particle Size Distribution and Chemical and Mineralogical Properties

Figure 1 shows the particle size distribution of 18 samples of non-recycled base and sub-base materials. Particle size distribution ranged from 0.0001 mm to 80 mm in diameter. Almost all samples included some proportion of larger aggregates (>2 mm). Although these aggregates are important for good drainage under saturated conditions, they contribute very little to water retention in soils. In fact, most of the water held in soil materials is by fractions <2 mm. Therefore, to be consistent with the earlier literature, we normalized the particle size data such that sand (0.05-2.0 mm), silt (0.002-.05 mm), and clay (<.002 mm) contents equaled 100%. In Appendix B are given the particle size distribution of these samples.

Figure 2 shows the particle size distribution of base and sub-base materials after normalization. In general, the data shows that most base and sub-base materials used for road construction are nearly similar in terms of traditional sand, silt, and clay contents. Based on the USDA classification, all the materials in this study will be classified as sandy soils. In Table 2 is given the range of sand, silt, and clay contents for various groups of materials. In general, the non-recycled material samples contained 79 to 99% sand, 1 to 17% silt, and 0 to 6% clay.

The range of sand, silt, and clay for Select Granular (SG) samples varied from 79 to 99%, 1 to 17%, and 0 to 6 %, respectively (Table 2). The corresponding values for Class 5 were 88 to 90%, 8 to 10% and 1 to 3% (Table 2). For Class 4 category, there was only one sample and the sand, silt and clay contents were 83%, 14% and 4%, respectively. The difference in gradation between samples for a given group is because the samples were collected from different sources. The three recycled material samples (CL-7) were concrete, crushed concrete and crushed concrete mixed with shingles (10%). The gradation for CL-7 materials didn't vary much with sand and silt contents equal to 92% and 8%, respectively. Particle size distributions of bottom ash samples were not available.

Chemical and mineralogical characteristics of all base and sub-base samples (excluding recycled materials) were nearly similar (Appendix C1 and C2). All these samples contained a mixture of montmorillonite, illite and kaolinite clay minerals. The other minerals included quartz, and plagioclase feldspar. The main chemical differences between samples were in soluble Ca, Fe and Al contents. However, these differences should have minimal impact on water retention characteristics of these samples.

Water Retention Curves (Desorption)

Figure 3 is an example of the measured and fitted water retention characteristic curve. The best-fit desorption curves for non-recycled and recycled materials are presented in Figs. 4 and 5, respectively. The dry bulk density of the samples ranged from 1.72 to 2.19 Mg m^{-3} for the non-recycled materials and from 1.98 to 2.04 Mg m^{-3} for the recycled materials (Table 2). In general, desorption curves of these materials are nearly similar (within a narrow range of water contents). The main differences among these curves are in the inflection points (air entry values) and in the water contents either near saturation or at 15,300 cm of suction. This is expected considering that particle size distribution of most samples were nearly similar.

Pedo-transfer Function Model

A Pedo-transfer function model was developed to predict water retention properties of roadbed materials from easily measurable properties such as sand, silt, and clay contents, and dry bulk density. Using the stepwise regression, we found the following model that gave the best results.

$$\theta_p = a + b \times \text{Sand (\%)} + c \times \text{BD}, \qquad \text{Eq. [8]}$$

where θ_p=water content at a given suction, BD = oven (105 °C) dry bulk density in Mg m^{-3}, and a, b, and c are empirical coefficients.

In Table 3 are listed the empirical coefficients of the Pedo-transfer model at various matric heads. Dry bulk density was the major factor contributing to water retention for these materials (Eq. [8]). This was partially because most of the roadbed materials were similar in texture (sandy) and the fact that the major difference between these materials was the density at which the samples were packed. The next important factor in predicting water retention of these materials was percent sand, partially because clay and silt contents in these samples were relatively small.

Pedo-transfer Function Model Validation

Predictions from the Pedo-transfer function model developed above were also tested against measurements made by Mn/DOT soil laboratory on 8 different samples. Table 4 lists the sand and silt contents along with dry bulk density of these samples. Figures 6-9 show the comparisons of measured and predicted water retention curves. In general, the observed and simulated water retention curves compared well with R^2 ranging from 0.84 to 0.99.

van Genuchten, Brook-Corey, and Fredlund-Xing Parameters

In Table 5 are summarized the values of the van Genuchten's function parameters by aggregate class. Individual sample values are given in Appendix C. The values for α, n, θ_r and θ_s varied from 0.0025 to 0.74 cm^{-1}, 1.30 to 1.98, 0.02 to 0.10 $m^3\ m^{-3}$ and 0.17 to 0.35 $m^3\ m^{-3}$, respectively, for non-recycled materials, and 0.024 to 0.15 cm^{-1}, 1.3 to 1.59, 0.08 to 0.09 $m^3\ m^{-3}$, 0.23 to 0.25 $m^3\ m^{-3}$ for recycled materials.

In Tables 6 and 7 are summarized the values of Brooks-Corey and Fredlund-Xing parameters by aggregate class. Individual values of Brooks-Corey and Fredlund-Xing parameters for each soil material are given in Appendix E2 and E3, respectively. Air entry value (h_a) in Brooks and Corey equation, ranged from 0.13 to 9.9 kPa for non-recycled soil samples, and 0.43 to 2.3 kPa for recycled materials (Table 6). For the pore index parameter (n_c), values ranged from 0.084 to 0.775 and 024 to 0.40 for non-recycled and recycled materials, respectively.

For the Fredlund and Xing's function model, a_f ranged from 0.004 to 21.7 kPa for non-recycled material, and 0.53 to 3.34 for recycled materials (Table 7). The values of h_r (kPa), varied from 1.43 to 52.8 for non-recycled material and 6.46 to 17.12 for recycled materials. The value of m_f ranged from 0.04 to 0.89 for non-recycled material and 0.073 to 0.11 for recycled materials. Comparatively, n_f values ranged from 0.58 to 20.0 for non-recycled material and 16.13 to 20.0 for recycled materials.

Values of van Genuchten's parameters obtained in this study were also tested against the prediction from the Rosetta Model (Table 8). Rosetta model predictions are based on the literature values that mainly encompass the agricultural soils. In general, there was very little variation in α values for various samples as predicted from the Rosetta model (Fig. 10). However, the n values predicted from the Rosetta model were higher than those measured in this study (Fig. 11). Although θ_s values predicted from the Rosetta model were close to the measured values (Fig. 12), θ_r values predicted from the Rosetta model were higher than the measured values (Figs. 13). This is expected considering that agricultural soils (Rosetta model) are finer, relatively loose, and contain higher organic matter content than the roadbed materials. Also, θ_r values predicted from the Rosetta model were nearly the same for all samples.

Regression analysis was also run to see if there exists relationships between van Genuchten parameters (Eq. [2]) and the particle size analysis. Table 9 lists various best-fit regression equations. These regression equations were developed using the step-wise regression approach (Appendix F). As expected, R^2 values increased when second-order terms were included in the regression. For practical application, regression equations with second-order terms appeared to be reasonable for predicting water retention characteristics using van Genuchetn's function. Regression relationships of van Genuchten's parameters with gradation indices such as D_{60} and D_{10} (Table 10) or gradation number (Table 11) were poor compared to similar relationships with particle size analysis. This is somewhat expected because (1) some gradation indices are based on one or two values on the particle size distribution curve and do not say much about the shape of the curve which really determines the water retention, and (2) other gradation indices include particle sizes that are >2 mm diameter that are shown not to contribute to water retention of soil materials. Regression equations with gradation number (Table 11) were slightly better than those with D_{60} and D_{10}.

Similar to above analysis, step-wise regression analysis was also done for Brooks-Corey parameters (Eq. [5]) and Fredlund-Xing parameters (Eq. [7]) with particle size analysis (Tables 12 and 15) or gradation indices (Tables 13, 14, 16, and 17). Like before, there was poor correlation between Brooks-Corey and Fredlund-Xing parameters with first order particle size analysis and bulk density (Tables 12 and 15). However, when second-degree variables were included, correlation coefficient improved significantly (Appendix G--Brooks-Corey and Appendix H--Fredlund-Xing). The improvement in correlation coefficient with second-degree variables was much higher for Brooks-Corey and Fredlund-Xing parameters than for the van Genuchten's parameters. Like earlier analysis, relationship of Brooks-Corey and Fredlund-Xing parameters to particle gradation indices (D_{60}, D_{10}, GN) was poor (Tables 13, 14 and 16, 17).

Predictions from Existing Models

We also tested the predictions of water retention from two commonly used models from the literature against our data. These models are the regression model of Gupta and Larson (1979) and a physico-empirical model of Arya and Paris (1986). Gupta and Larson (1979) model is a regression based model that was developed using 43 mixtures of soil and dredged sediments. The generic regression equation describing this model is:

θp=a x sand% + b x silt% +c x clay % + d x OM % + e x bulk density   Eq. [9]

where θp is the water content at a given suction; sand, silt, and clay are in percent; OM is the organic matter in percent; and a, b, c, d, and e are empirical coefficients. The values of empirical coefficients at a given suction for the Gupta and Larson model are given in Appendix E.

Arya and Paris model is based on the concept that soil water retention curve is similar to the particle size distribution curve and then it is a matter of converting particle amount into pore volume (water content) and particle radii into pore radii (suction). These authors used particle packing along with an empirical coefficient to predict water retention from particle size distribution curve.

$$V_{n_i} = \left(\frac{W_i}{r_p} \right) e; \qquad i = 1, 2, ..., n \qquad \text{Eq. [10]}$$

$$q_{v_i} = \sum_{j=1}^{j=i} \frac{V_{v_j}}{V_b} \qquad \text{Eq. [11]}$$

where Vv_i is the pore volume per unit sample mass associated with the solid particle in the *i*th particle-size range, W_i is the solid mass per unit sample mass in the *i*th particle-size range, V_b is the total bulk volume, ρ_p is the particle density, and e is the void ratio.

$$r_i = R_i \left[\frac{4 e n_i^{(1-a)}}{6} \right]^{1/2} \qquad \text{Eq. [12]}$$

$$h_i = \frac{2g \cos b}{r g r_i} \qquad \text{Eq. [13]}$$

where r_i is the mean pore radius, R_i is the mean particle radius, n_i is number of spherical particles in the *i*th particle-size range, γ is water surface tension , g is acceleration due to gravity, β is contact angle (assumed zero), and α is an empirical parameter with a best value of 1.38.

Both Gupta and Larson and Arya and Paris models have extensively been used for predicting water retention of loose agricultural soils (dry bulk densities less than 1.8 Mg m^{-3}). Figures 14 and 15 show two comparisons of predicted and measured water retention for two roadbed materials. In general, Gupta and Larson model predicted well the water retention characteristics for roadbed materials with densities up to 1.95 Mg m^{-3}. But the model did not perform as well for higher bulk densities. This is mainly because the water retention database of Gupta and Larson did not cover high bulk densities such as those used in roadbed construction. Since smaller particles have a greater influence on water retention in Arya and Paris model, this model didn't predict well the water retention of roadbed materials (Figs. 14 and 15), because the roadbed materials tested in this study were mostly the sand fraction.

Wetting Curves

Figures 16 through 19 show a comparison between the wetting and drying water retention curves for four non-recycled road-bed materials. Except for 2 samples (SG02-A, SG02-F), water content differences between wetting and drying curves were relatively small. This is mainly because all roadbed materials had nearly similar particle size distribution. In SG02-A and SG02-F, the differences in water content between the wetting and the drying curves were as large as 0.12 and 0.20 cm^3 cm^{-3}.

Water Retention of Recycled Materials

Figures 20 through 22 show both the wetting and drying curves of Class 7 concrete, and Class 7 crushed concrete with and without shingles. In general, there was a slight difference in water retention of crushed concrete with and without shingles. This is partially because shingle chips were large and imbedded in the concrete and thus did not alter the properties of the concrete. Even though this data show little impact of the shingle on water retention of concrete, presence of shingle chips can alter the flow paths and in some cases it may provide a preferential pathway along the chip surface. Water retention curves for bottom ash samples in included in Appendix D.

Chapter 6: DISCUSSION

There is limited variation in the water retention characteristics of base and sub-base materials used for road construction in Minnesota. This is mainly because the particle size distributions of all the samples used in this study fall in a relatively narrow range. The major difference between the materials is the presence of large aggregates (>2 mm diameter), which contribute very little to water retention properties but have a strong influence on saturated hydraulic conductivity and thus on saturated water flow and drainage. These large aggregates, especially gravel, may also act as pathways for preferential movement of water. This data suggest that the use of water retention characteristics (more controlled by smaller particles) along with saturated hydraulic conductivity (more controlled by larger aggregates) to predict unsaturated hydraulic conductivity of roadbed materials (Eqs. [2] and [6]) may not be prudent. Studies should be undertaken to develop databases of road-bed materials of various aggregate sizes used in road-bed construction. These databases should then be used to develop Pedo-transfer functions that can predict hydraulic conductivity of materials from simple parameters such as aggregate size distribution or gradation indices.

Several different types of Pedo-transfer function models are given in this report that can be used to predict water retention characteristics of base and sub base materials. These models include simple regression models that predict water retention at a given suction using bulk density and particle size distribution. Other models predict function (van Genuchten, Brooks-Corey, and Fredlund-Xing) parameters using similar input variables. However, one should be careful in using predicted function parameters to predict hydraulic conductivity using van Genuchten or Brook and Corey equations [Eqs. [2] and [6]). This is mainly because all three functions depend heavily on measured saturated hydraulic conductivity, which is mainly controlled by large aggregates.

Chapter 7: EXPECTED BENEFITS

Pavement aggregate base and sub-base are constructed under unsaturated conditions, generally around 90% of optimum water content at maximum density (Standard Proctor). The influence of matric suction has traditionally not been directly considered in pavement design. This is one of the key limitations in the design procedure because matric suction has a significant influence on engineering behavior of pavements related to the soil volume change, coefficient of permeability, freeze-thaw susceptibility, and the shear strength and modulus of pavement aggregate layers.

One of the features of Minnesota Flexible Pavement Design Program (MnPAVE), Mn/DOT's mechanistic-empirical pavement design software, is consideration of the effect of soil moisture on thickness design. Pore suction resistance factors are proposed as a means of incorporating variably saturated material conditions into pavement thickness design. Pore suction resistance factors are proposed for aggregate base by identifying the relationship between suction and resilient modulus. The water retention data in this report will be helpful in developing these resistance factors either through physical modeling or through statistical relationships between design criteria and the water contents.

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Table 1. Gradation number (GN) and optimum moisture content with Proctor Density. Samples 1 to 18 are non-recycled materials; samples 19 to 21 are recycled Class 7 materials); and samples 22 to 25 are recycled bottom ash materials.

Sample No.	Sample Sites	GN	CGN†	FGN†	% passing # 200 sieve	Optimum Moisture Content (%)	Max. Dry Proctor Density (pcf)	Max. Dry Proctor Density (Mg m^{-3})
1	Blue Earth County Road 90	4.65	3.59	1.06	6.9	9.2	111.8	1.790
2	I 35W Richfield	4.19	3.41	0.78	5.0	4.3	128.1	2.052
3	TH 610 Brooklyn Center SG	5.14	3.76	1.38	0.0	4.2	126.4	2.025
4	US 212 Eden Prairie SG	5.52	3.91	1.61	8.0	9.1	111.8	1.790
5	TH 22 St. Peter SG	4.59	3.62	0.97	11.9	5.1	127.3	2.039
6	TH 14 Mankato SG	5.44	3.93	1.51	10.2	7.6	118.0	1.890
7	SG02-A	3.53	2.78	0.75	3.6	7.9	134.7	2.160
8	SG02-D	4.75	3.66	1.09	4.3	10.0	114.8	1.830
9	SG02-F	5.97	3.97	2.00	10.3	9.3	118.6	1.900
10	SG02-H	6.18	4.00	2.18	21.4	12.6	107.7	1.725
11	SG02-J	5.85	4.00	1.85	2.0	9.5	111.8	1.790
12	SG02-N	5.00	3.82	1.18	7.4	8.8	125.7	2.013
13	TH 5 Eden Prairie	3.67	3.11	0.56	3.4	6.4	130.8	2.095
14	US 169 Jordan	4.56	3.56	1.00	7.2	4.8	124.5	1.994
15	TH 371 Brainerd Sand (North)	4.81	3.75	1.06	0.5	7.2	109.1	1.747
16	I 94 Mpls Sand	4.83	3.65	1.18	8.0	3.8	125.3	2.007
17	MnRoad Cell 52	4.41	3.54	0.87	9.2	7.5	137.1	2.196
18	US 12 Cokato	4.32	3.43	0.89	8.0	5.2	123.6	1.980
19	CL 7 Concrete	3.82	3.23	0.60	5.3	8.8	127.4	2.040
20	CL-7 Crushed Concrete	4.52	3.46	1.06	7.3	9.6	124.4	1.990
21	CL-7 cConcrete+Shingles	4.50	3.48	1.02	8.0	10.1	124.0	1.980
22	Bottom Ash C	3.03	2.57	0.46	6.3	19.6	110.0	1.760
23	Bottom Ash D	2.74	2.33	0.41	5.4	14.2	116.8	1.870
24	Bottom Ash E	3.24	2.71	0.53	7.8	15.7	112.5	1.800
25	Bottom Ash F	3.22	2.69	0.53	7.7	19.2	111.8	1.790

† CGN and FGN are coarse and fine gradation numbers, respectively.

Table 2. Particle size distribution of road-bed materials assuming 2 mm aggregates were the largest aggregates present. Bulk density values are the Proctor densities (Mg M^{-3}) supplied by Mn/DOT.

Samples Types	Sand,	Silt,	Clay,	Bulk Density
Select Granular	78.6 – 99.3	0.48 -16.58	0.17 - 3.00	1.72-2.16
CL-5	88.2 - 89.8	8.19 - 9.60	1.02 - 3.00	1.99-2.09
CL-4	82.48	13.65	3.87	2.19
Non-Recycled	78.6 - 99.3	0.48 -16.58	0.17 - 5.93	1.72-2.19
Recycled (CL-7)	92-93	7.00-8.00		1.98-2.04

Table 3. Regression coefficients (a, b, c) of the Pedo-transfer model for predicting water content (θ_p) at a given suction. θ_p = a + b x sand (%) + c x BD (Mg m^{-3})

Suction (cm)	a	b	c	Probability	R^2
1.0	0.9765	0.00	-0.3686	0.0001	0.985
10.2	0.6004	0.00	-0.2062	0.0129	0.4153
102	0.2711	-0.00433	0.1253	0.0086	0.4626
306	*0.1599*	-0.00417	*0.1633*	*0.0048*	0.6200
510	0.135	-0.00400	0.1623	0.0030	0.6513
714	0.1246	-0.00380	0.1580	0.0027	0.6600
1020	0.1162	-0.00360	0.1525	0.0026	0.6623
3060	0.1013	-0.00325	0.1388	0.0032	0.6488
5100	0.0966	-0.00314	0.1300	0.0035	0.6417
10200	0.0927	-0.00304	0.1314	0.0040	0.6337
15300	0.091	-0.00300	0.1299	0.0043	0.6290

Table 4. Sand and silt contents along with dry bulk density for 8 independent samples used to test the Pedo-transfer function model developed in this study.

Sample	Sand (%)	Silt (%)	B.D. (Mg m^{-3})
TH 371 Brainerd, Class 6	93.5	6.5	2.19
Mn Road Class 5	96.5	5.5	1.92
Mn Road Class 6 (crushed granite)	97.5	4.5	1.92
Mn Road Class 4	99.0	1.0	2.02
TH 371 Brainerd, SG	94.0	6.0	1.81
US 169 Mille Lacs	93.0	7.0	2.11
TH 25 Monticello, Class 6	93.5	6.5	2.12
Blue Earth Cty Rd 90, Class 3	91.5	8.5	1.70

Table 5. Range of van Genuchten parameters for different classes of road bed materials.

Samples Types	α	n	θ_r	θ_s	Air Entry Value
Selected Granular	0.020-0.51	1.30-1.98	0.02-0.10	0.18-0.35	1.96-40
Class-5	0.04-0.74	1.34-1.68	0.05-0.10	0.21-0.25	1.35-25
Class-4	0.0025	1.57	0.067	0.17	500
Non-Recycled	0.0025-0.74	1.30-1.98	0.02-0.10	0.17-0.34	1.35-500
Recycled	0.024-0.15	1.3-1.59	0.08-0.09	0.23 - 0.25	6.57-41.7

Table 6. Range of Brooks and Corey parameters for different classes of road bed materials.

Samples Types	a_C	n_C
Selected Granular	0.15-2.16	0.255-0.775
Class-5	0.132-0.856	0.084-0.385
Class-4	9.894	0.127
Non-Recycled	0.132-9.894	0.084-0.775
Recycled	0.429-2.295	0.244-0.395

Table 7. Range of Fredlund and Xing parameters for different classes of road bed materials.

Samples Types	a_f	h_R	m_F	n_F
Selected Granular	0.004-3.06	3.26-27.96	0.14-0.881	0.58-7.27
Class-5	0.008-1.564	1.43-7.90	0.039-0.629	1.01-20.0
Class-4	21.65	52.81	0.040	20.0
Non-Recycled	0.004-21.65	1.43-52.81	0.039-0.885	0.579-20.0
Recycled	0.53-3.34	6.46-17.12	0.073-0.106	16.13-20.0

Table 8. A comparison of measured and predicted (Rosetta Model) van Genuchten parameters for roadbed materials.

Sample No	Sample Description	α (obsv)	α (Rosetta)	n (obsv)	n (Rosetta)	θ_r (obsv)	θ_r (Rosetta)	θ_s (obsv)	θ_s (Rosetta)
1	Blue Earth County Road 90	0.4047	0.037	1.458	2.348	0.0487	0.043	0.24	0.255
2	I 35W Richfield	0.7396	0.037	1.373	2.665	0.0595	0.042	0.225	0.247
3	TH 610 Brooklyn Center SG	0.4896	0.035	1.349	3.09	0.058	0.044	0.236	0.251
4	US 212 Eden Prairie SG	0.153	0.038	1.553	2.702	0.1	0.044	0.32	0.301
5	TH 22 St. Peter SG	0.5094	0.048	1.304	1.611	0.087	0.038	0.2305	0.253
6	TH 14 Mankato SG	0.4912	0.039	1.464	2.227	0.0869	0.043	0.2867	0.28
7	SG02-A	0.1493	0.031	1.305	3.225	0.06	0.046	0.1849	0.233
8	SG02-D	0.2437	0.035	1.441	3.012	0.033	0.046	0.3094	0.29
9	SG02-F	0.0336	0.038	1.982	2.385	0.05	0.043	0.283	0.277
10	SG02-H	0.089	0.049	1.59	1.632	0.0569	0.037	0.349	0.321
11	SG02-J	0.1197	0.032	1.788	3.666	0.0244	0.048	0.3245	0.3
12	SG02-N	0.327	0.036	1.342	2.579	0.071	0.043	0.2402	0.255
13	TH5 Eden Prarie Class 5	0.0643	0.035	1.338	2.664	0.096	0.044	0.209	0.242
14	US 169 Jordan Class 5	0.0423	0.039	1.685	2.34	0.1	0.042	0.2475	0.258
15	TH 371 Brainerd Sand (North)	0.1074	0.031	1.954	3.979	0.02505	0.049	0.3407	0.311
16	I 94 Mpls Sand	0.0783	0.037	1.568	2.467	0.0671	0.043	0.2426	0.256
17	MnRoad Cell 2 Class 4	0.0025	0.041	1.832	2.074	0.0966	0.041	0.1713	0.228
18	US 12 Cokato SG	0.0209	0.043	1.656	2.055	0.0935	0.04	0.2529	0.261
19	CL-7 Concrete	0.024	0.035	1.59	3.14	0.0935	0.044	0.2302	0.248
20	CL-7 cConcrete	0.139	0.035	1.31	3.059	0.077	0.043	0.249	0.257
21	CL-7 cConcrete+Shingle	0.152	0.037	1.299	2.922	0.094	0.043	0.253	0.258

Table 9. Regression relationships between van Genuchten Parameters and the soil particle analysis and bulk density.

REGRESSION EQUATIONS	r^2
α = 1.386 + 4.914***Silt** - 5.229***Clay** - 0.718***BD**	0.282
α = 671.129 - 1325.005* **Silt** - 1276.152* **Clay** - 17.758***BD** + 1.115***BD**^{2} – 669.248* **Sand**^{2} + 2479.904* **Clay**^{2} + 941.681* **Silt**^{2} + 14.792***BD*Sand**	0.778
n = 2.764 - 0.855* **Silt** + 1.390* **Clay** - 0.598***BD**	0.221
n = -102.401 + 180.496* **Sand** + 35.003* **Clay** + 11.987***BD** - 72.496* **Sand**^{2} - 267.303* **Clay**^{2} + 156.226* **Silt**^{2} - 14.103***BD* Sand**	0.630
θ_s = 0.999 - 0.018* **Silt** + 0.043* **Clay** - 0.376***BD**	0.999
θ_r = -160 + 0.094* **Sand** + 0.438* **Silt** + 0.055***BD**	0.441
θ_r = 0.009 + 0.272***BD** - 17.315* **Clay**^{2} - 0.264***BD* Sand**	0.512

Table 10. Regression between van Genuchten Parameters and gradation indices (D_{60} and D_{10}).

REGRESSION EQUATIONS	r^2
α = 0.398 - 0.006***D60** - 0.849***D10**	0.067
α = 1.064-0.250***D60**-10.033***D10**-0.044***D60**^{2}+17.898***D10**^{2}+3.451***D60*D10**	0.513
n = 1.555 - 0.034***D60** + 0.586***D10**	0.201
n = 1.719 - 2.153***D10** + 0.005***D60**^{2}+ 9.373***D10**^{2} - 0.407***D60*D10**	0.289
θ_s = 0.264 - 0.012***D60** + 0.174***D10**	0.424
θ_s = 0.383 -0.053***D60**-1.206***D10**-0.001***D60**^{2}+ 3.311***D10**^{2}+0.260***D60*D10**	0.778
θ_r = 0.088 + 0.004***D60** - 0.227***D10**	0.397
θ_r = 0.065+0.016***D60**+0.039***D10**+0.001***D60**^{2}-0.441***D10**^{2}-0.123***D60*D10**	0.453

Table 11. Regression relationships between van Genuchten Parameters and gradation numbers (CGN and FGN). CGN and FGN are coarse (4.75 to 25 mm diameter aggregates) and fine (0.075 to 2.0 mm diameter aggregates) gradation numbers (Eq. 1).

REGRESSION EQUATION	R^2
α = -0.021 + 0.035***CGN** + 0.135 ***FGN**	0.071
α = 4.497 - 4.867***CGN** + 7.277***FGN** + 1.179***CGN^2** + 1.408***FGN^2** - 2.962***CGN x FGN**	0.181
n = 0.688 + 0.215***CGN** + 0.069***FGN**	0.190
n= 1.544 -1.134***CGN** + 2.695***FGN** + 0.390***CGN^2** + 0.669***FGN^2** - 1.202***CGN x FGN**	0.238
θ_s = -0.039 + 0.068***CGN** + 0.043***FGN**	0.566
θ_s = 1.271 - 0.786***CGN** + 0.142***FGN** + 0.148***CGN^2** + 0.065***FGN^2** - 0.091***CGN x FGN**	0.590
θ_r = 0.077 + 0.004***CGN** - 0.021***FGN**	0.104
θ_r = -1.094 + 0.944***CGN** - 0.811***FGN** - 0.182***CGN^2** - 0.095***FGN^2** + 0.286***CGN x FGN**	0.195

Table 12. Regression between Brooks and Corey Parameters and soil particle analysis and bulk density.

REGRESSION EQUATIONS	r^2
a_c = 0.436 - 10.830***Sand** + -3.559***Clay** + 5.335***BD**	0.208
a_c = - 10.394 + 7.319***Clay** + 10.800***Silt** + 5.337***BD**	0.208
a_c = - 2.800 + 3.106***Silt** - 7.601***Sand**+ 5.341***BD**	0.208
a_c = 13425.675 -16961.379***Sand** - 10896.403***Silt** - 5671.317***Clay** + 610.254***BD** + 3785.301***Sand^2** - 55507.301***Silt^2** - 13779.648***Clay^2**+ 54.551***BD^2** -848.026***BD*Sand** - 2813.088***BD*Clay**	0.922
n_C = 1.592 + 0.837***Sand** - 0.625***Clay** - 0.982***BD**	0.670
n_C = 2.429 - 1.461***Clay** – 0.837***Silt** – 0.982***BD**	0.669
n_C = 0.957 + 1.472***Sand** + 0.639***Silt** – 0.982***BD**	0.670

Table 13. Regression between Brooks and Corey Parameters and gradation indices (D_{60} and D_{10}).

REGRESSION EQUATIONS	r^2
a_c = 1.805 + 0.103***D60** - 6.790***D10**	0.039
a_c = -0.873 + 2.115***D60** + 14.390***D10** + 0.106***D60²** - 17.354***D10²** - 15.069***D60*D10**	0.235
n_C = 0.364 -0.036***D60** + 0.915***D10**	0.301
n_C = 0.708 - 0.142***D60** - 3.240***DT** - 0.003***D60²** + 10.331***D10²** + 0.669***D60*D10**	0.505

Table 14. Regression between Brooks & Corey Parameters and gradation numbers (CGN and FGN). CGN and FGN are coarse (4.75 to 25 mm diameter aggregates) and fine (0.075 to 2.0 mm diameter aggregates) gradation numbers (Eq. 1).

Equations	R^2
a_c = -0.999 + 1.033***CGN** - 1.339***FGN**	0.029
a_c = -8.520 -4.310***CGN** + 30.702***FGN** + 3.008***CGN²** + 8.199***FGN²** - 14.509***CGN x FGN**	0.115
n_c = -0.284 + 0.129 ***CGN** + 0.179 ***FGN**	0.364
n_c = 6.431 - 3.812***CGN** - 0.756***FGN** + 0.603***CGN²** + 0.012***FGN²** + 0.154***CGN x FGN**	0.422

Table 15. Regression relationships between Fredlund and Xing Parameters and the soil particle analysis and bulk density.

REGRESSION EQUATIONS	r^2
a_f = - 6.955 - 18.046***Sand** + 4.371***Silt** + 12.549***BD**	0.218
a_f = -352.900 + 5880.153***Clay** + 466.563***BD** + 1023.602***Sand²** - 1577.359***Silt²** - 8635.957***Clay²** + 154.391***BD²** - 1118.018***BD*Sand** - 2972.789***BD*Clay**	0.915
h_r = - 439.426 + 391.528***Sand** + 586.174***Silt** + 26.338***BD**	0.291
h_r = -16957.844 + 29913.633***Silt** + 54074.753***Clay** + 2680.515***BD** + 18333.244***Sand²** - 27891.967* **Silt²** - 55489.594***Clay²** + 311.442***BD²** - 4007.585***BD*Sand** - 13780.133***BD*Clay**	0.668
m_f = 2.729 - 2.533***Silt** -0.853***Clay** - 1.085***BD**	0.617
n_f = - 87.487 + 50.125***Sand** + 90.296***Silt** + 20.677***BD**	0.241
n_f = 46688.085 - 78043.667***Sand** - 19827.491***Silt** + 2861.115***BD** + 31665.996***Sand²** -45537.825***Silt²** - 102480.886***Clay²** + 54.414***BD²** - 3133.604***BD*Sand** - 11762.812***BD*Clay**	0.612

Table 16. Regression relationships between Fredlund and Xing Parameters and gradation indices (D_{60} and D_{10}).

REGRESSION EQUATIONS	r^2
$a_f = 3.135 - 13.185 \cdot D10 + 0.219 \cdot D60$	0.031
$a_f = -2.885 + 34.214 \cdot D10 + 4.669 \cdot D60 - 42.835 \cdot D10^2 + 0.212 \cdot D60^2 - 32.202 \cdot D10 \cdot D60$	0.232
$h_r = 13.728 - 24.081 \cdot D10 + 0.202 \cdot D60$	0.015
$h_r = -8.797 + 215.863 \cdot D10 + 11.774 \cdot D60 - 428.641 \cdot D10^2 + 0.790 \cdot D60^2 - 96.776 \cdot D10 \cdot D60$	0.259
$m_f = 0.198 + 2.411 \cdot D10 - 0.065 \cdot D60$	0.558
$m_f = 0.318 + 1.351 \cdot D10 - 0.113 \cdot D60 + 2.966 \cdot D10^2 + 0.005 \cdot D60^2$	0.597
$n_f = 4.454 - 14.174 \cdot D10 + 1.200 \cdot D60$	0.259
$n_f = -1.636 + 66.995 \cdot D10 + 4.018 \cdot D60 - 132.595 \cdot D10^2 + 0.503 \cdot D60^2 - 39.665 \cdot D10 \cdot D60$	0.338

Table 17. Regression between Fredlund & Xing Parameters and gradation numbers (CGN and FGN). CGN and FGN are coarse (4.75 to 25 mm diameter aggregates) and fine (0.075 to 2.0 mm diameter aggregates) gradation numbers (Eq. 1).

Equation	R^2
$a_f = -4.189 + 2.871 \cdot CGN - 3.604 \cdot FGN$	0.042
$a_f = 7.870 - 30.0 \cdot CGN + 79.167 \cdot FGN + 10.511 \cdot CGN^2 + 19.729 \cdot FGN^2 - 36.646 \cdot CGN \times FGN$	0.125
$h_r = 7.633 + 2.349 \cdot CGN - 4.291 \cdot FGN$	0.013
$h_r = -300.842 + 135.324 \cdot CGN + 210.770 \cdot FGN - 11.963 \cdot CGN^2 + 24.338 \cdot FGN^2 - 70.121 \cdot CGN \times FGN$	0.098
$m_f = -0.871 + 0.305 \cdot CGN + 0.109 \cdot FGN$	0.266
$m_f = 5.912 - 4.935 \cdot CGN + 4.055 \cdot FGN + 0.974 \cdot CGN^2 + 0.361 \cdot FGN^2 - 1.348 \cdot CGN \times FGN$	0.296
$n_f = 21.653 - 2.766 \cdot CGN - 5.126 \cdot FGN$	0.199
$n_f = -243.818 + 209.641 \cdot CGN - 203.247 \cdot FGN - 38.388 \cdot CGN^2 - 4.062 \cdot FGN^2 + 55.604 \cdot CGN \times FGN$	0.414

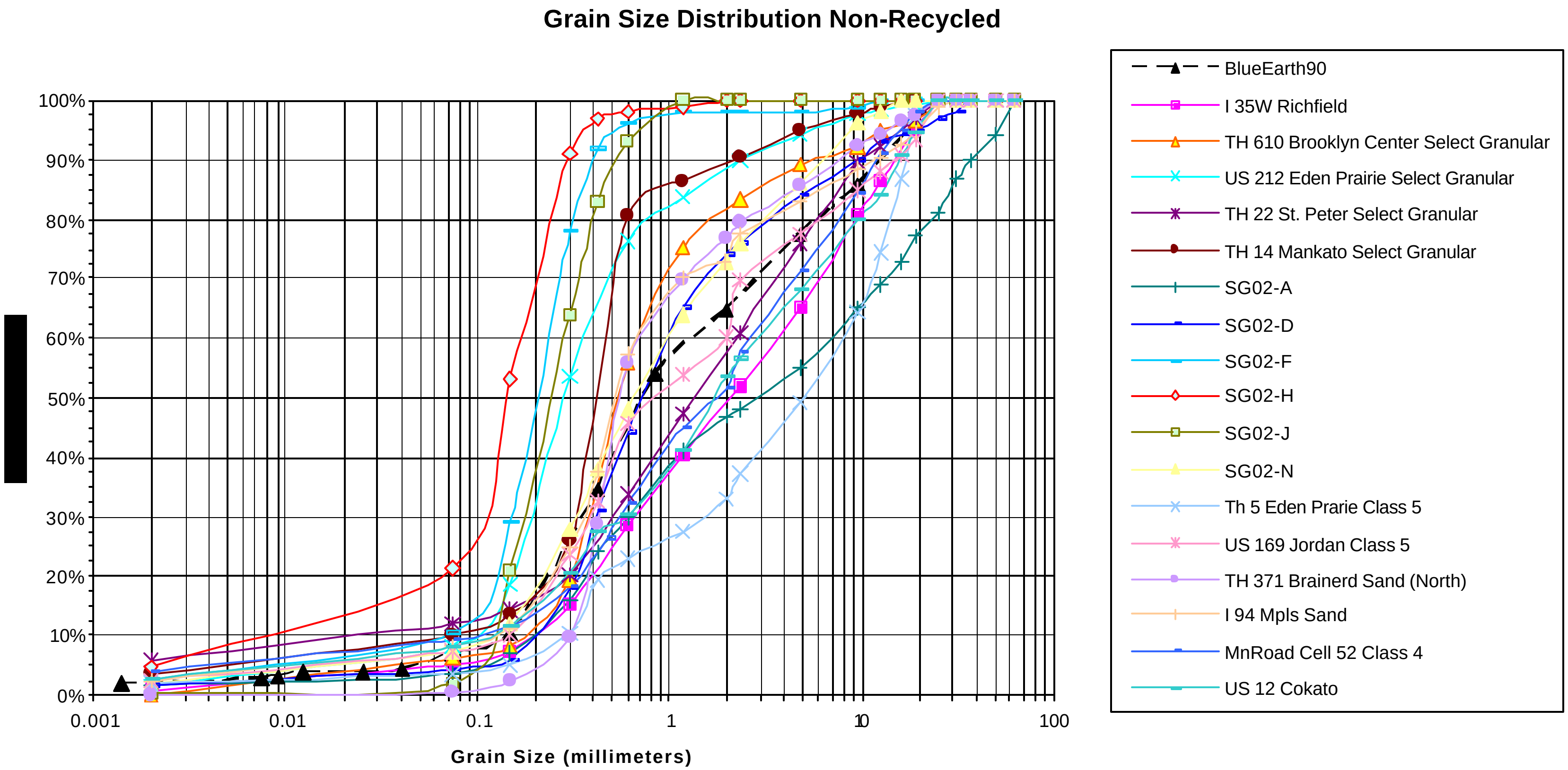


Figure 1. Particle size distribution for non-recycled road-bed materials.

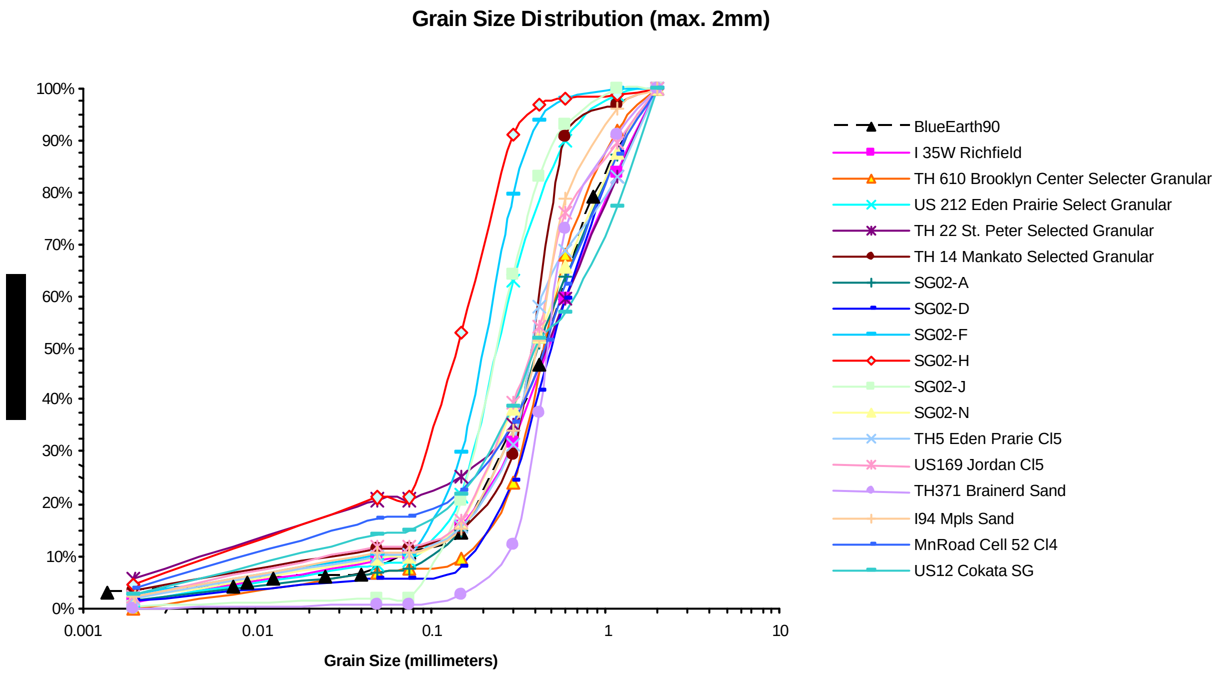


Figure 2. Particle size distribution for non-recycled road-bed materials at maximum grain size of 2.0 mm.

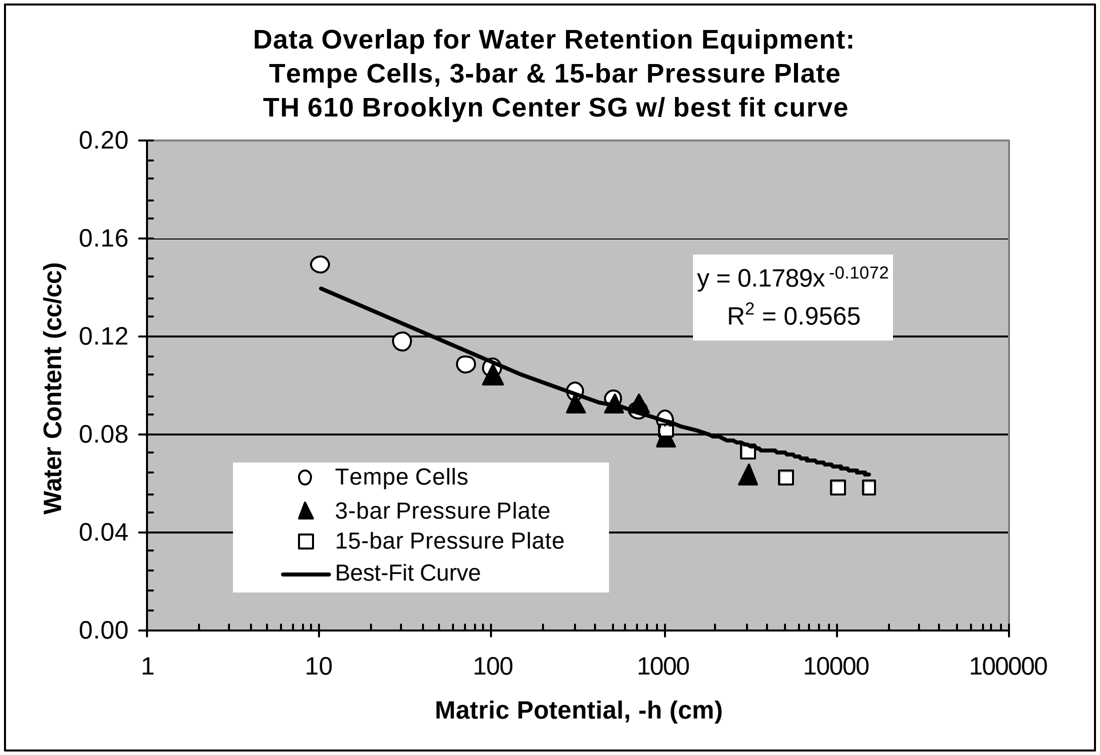


Figure 3. Measured and fitted water retention curve of select granular from TH610 Brooklyn Center.

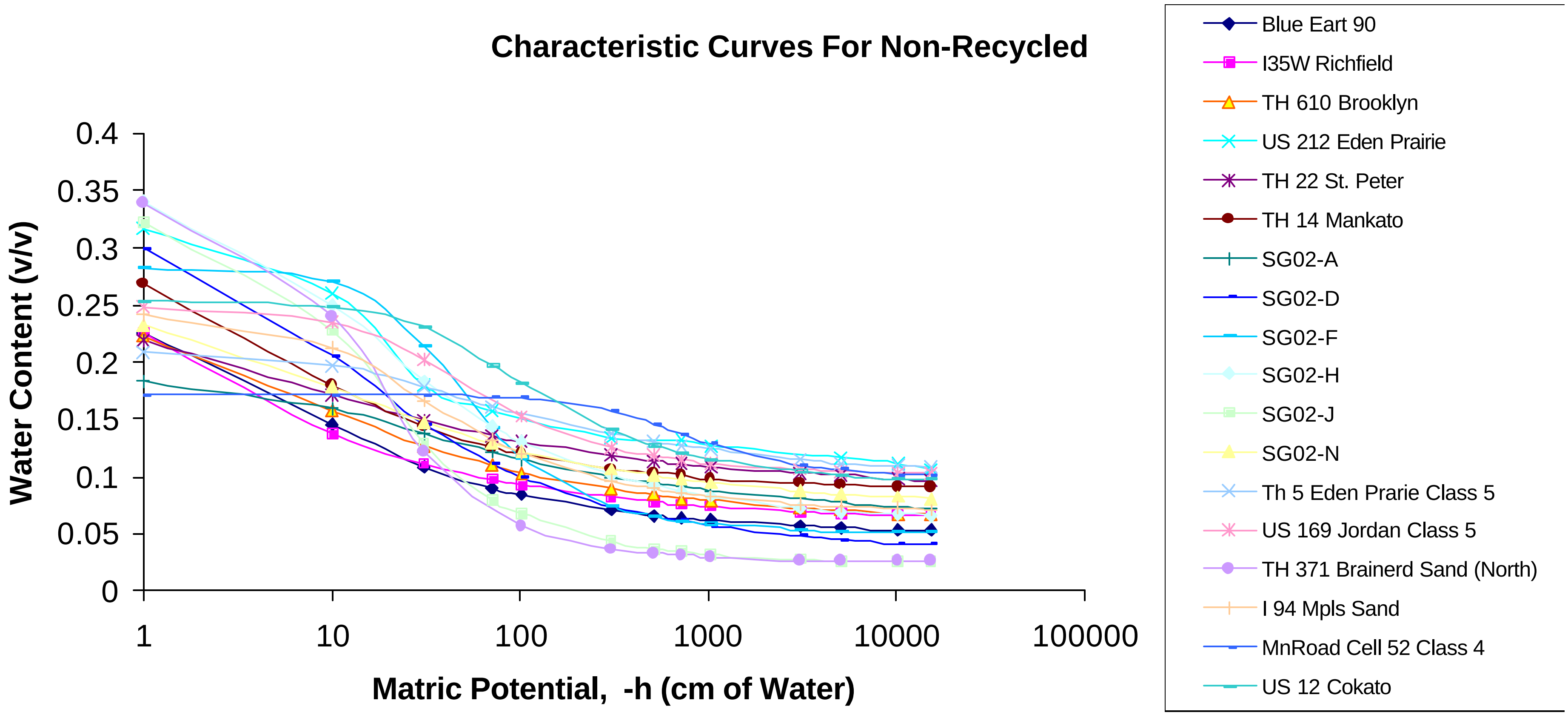


Figure 4. Water retention characteristic (drying) curves for non-recycled road-bed materials.

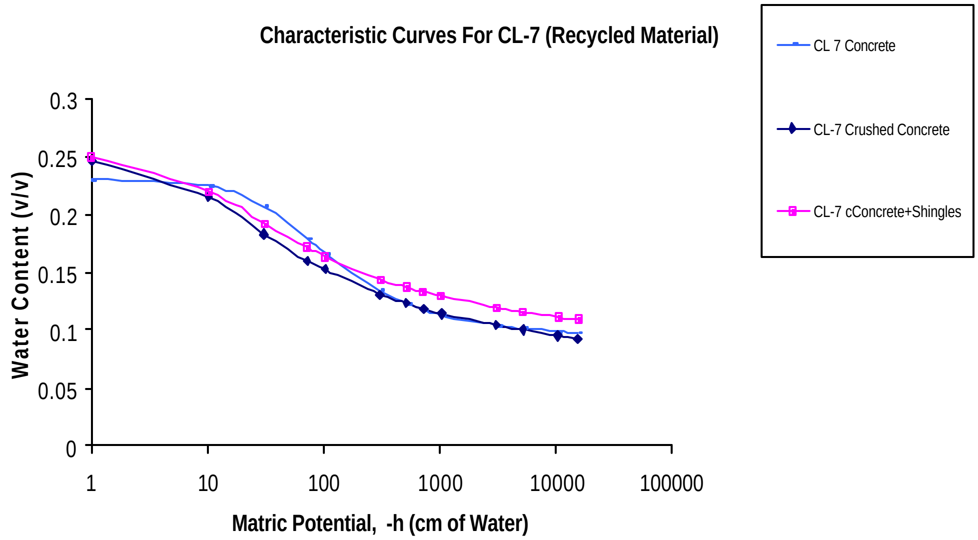


Figure 5. Water retention characteristic (drying) curves for Class 7 recycled material.

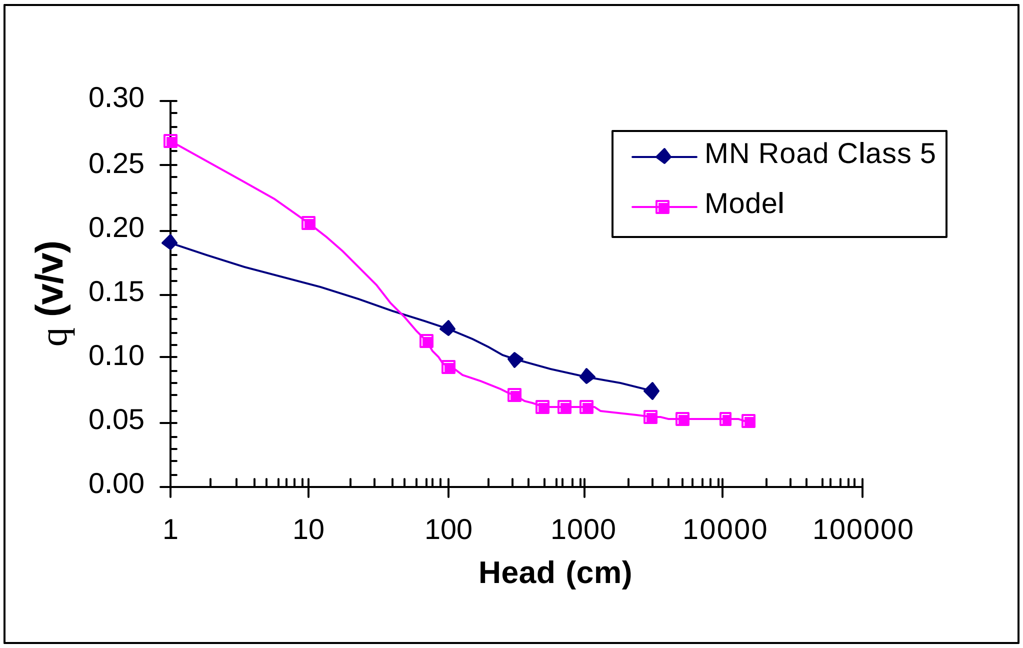


Figure 6. Simulation of water retention characteristics (drying) curve for MN Road, Class 5

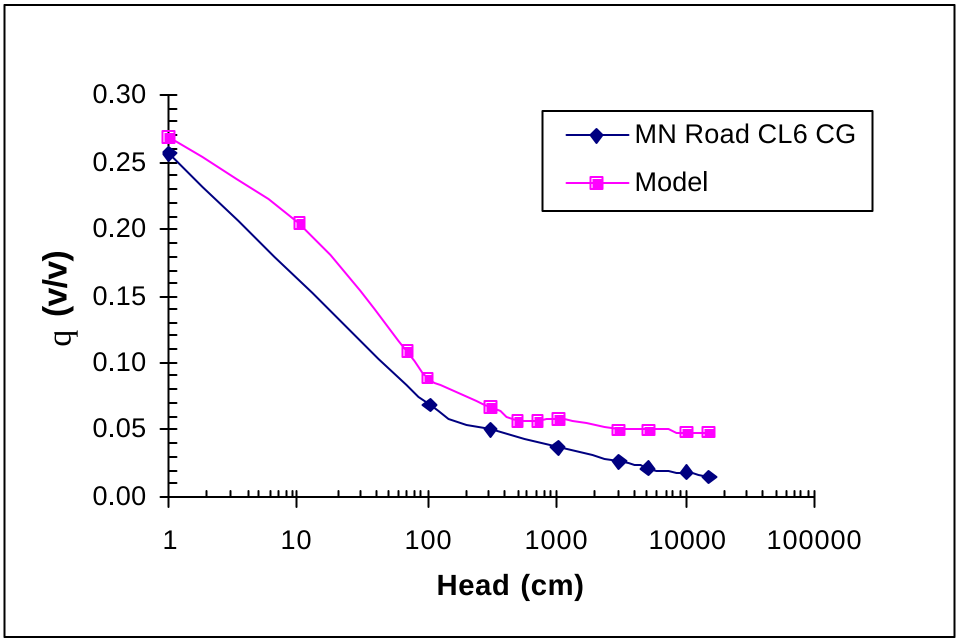


Figure 7. Simulation of water retention characteristics (drying) curve for MN Road, crushed granite, Class 6.

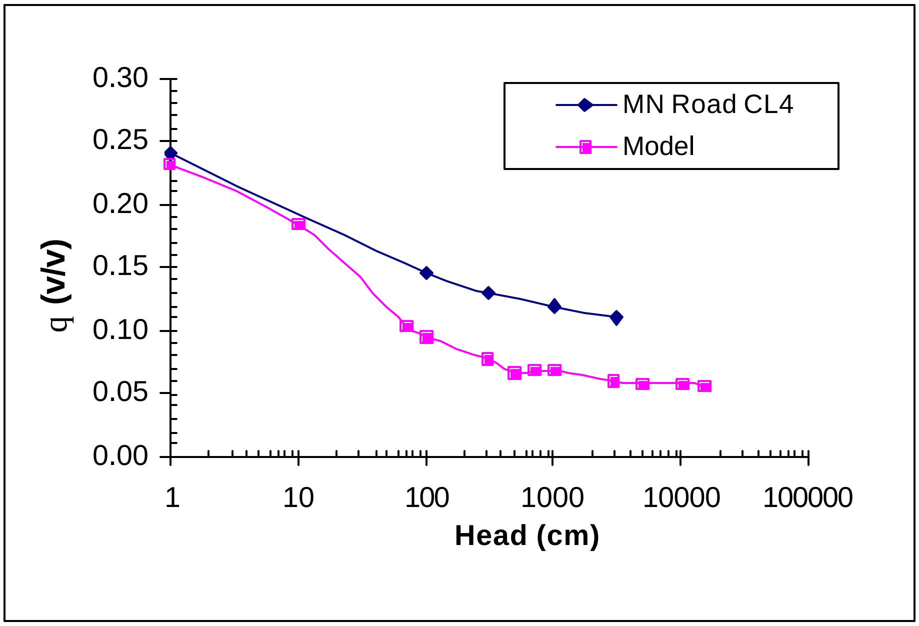


Figure 8. Simulation of water retention characteristics (drying) curve for MN Road, Class 4

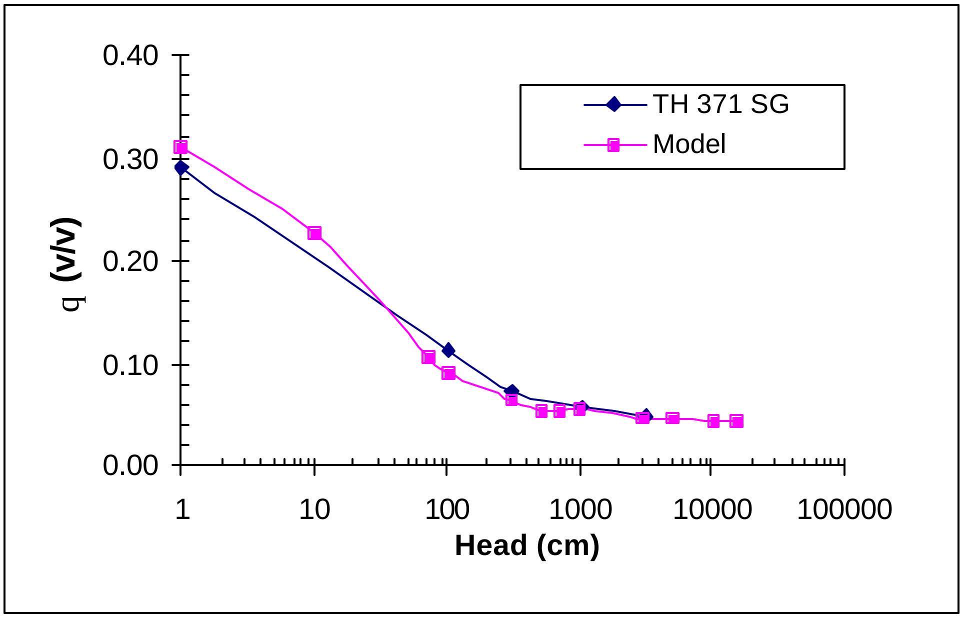


Figure 9. Simulation of water retention characteristics (drying) curve for TH 371 Brainerd, Sand (SP-SM), select granular.

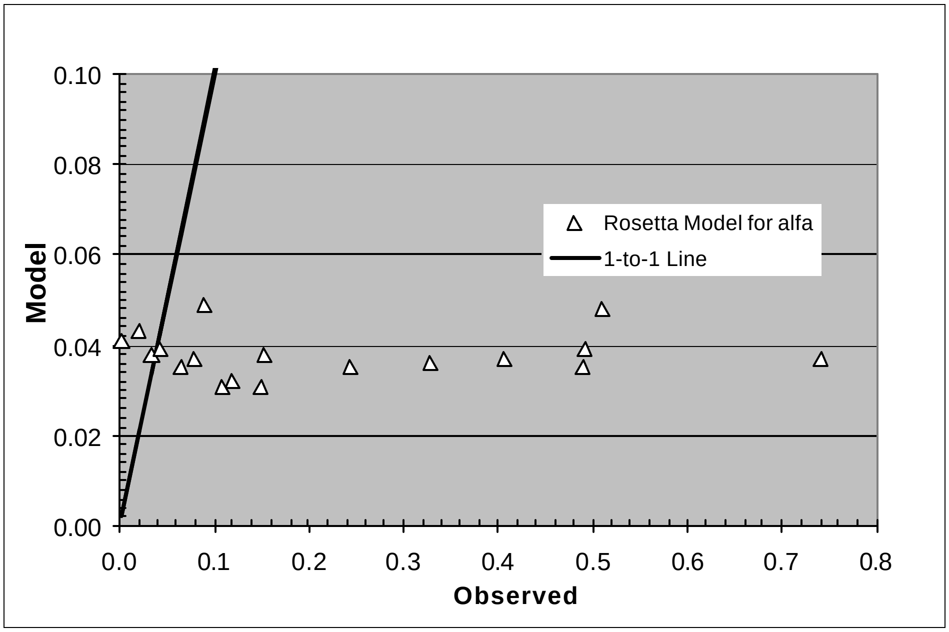


Figure 10. A comparison of van Genuchten's α parameter predicted from the Rosetta model vs. the observed values.

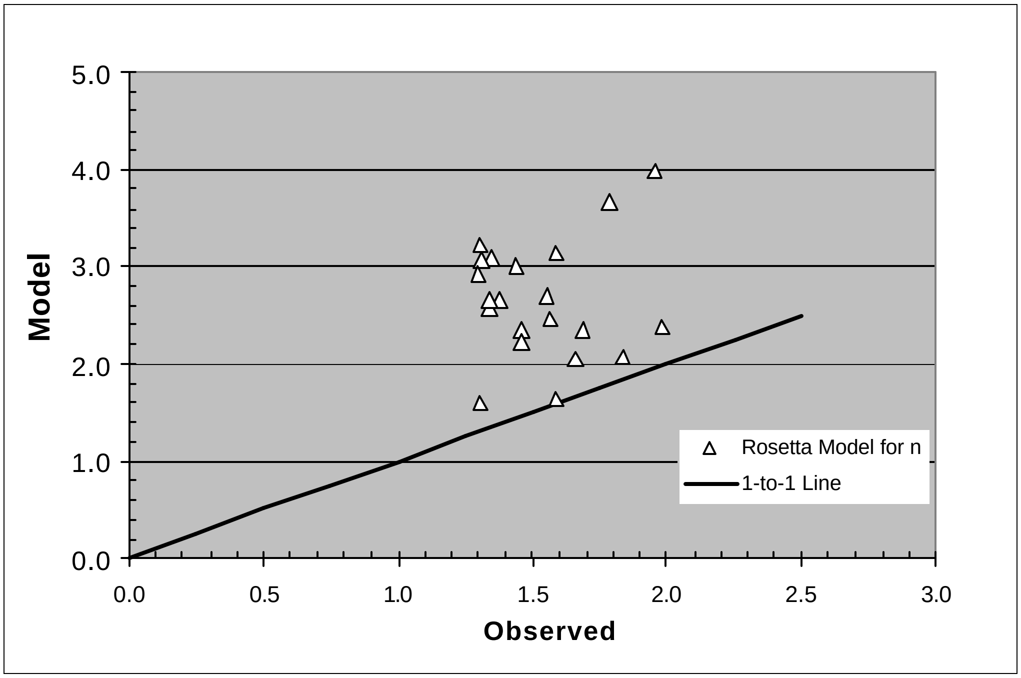


Figure 11. A comparison of van Genuchten’s n parameter predicted from the Rosetta model vs. the observed values.

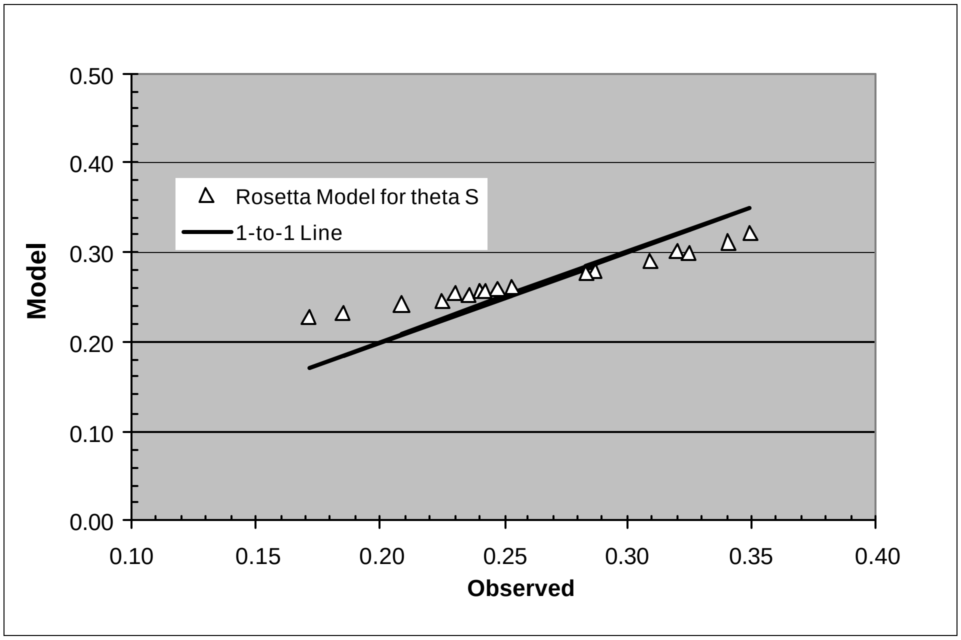


Figure 12. A comparison of van Genuchten's θ_s parameter predicted from the Rosetta model vs. the observed values.

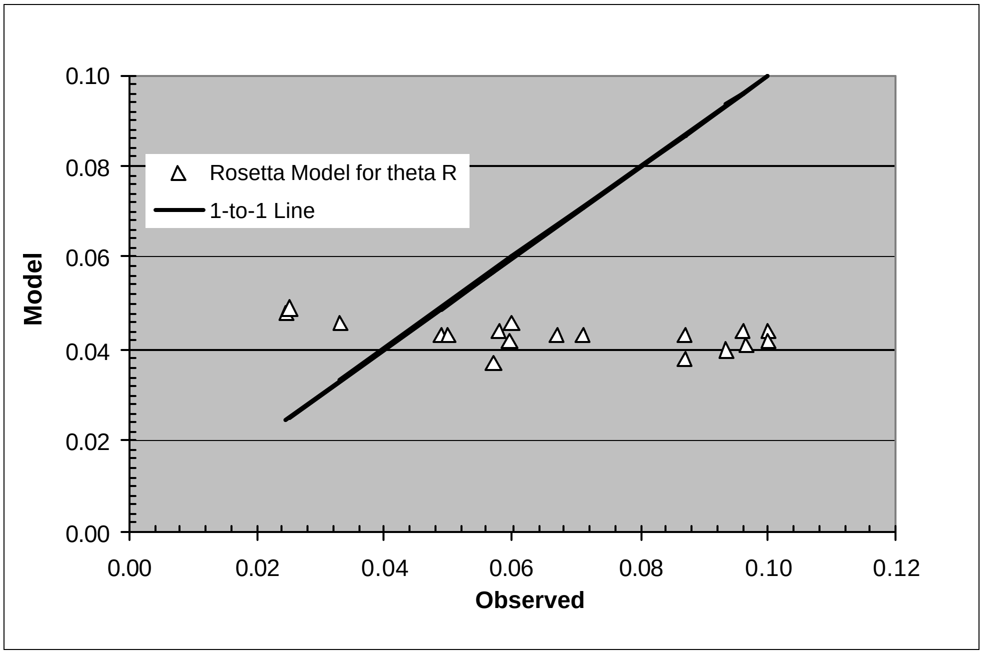


Figure 13. A comparison of van Genuchten's θ_r parameter predicted from the Rosetta model vs. the observed values.

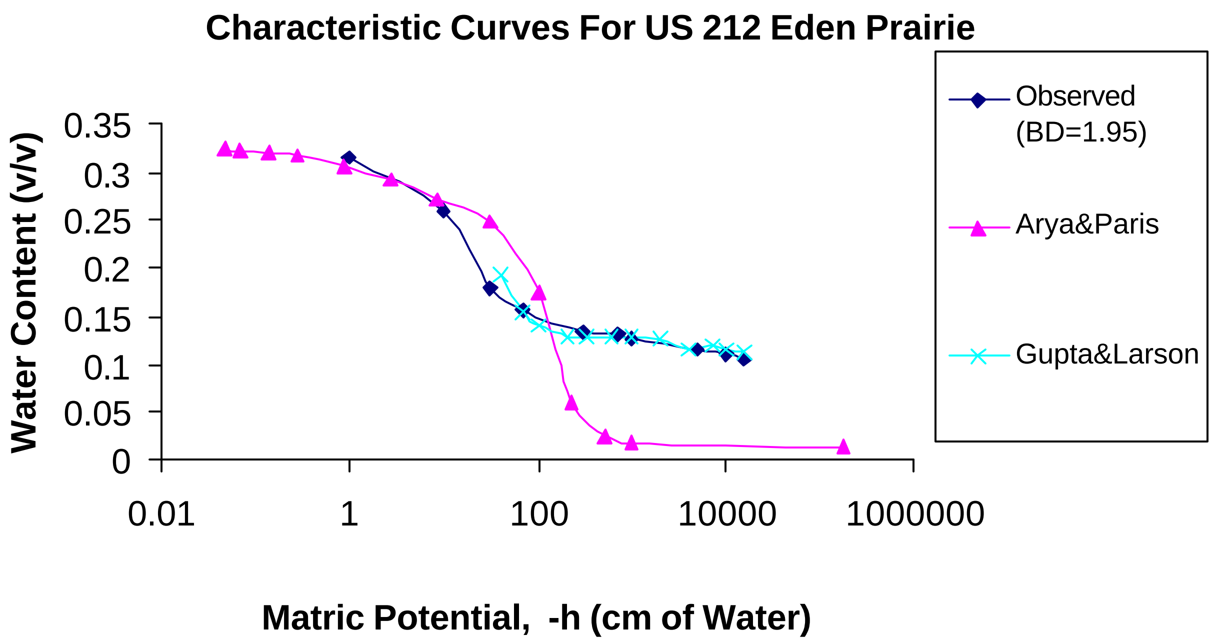


Figure 14. A comparison of predicted water retention characteristic (drying) curves based on Arya & Paris and Gupta & Larson models vs. the measured curve for US 212 Eden Prairie sample.

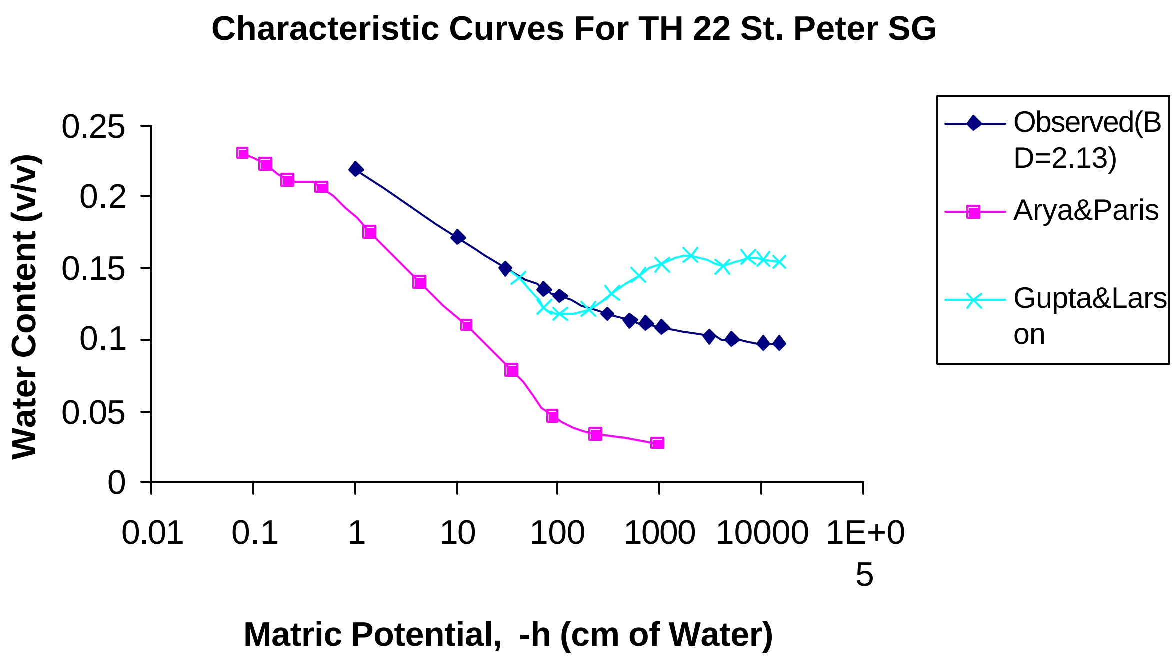


Figure 15. A comparison of predicted water retention characteristic (drying) curves based on Arya & Paris and Gupta & Larson models vs. the measured curve for TH 22 St. Peter SG sample.

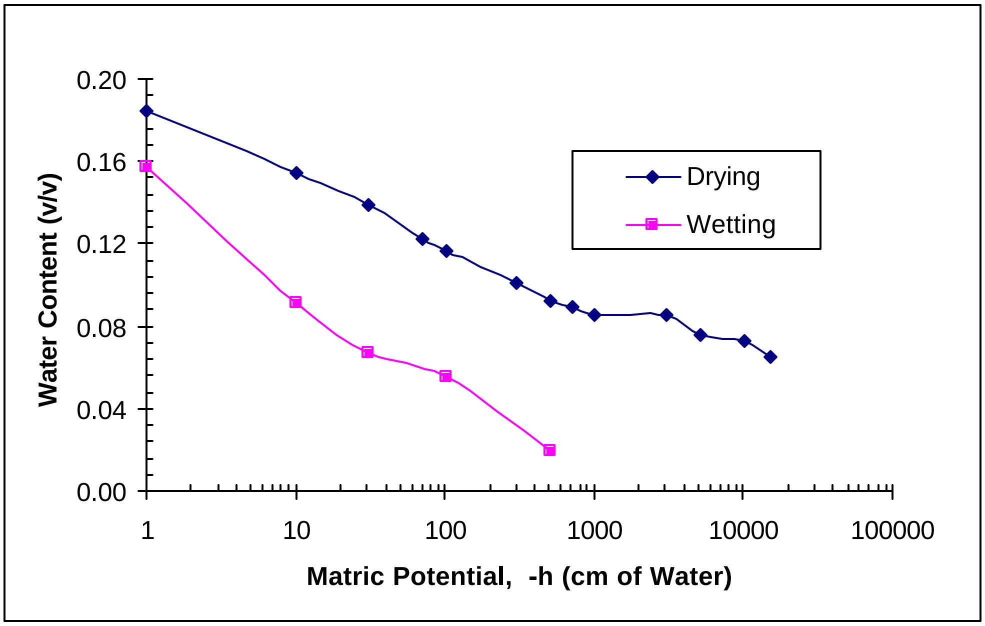


Figure 16. Hysteresis Curves for SG02-A.

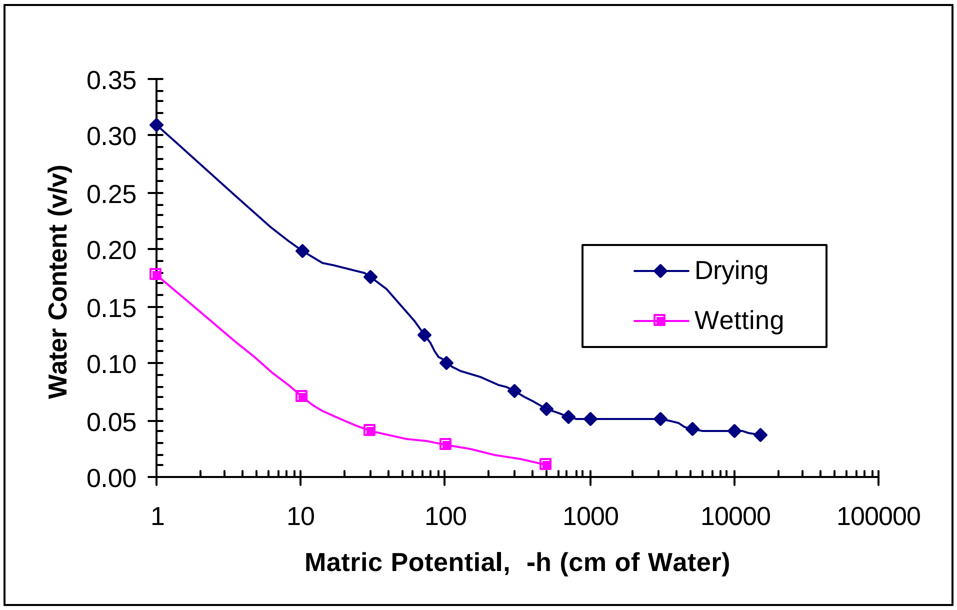


Figure 17. Hysteresis Curves for SG02-D.

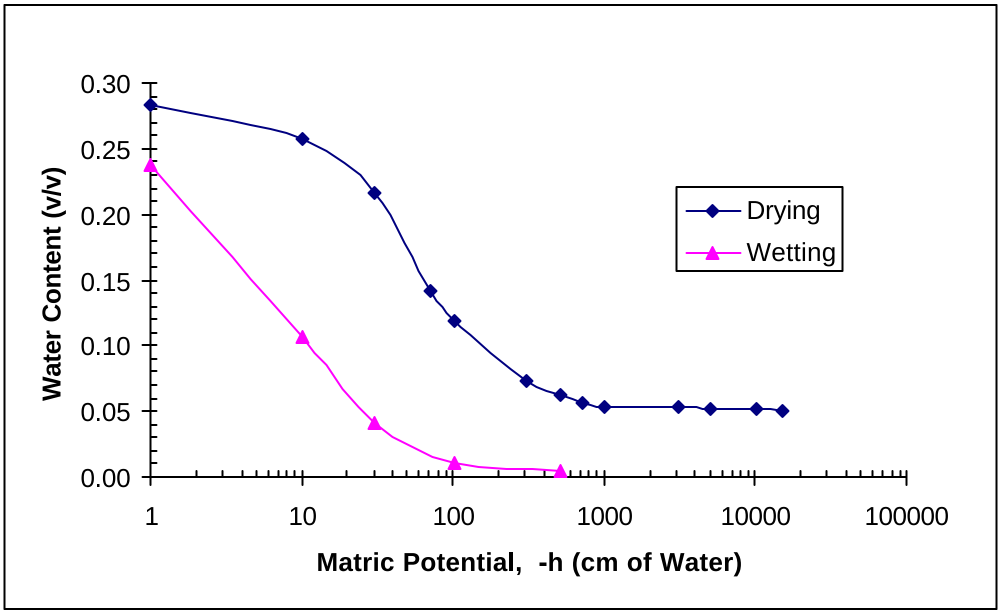


Figure 18. Hysteresis Curves for SG02-F.

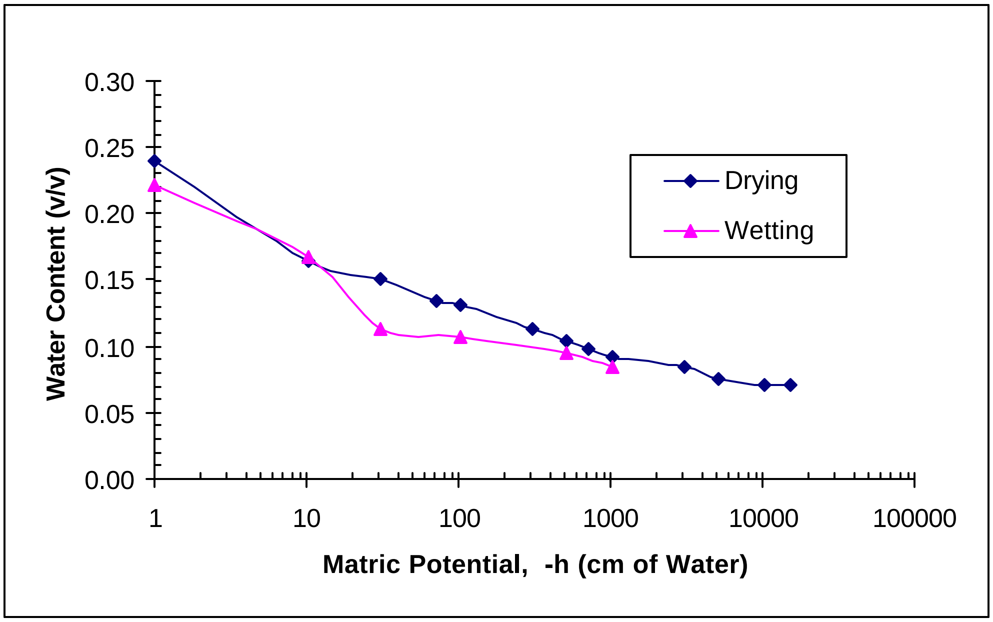


Figure 19. Hysteresis Curves for SG02-N.

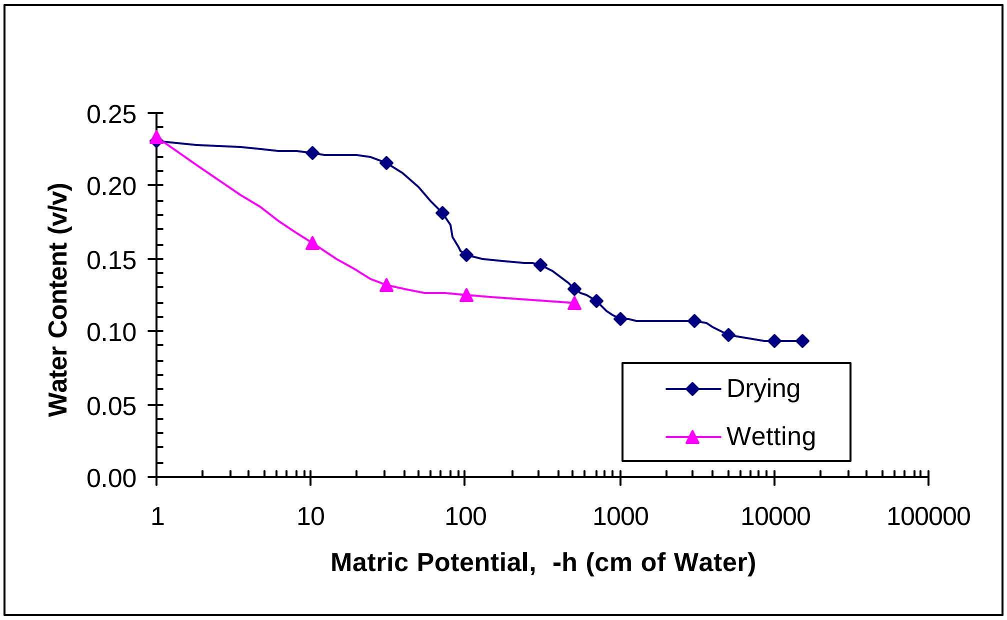


Figure 20. Hysteresis Curves for Concrete, Class 7.

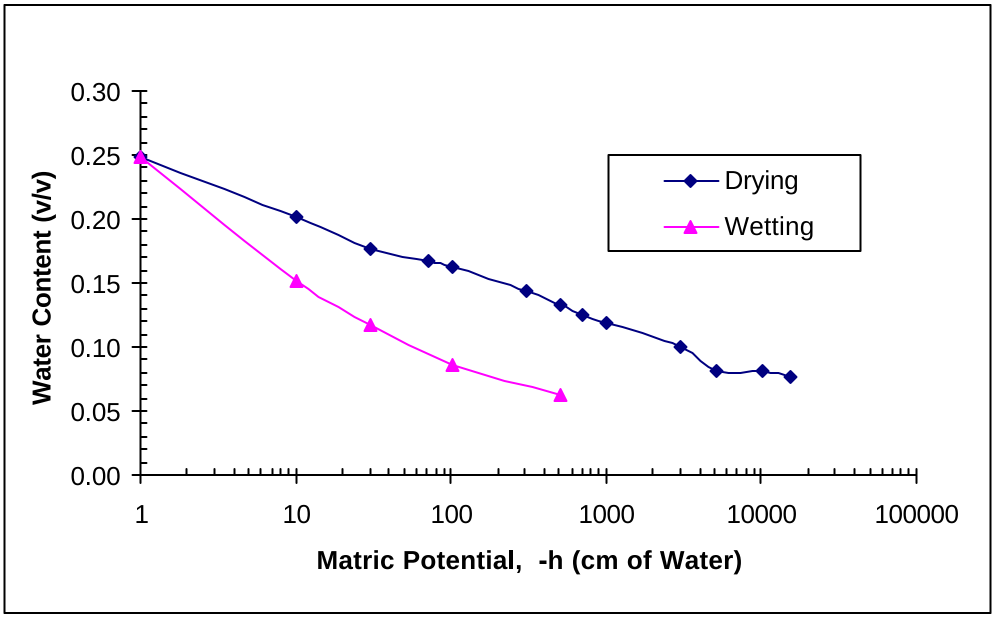


Figure 21. Hysteresis Curves for crushed Concrete, Class 7.

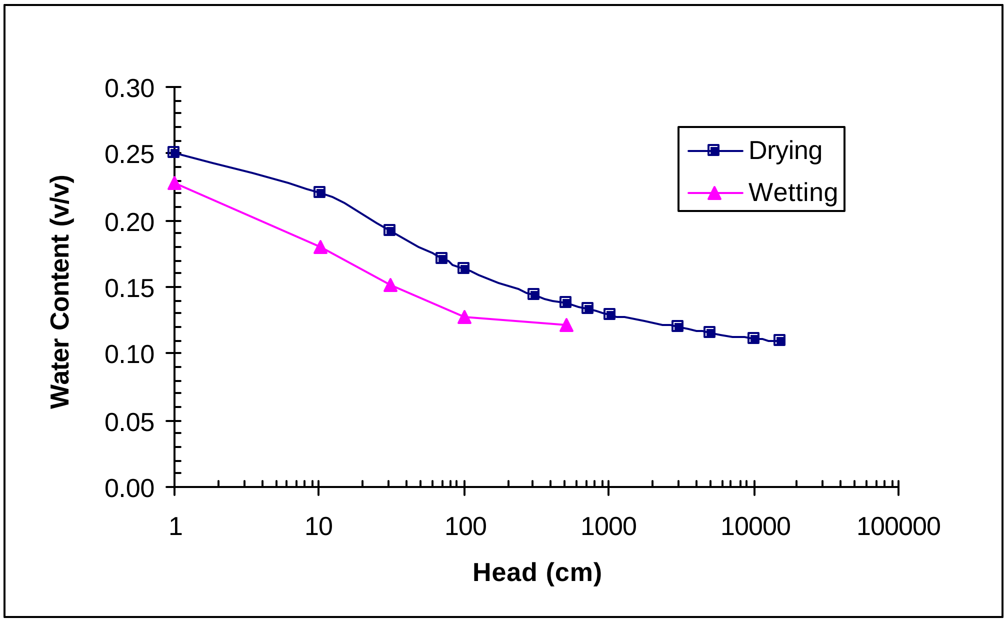


Figure 22. Hysteresis Curves for crushed Concrete and shingles, Class 7.

Appendix A

Sampling Procedure for Pressure Plate Apparatus, Tempe Cells, and Wetting Curve

A1. Sampling Procedure for Pressure Plate Apparatus

Apparatus

The apparatus setup for the analysis of road bed soils from a pressure range of 102 – 15300 cm H_2O was established in two parts. Two sets of pressure plate apparatus, 5 bar pressure chamber (102 – 3060 cm H_2O) and 15 bar pressure chamber (1020 – 15300 cm H_2O), comprise the setup for pressure application.

Procedure

1. **Sample Preparation**
   - i) Remove aggregates larger than 3/8th of an inch. This was done because our cores were only 4 inch in diameter and we wanted to make sure that large aggregates and gravel did not unduly influenced the water desorption.
   - ii) Since even the small aggregates are not evenly distributed when taking a soil sample for packing, it is better to prepare a large soil sample and have it ready packing of 4-5 rings at one time. This helps achieve uniformity among the packed samples.
   - iii) Weigh the dry soil required for 5 samples (Data base file "*Pressure Plates.mdb*") and put in the polythene bags of size 1.5'x2.5' and 4 ply thick.
   - iv) Weigh the water required to attain optimum density in a spray bottle.
   - v) Spray the soil in the bag with waters and shake the bag side by side for thorough mixing. Seal the bag and keep it for 24 hours. Keep shaking the bag for uniform mixing.
   - vi) Weigh the sample required for one ring (According to the Data base file "*Pressure Plates.mdb*").

2. **Packing The Rings**
   - i) Take a ring and weigh it.
   - ii) Tape an additional ring at the top of the ring to be filled with soil sample.
   - iii) Place the rings in the can.
   - iv) Weigh the wet soil required for one ring.
   - v) Fill the rings with the soil and place the can with rings in the hydraulic press.
   - vi) Compress the sample soil in the press until the head of the piston reaches the top of the upper ring.
   - vii) Remove the can with rings from the hydraulic press.
   - viii) Remove the top ring.
   - ix) Soil in the bottom ring is now compressed to the desired density.

3. Saturating the Sample

i) Spread a small amount of fine clay soil on the pressure plate where the soil ring will be placed. This helps to improve the contact surface between plate and the soil in the ring.
ii) Gently, embed the sample ring into the clay layer on the ceramic plate.
iii) Take a dish washing bucket and fill it half with water (preferably deionized).
iv) Place three 1" rings in the dish.
v) Place the ceramic plate with sample ring on the top of the rings.
vi) Add the water in the bucket so that almost $3/4^{th}$ of the ring is submerged in water.
vii) Allow the sample and the ceramic plate to saturate for 2-3 days and the top of the soil glistens.

4. Using the Pressure Plates

i) Place the saturated ceramic plate with sample on the top in a pressure chamber (5-bar or 15-bar, as planned).
ii) Attach the outlet on the ceramic plate to the outlet on the pressure chamber with a small diameter neoprene tube.
iii) Place the lid at the top of the pressure chamber and tighten the two screws (cross-wise) at a time until the chamber if fully tightened.
iv) Insert the drain tube from the pressure chamber to a burette used for recording the quantity of water coming out of the sample.
v) Attach the pressure hose of the pressure chamber to a pressurized air outlet connected to a compressor.
vi) Apply the desired pressure.

5. Measuring the Water Loss

i) Record the water in the burette at different time intervals till the water stops draining out of the sample.
ii) Shift to the next pressure (if required) and repeat the first step.
iii) Release the pressure in the chamber when a given set of pressure range is completed.
iv) Remove the ceramic plate from the chamber.
v) Take out of the sample ring and weigh out the sample.
vi)

6. Drying the Sample

i) Since the samples contain some aggregates and stones, entire sample is emptied into a can for drying.
ii) Set the temperature of the oven at 105^0 C and dry the soil for 24 hrs.
iii) Weigh the dried sample.

7. **Developing Moisture Curves**

    i) Enter the data into pressure plate calculation spreadsheet.
    ii) The spread sheet calculates the moisture content at each pressure.
    iii) Plot the moisture retention curves.

A2. Sampling Procedure for Tempe Cell Apparatus

Apparatus

The Tempe cell apparatus is used for moisture retention at small pressure ranges (10.2 – 1020 cm H_2O) Two different ceramic plates with bubbling pressures of 0.5 and 1.0 bars were used in Tempe Cells desorption measurements.

Procedure

1. **Sampling Calculation:** Use procedure described in program module "*pressure Plates.mdb*" (Fig. 1) to calculate amount of dry soil, water needed to achieve optimum moisture content and weight of wet soil required per ring.
2. **Sample Preparation**
    a. Remove aggregates larger than 3/8th of an inch. This was done because our cores were only 4 inch in diameter and we wanted to make sure that large aggregates and large stones did not unduly influenced the water desorption.
    b. Since even the small aggregates are not evenly distributed when taking a soil sample for packing, it is better to prepare a large soil sample and have it ready packing of 4-5 rings at one time. This helps achieve uniformity among the packed samples.
    c. Weigh the dry soil required for 5 samples (Data base file "*Pressure Plates.mdb*") and put in the polythene bags of size 1.5'x2.5' and 4 ply thick.
    d. Weigh the water required to attain optimum density in a spray bottle.
    e. Spray the soil in the bag with waters and shake the bag side by side for thorough mixing. Seal the bag and keep it for 24 hours. Keep shaking the bag for uniform mixing.
    f. Weigh the sample required for one ring (According to the Data base file "*Pressure Plates.mdb*").
3. **Packing The Rings**
    a. Take a ring and weigh it.
    b. Tape an additional ring at the top of the ring to be filled with soil sample.
    c. Place the rings in the can.
    d. Weigh the wet soil required for one ring.
    e. Fill the rings with the soil and place the can with rings in the hydraulic press.
    f. Compress the sample soil in the press until the head of the piston reaches the top of the upper ring.
    g. Remove the can with rings from the hydraulic press.

h. Remove the top ring.
i. Soil in the bottom ring is now compressed to the desired density.

4. Saturating the Sample

a. Place the sample ring on the ceramic plate rated for the planned test pressure fixed to the bottom part of the Tempe Cell.
b. Press the sample ring tight in the O-ring of the Tempe cell.
c. Take a dish washing bucket and fill it half with water (preferably deionized).
d. Place a 1" rings in the bucket.
e. Place the Tempe Cell with sample ring in it.
f. Add the water in the bucket so that almost $3/4^{th}$ of the ring is submerged in water.
g. Allow the sample and the plate to saturate for 2-3 days or till the top of the soil glistens.

5. Using the Tempe Cells

a. Cover the top of the sample ring with the top part of the Tempe Cell and tighten two screws (cross-wise) at a time until it is fully tightened.
b. Put the drain tube of the Tempe Cell into a burette for recording the quantity of water that is draining from the sample.
c. Attach the pressure hose of the pressure chamber to the compressed air set-up and apply the desired pressure.

6. Measuring the Water Loss

a. Record the water in the burette at different time intervals till the water stops draining out of the sample.
b. Shift to the next pressure (if required) and repeat the first step.
c. When the sample has gone through all required pressure steps, release the pressure.
d. Remove the sample from the Tempe Cell.
e. Weigh the sample.

7. Drying the Sample

a. Since the samples contain some aggregates and stones, entire sample is emptied into a can for drying.
b. Set the temperature of the oven at 105^0 C and dry the soil for 24 hrs.
c. Weigh the dried sample.

8. Developing Moisture Curves

a. Enter the data into pressure plate calculation spreadsheet.
b. The spreadsheet calculates the moisture content at each pressure.
c. Plot the moisture retention curves.

A3. Wetting Curve Procedure

Closed System Setup for Sorption Curve Estimation

Principal: The soil core is subjected at an air pressure corresponding to the suction desired while the soil cores is in contact with reservoir of water that is at atmospheric pressure. Atmospheric pressure at the base of the ceramic plate is maintained with a Marriot apparatus. The drop in level of water in the Marriot bottle thus corresponds to the volume of water that is sucked by the soil at a given air pressure.

Apparatus: Tempe Cells, Marriot apparatus, spaghetti tubing, air pressure source. (Fig. 2)

Procedure:

1. Pack the soil in the core at required density.
2. Take Tempe cell, clean it thoroughly and insert the core.
3. Place the upper lid of the Tempe cell on to the soil core and clamp the screws to make the system air tight.
4. Apply maximum pressure (say 1 bar) to the Tempe cell and let the excess water drained out of the soil and the core is at equilibrium at 1 bar.
5. Add water to the bottom jacket of the Tempe cell with the help of surgical tube until the trapped air is out and the space below the ceramic plate is filled with water. This should be done with the core under pressure.
6. Attach the outlet of the Tempe cell with the marriot apparatus.
7. Lower the air pressure to desired level. The soil will suck water from the bottom jacket of the Tempe cell which in turn will be replenished from the Marriot apparatus.
8. Record the reading on the Marriot bottle until equilibrium reaches i.e. there is no further decrease in the water level in the Marriot bottle. The volume of water lost in the Marriot tube is the volume of moisture gained by the soil at that air pressure.
9. Reduce the air pressure to the next desired suction and again measure the volume of water taken up by the soil.
10. Repeat the above process until the soil sample is zero pressure.
11. Remove the top lid of the Tempe cell. Remove the core out and dry it in an oven at 105^0 C for 24 hrs.
12. Determine the volume of water in the soil and then back calculate the volume of water at a given air pressure by subtracting the amount of water taken up by the soil as it went through the sorption process. Convert the volume of water in the soil at each air pressure to water content by dividing it with the weight of the oven dry soil. Multiply water content by weight with bulk density to convert it into water content by volume.
13. A plot of volumetric water content against air pressure is the wetting retention curve.

Precautions:

1. Desired core dimensions (6cm x 3 cm).
2. Clean Tempe cell thoroughly so that there is no soil grains struck to o-rings.
3. Oil the o-rings of the Tempe cell so that the soil easily for core to easily slides and sit properly on the ceramic plate.
4. Check for any pressure leakage.
5. Bleed all the trapped air from the system for proper flow of water from the Marriot bottle system to the Tempe cell.

Advantages:

1. The system replicates the dry front procedure.
2. Since the system is closed, there are no evaporation losses.

A wide range of pressure could be applied which is not possible with the hanging water columns.

Appendix B

Particle Size Distribution for non-recycled and recycled samples

Table B1. Particle size distribution for non-recycled samples

Sieve Size		Blue Earth County Road 90	I 35W Richfield	TH 610 Brooklyn Center SG	US 212 Eden Prairie SG	TH 22 St. Peter SG	TH 14 Mankato SG
English	Metric (mm)						
2 1/2	63.0						
2"	50.0						
1 1/2"	37.5						
1 1/4"	31.5						
1"	25.0	100	100	100	100	100	100
3/4"	19.0	96.0	95.0	96.4	99.2	96.9	100.0
5/8"	16.0						
1/2"	12.5		86.5	94.5	98.6	92.2	98.8
3/8"	9.5	85.7	80.5	91.6	97.8	89.6	97.7
#4	4.75	77.4	65.2	88.3	94.3	75.9	95.0
#8	2.36		51.9	82.4	89.9	61.0	90.1
#10	2.00	64.9	50.0	82.0	88.0	58.0	89.0
#16	1.18		40.3	73.6	83.9	47.4	86.4
#30	0.600		28.6	52.9	76.4	33.9	80.7
#40	0.425	34.4	23.0	55.8	65.0	27.0	52.0
#50	0.300		15.1	14.2	53.6	20.1	26.1
#100	0.150	10.5	7.5	2.0	18.5	14.4	13.6
#200	0.075	6.9	5.0		8.0	11.9	10.2

Table B2. Particle size distribution for non-recycled samples

Sieve Size		SG02-A	SG02-D	SG02-F	SG02-H	SG02-J	SG02-N
English	Metric (mm)						
2 1/2	63.0	100.0	100.0	100.0	100.0	100.0	100.0
2"	50.0	94.0	100.0	100.0	100.0	100.0	100.0
1 1/2"	37.5	90.0	100.0	100.0	100.0	100.0	100.0
1 1/4"	31.5	87.0	98.0	100.0	100.0	100.0	100.0
1"	25.0	81.0	97.0	100.0	100.0	100.0	100.0
3/4"	19.0	77.0	95.0	100.0	100.0	100.0	100.0
5/8"	16.0	73.0	94.0	100.0	100.0	100.0	100.0
1/2"	12.5	69.0	93.0	100.0	100.0	100.0	98.0
3/8"	9.5	65.0	90.0	99.0	100.0	100.0	96.0
#4	4.75	55.0	84.0	98.0	100.0	100.0	86.0
#8	2.36	48.0	76.0	98.0	100.0	100.0	76.0
#10	2.00	47.0	74.0	98.0	100.0	100.0	73.0
#16	1.18	41.0	65.0	98.0	99.0	100.0	64.0
#30	0.600	30.0	44.0	96.0	98.0	93.0	48.0
#40	0.425	24.0	31.0	92.0	97.0	83.0	38.0
#50	0.300	16.0	18.0	78.0	91.0	64.0	28.0
#100	0.150	7.0	6.0	29.0	53.0	21.0	12.0
#200	0.075	3.6	4.3	10.3	21.4	2.0	7.4

Table B3. Particle size distribution for non-recycled and recycled samples (concrete)

Sieve Size		TH 5 Eden Prairie	US 169 Jordan	TH 371 Brainerd Sand (North)	I 94 Mpls Sand	MnRoad Cell 52	US 12 Cokato	CL 7 Concrete	CL-7 Crushed Concrete	CL-7 cConcrete+ Shingles
English	Metric (mm)									
2 1/2	63.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2"	50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2"	37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/4"	31.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1"	25.0	100.0	100.0	100.0	98.9	100.0	100.0	100.0	100.0	100.0
3/4"	19.0	97.3	93.5	97.3	94.5	97.9	94.7	98.3	96.4	97.9
5/8"	16.0	86.9	90.6	96.4	92.8	95.0	90.6	95.7	92.4	94.0
1/2"	12.5	74.3	88.1	94.3	90.5	91.2	84.0	86.0	87.0	89.6
3/8"	9.5	64.4	85.0	92.3	88.2	84.5	79.8	72.5	80.8	82.6
#4	4.75	49.3	77.6	85.8	83.1	71.3	68.1	51.7	69.1	67.6
#8	2.36	37.4	69.7	79.3	77.4	57.9	56.7	39.2	62.3	61.2
#10	2.00	33.1	60.0	76.6	72.9	51.5	53.3	36.7	60.6	59.4
#16	1.18	27.5	53.7	69.9	70.0	44.9	41.2	30.4	55.2	53.3
#30	0.600	22.8	45.7	56.0	57.4	32.1	30.2	21.7	45.1	41.7
#40	0.425	19.2	32.4	28.7	37.5	26.5	27.6	17.5	37.9	34.4
#50	0.300	10.3	23.7	9.6	24.8	18.3	20.6	13.4	28.7	25.4
#100	0.150	5.2	10.2	2.2	11.3	11.5	11.6	7.7	13.3	12.8
#200	0.075	3.4	7.2	0.5	8.0	9.2	8.0	5.3	7.3	8.0

Appendix C

Clay Mineral Characterization and Chemical Analysis

Table C1. Clay Mineral Characterization

Sample No.	Clay Species	Other Minerals
1**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
2	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
3**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
4**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
5	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
6**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
7**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
8**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
9**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
10**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
11**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
12**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
13	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
14**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
15**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
16**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
17**	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*
18	Montmorillonite, Illite, Kaolinite	Quartz, Plagioclase Feldspar*

* Feldspars cannot be further identified, due to the interference of the quartz peak, and the limits of XRD on identifying feldspars. The best match was that of Na-rich Anorthite, which is a plagioclase feldspar, but other feldspars could also be present.

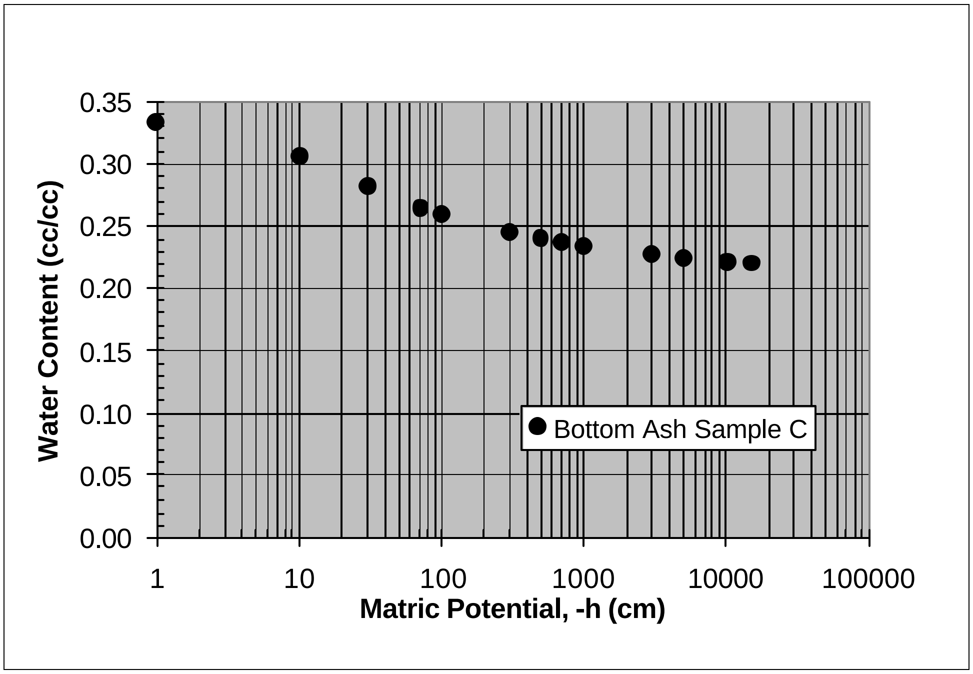
**These samples show strong evidence for inter-stratification of Montmorillonite and Illite.

Table C2. Chemical analysis for clay material

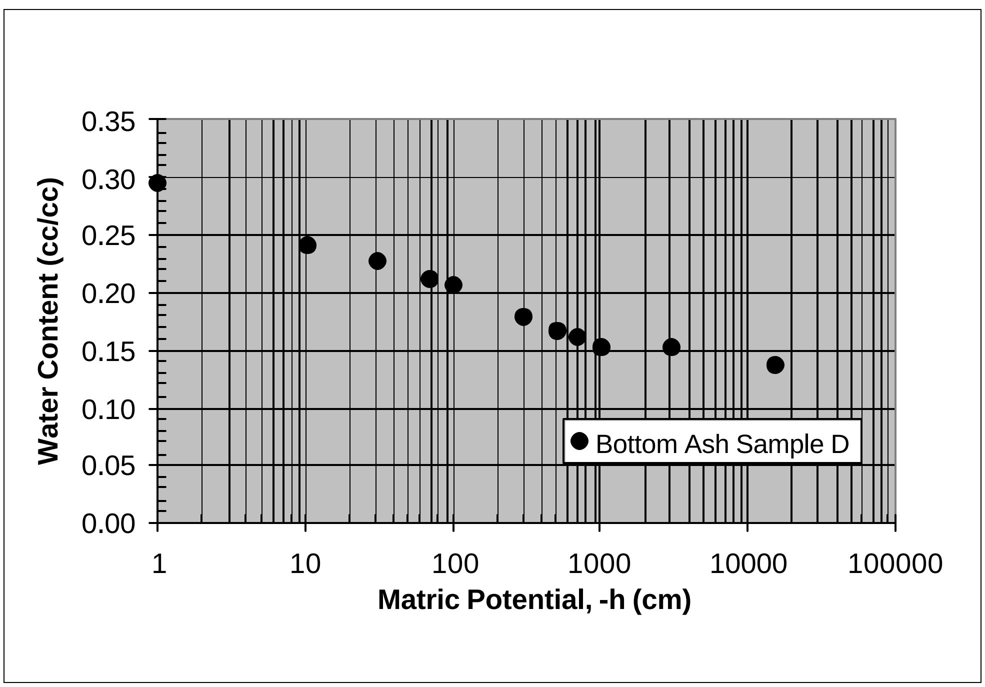
Sample	Al	B	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Zn
1	0.179	0.023	10.593	0.006	0.014	0.026	0.023	0.707	1.682	0.003	1.081	0.022	0.035	0.084	0.014
2	0.179	0.073	23.389	0.006	0.014	0.026	0.026	2.527	1.336	0.003	21.018	0.022	0.035	0.084	0.009
3	0.602	0.023	18.570	0.006	0.014	0.026	0.772	1.255	2.077	0.115	5.424	0.022	0.115	0.084	0.008
4	0.179	0.023	11.039	0.006	0.014	0.026	0.280	0.707	2.291	0.013	2.942	0.022	0.178	0.084	0.008
5	0.179	0.023	22.861	0.006	0.014	0.026	0.074	1.403	3.626	0.009	2.063	0.022	0.035	0.084	0.007
6	0.179	0.023	17.713	0.006	0.014	0.026	0.291	2.321	4.042	0.043	3.299	0.022	0.035	0.084	0.007
7	41.636	0.038	4.732	0.006	0.051	0.141	36.992	1.828	5.226	0.554	1.754	0.063	0.443	0.084	0.089
8	0.356	0.023	11.479	0.006	0.014	0.026	0.502	0.707	1.568	0.021	1.323	0.022	0.088	0.084	0.007
9	26.692	0.029	2.923	0.006	0.031	0.031	18.917	2.586	2.787	0.350	1.111	0.027	0.507	0.084	0.056
10	0.179	0.023	22.282	0.006	0.014	0.026	0.048	0.707	2.498	0.003	0.890	0.022	0.035	0.084	0.007
11	13.471	0.056	6.527	0.006	0.035	0.035	24.738	7.167	3.959	0.233	0.989	0.022	1.814	0.084	0.054
12	0.179	0.023	13.822	0.006	0.014	0.026	0.290	1.289	2.780	0.025	1.414	0.022	0.035	0.084	0.007
13	0.179	0.087	34.667	0.006	0.014	0.026	0.017	7.586	2.799	0.003	6.048	0.022	0.035	0.084	0.020
14	0.179	0.023	21.760	0.006	0.014	0.026	0.017	2.244	1.985	0.003	9.501	0.022	0.035	0.084	0.007
15	0.179	0.023	12.433	0.006	0.014	0.026	0.078	0.900	0.962	0.010	0.949	0.022	0.143	0.084	0.007
16	4.260	0.023	6.037	0.006	0.014	0.026	4.193	1.349	1.124	0.140	34.159	0.022	0.651	0.084	0.035
17	0.575	0.023	15.554	0.006	0.014	0.026	0.656	1.034	3.032	0.037	1.439	0.022	0.035	0.084	0.007
18	0.179	0.023	13.347	0.006	0.014	0.026	0.151	1.531	2.517	0.009	2.257	0.022	0.094	0.084	0.007
19	0.766	0.049	49.458	0.006	0.020	0.026	0.017	6.791	0.249	0.003	25.539	0.022	0.035	0.084	0.009
20	0.179	0.099	22.488	0.006	0.014	0.026	0.017	4.626	0.560	0.003	28.265	0.022	0.102	0.084	0.007
21	0.241	0.080	21.483	0.006	0.014	0.026	0.206	3.544	2.483	0.003	11.459	0.022	0.065	0.084	0.007
22	5.018	0.023	1.077	0.006	0.014	0.026	4.814	0.707	1.493	0.222	16.043	0.022	0.170	0.084	0.024
Blank	0.179	0.023	0.041	0.006	0.014	0.026	0.017	0.707	0.190	0.003	0.180	0.022	0.035	0.084	0.007

Appendix D

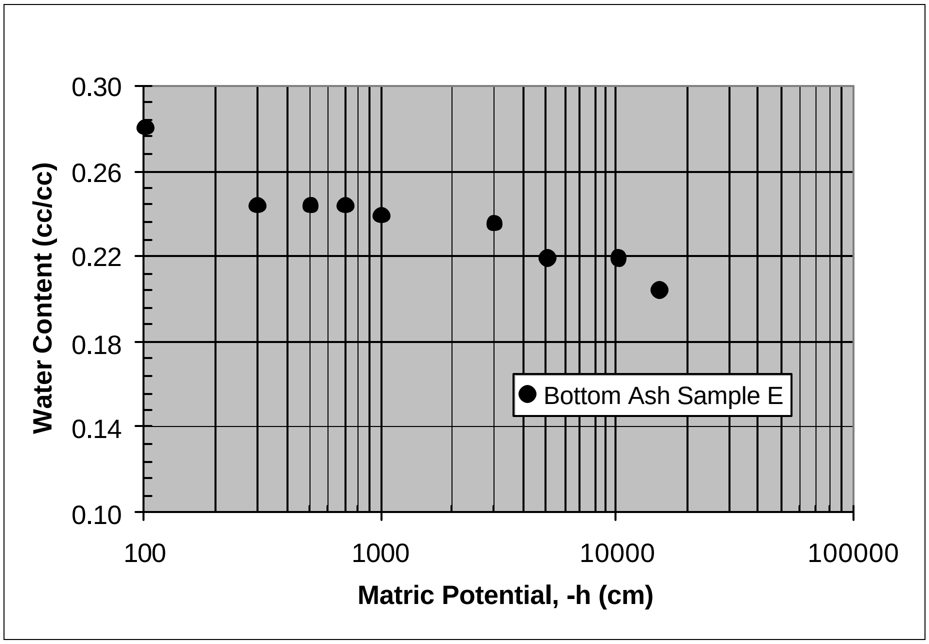
Water Characteristic Curves
for Bottom Ash Samples



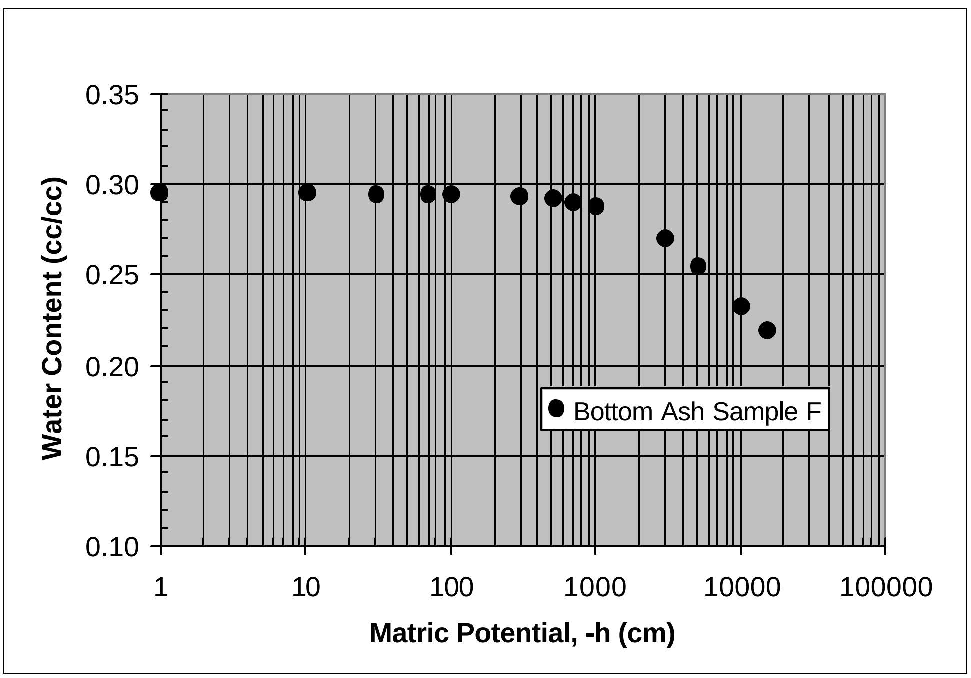
Water Characteristic Curve for Bottom Ash Sample C



Water Characteristic Curve for Bottom Ash Sample D



Water Characteristic Curve for Bottom Ash Sample E



Water Characteristic Curve for Bottom Ash Sample F

Appendix E

Model Parameters for Brooks and Corey and Fredlund and Xing

Regression Coefficients for Gupta and Larson Model

Table E1. van Genuchten parameters of roadbed samples

Sample Nº	Location or Sample Types	Granular Type	α	n	θ_r	θ_s	Air Entry (cm)	BD (g/cc)
1	Blue Earth County Road 90	CL-5	0.4047	1.458	0.0487	0.24	2.47	2.016
2	I 35W Richfield	CL-5	0.7396	1.373	0.0595	0.225	1.352	2.051
3	TH 610 Brooklyn Center	SG	0.4896	1.349	0.058	0.236	2.042	2.024
4	US 212 Eden Prairie	SG	0.153	1.553	0.1	0.32	6.535	1.79
5	TH 22 St. Peter	SG	0.5094	1.304	0.087	0.2305	1.963	2.039
6	TH 14 Mankato	SG	0.4912	1.464	0.0869	0.2867	2.035	1.89
7	SG02-A	SG	0.1493	1.305	0.06	0.1849	6.697	2.157
8	SG02-D	SG	0.2437	1.441	0.033	0.3094	4.103	1.838
9	SG02-F	SG	0.0336	1.982	0.05	0.283	29.761	1.899
10	SG02-H	SG	0.89	1.59	0.0569	0.349	5.175	1.725
11	SG02-J	SG	0.1197	1.788	0.0244	0.3245	8.354	1.79
12	SG02-N	SG	0.327	1.342	0.071	0.2402	3.058	2.013
13	TH5 Eden Prarie Class 5	CL-5	0.0643	1.338	0.096	0.209	15.552	2.095
14	US 169 Jordan Class 5	CL-5	0.0423	1.685	0.1	0.2475	23.64	1.994
15	TH 371 Brainerd Sand (north)	Sand	0.1074	1.954	0.02505	0.3407	9.31	1.747
16	I-94 Mpls Sand	Sand	0.0783	1.568	0.0671	0.2426	12.771	2.007
17	MnRoad Cell 2 Class 4	CL-4	0.0025	1.832	0.0966	0.1713	400	2.196
18	US 12 Cokato SG	SG	0.0209	1.656	0.0935	0.2529	47.846	1.979
19	CL-7 Concrete	CL-7	0.024	1.59	0.0935	0.2302	41.666	2.045
20	CL-7 cConcrete	CL-7	0.139	1.31	0.077	0.249	7.194	1.992
21	CL-7 cConcrete+Shingle	CL-7	0.152	1.299	0.094	0.253	6.578	1.986

Table E2. Brooks and Corey Parameters

Sample Name	a_c	n_c	R^2
I-35W Richfield CL5	0.1322796	0.3812095	0.9990586
TH 160 brooklyn Center, SG	0.159662	0.31743	0.9994156
US 212 Eden Prairie, SG	0.5322359	0.6101674	0.9875091
TH 22 St. Peter, SG	0.1517624	0.2780372	0.9991143
TH 14 Mankato, SG	0.1499766	0.4149348	0.999106
SG02-A	0.4266122	0.2547433	0.9987356
SG02-D	0.3094144	0.3971035	0.9993075
SG02-F	1.883357	0.7494154	0.9950918
SG02-H	0.6235372	0.4461422	0.9964814
SG02-J	0.5637214	0.6667535	0.9990214
SG02-N	0.2445257	0.3228838	0.9992976
TH Eden Prairie, CL 5	0.6817882	0.2209865	0.9950541
US 169 Jordan , CL5	0.8561873	0.3845206	0.9855698
TH 371 Brainerd Sand	0.6132209	0.7753988	0.998625
I-94 Mpls Sand	0.662744	0.4140756	0.9962401
MN Road Cell 52, CL 4	9.893868	0.1272815	0.9882448
US 12 Cokata, SG	2.159647	0.3903598	0.9928718
Blue Earth 90, CL 5	0.2751533	0.08443055	0.9906359
CL-7 Concrete	2.29523	0.3953352	0.9965184
Crushed Concrete	1.42608	0.3138214	0.9907807
cConcrete Shingles	0.4292572	0.2442022	0.9990689

Table E3. Fredlund and Xing Parameters

Sample Name	a_f	n_f	m_f	h_r (kPa)	R^2
MN Road Cell 52, CL 4	21.65182	20.0	0.040406	52.80828	0.998074
I-35W Richfield	0.008036	1.00971	0.348399	4.312483	0.99795
TH Eden Prairie, CL 5	0.762116	20.0	0.039161	5.063928	0.987173
US 169 Jordan , CL5	1.564136	20.0	0.102271	7.901597	0.993201
Blue Earth 90, CL 5	0.035354	1.207151	0.628728	1.425812	0.997436
CL-7 Concrete	3.341899	20.0	0.092008	17.11644	0.995277
Crushed Concrete	2.252228	16.1327	0.106268	14.78232	0.995189
cConcrete Shingles	0.528266	17.15703	0.073239	6.455328	0.990175
TH 371 Brainerd Sand	0.817138	2.37019	0.884635	4.40568	0.999806
I-94 Mpls Sand	0.850854	3.877112	0.259539	8.307381	0.996655
TH 160 brooklyn Center, SG	0.032077	0.57921	0.579424	27.9548	0.998493
US 212 Eden Prairie, SG	0.119753	2.25968	0.225602	5.019424	0.992552
TH 22 St. Peter, SG	0.038838	2.241123	0.13975	3.25506	0.988612
TH 14 Mankato, SG	0.003536	1.135443	0.292553	3.540426	0.993747
SG02-A	0.443737	3.89053	0.15142	9.249767	0.993405
SG02-D	0.381175	1.325955	0.691106	8.669333	0.999261
SG02-F	2.132489	3.489151	0.487384	11.50863	0.999296
SG02-H	0.864286	2.11284	0.521049	10.03618	0.999029
SG02-J	0.774499	2.016377	0.881411	5.33391	0.999771
SG02-N	0.068739	1.386257	0.262732	7.885229	0.994117
US 12 Cokata, SG	3.057676	7.273835	0.1586	20.44065	0.99679

Table E4. Gupta and Larson: regression and correlation coefficients for prediction of soil water content at specific matric potentials. (Gupta and Larson, 1979)

Matric Potential, bars	Regression Coefficients					Correlation Coefficient, R
	$ax10^3$	$bx10^3$	$cx10^3$	$ex10^3$	$dx10^3$	
-0.04	7.053	10.242	10.070	6.333	-32.120	0.950
-0.07	5.678	9.228	9.135	6.103	-26.960	0.959
-0.10	5.018	8.548	8.833	4.966	-24.230	0.961
-0.20	3.890	7.066	8.408	2.817	-18.780	0.962
-0.33	3.075	5.886	8.039	2.208	-14.340	0.962
-0.60	2.181	4.557	7.557	2.191	-9.276	0.964
-1.00	1.563	3.620	7.154	2.388	-5.759	0.966
-2.00	0.932	2.643	6.636	2.717	-2.214	0.967
-4.00	0.483	1.943	6.128	2.925	-0.204	0.962
-7.00	0.214	1.538	5.908	2.855	1.530	0.954
-10.0	0.076	1.334	5.802	2.653	2.145	0.951
-15.0	-0.059	1.142	5.766	2.228	2.671	0.947

Sand (%) + silt(%) + clay(%) = 100. Sand = 2.0 – 0.05 mm. Silt = 0.05 – 0.02 mm. Clay <0.002mm

Appendix F

Linear and non-Linear Regression for van Genuchten parameters with particle size distribution, gradation indices, and gradation numbers

Alpha & PSD

Model

a = 1.386 + 4.914***Silt** - 5.229***Clay** - 0.718***BD. (BD = bulk density)**

Dep Var: ALPHA N: 18 Multiple R: 0.531 Squared multiple R: 0.282
Adjusted squared multiple R: 0.129 Standard error of estimate: 0.246

Effect	Coefficient	Std Error	Std Coef.	Tolerance	t	P (2-Tail)
CONSTANT	1.386	0.879	0	.	1.577	0.137
SILT	4.914	2.854	0.767	0.258	1.722	0.107
CLAY	-5.229	7.232	-0.31	0.279	-0.723	0.482
BD	-0.718	0.467	-0.375	0.86	-1.538	0.146

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.333	3	0.111	1.837	0.187
Residual	0.846	14	0.06		

Durbin-Watson D Statistic 1.109
First Order Autocorrelation 0.343

Model

a = 671.129 - 1325.005* **Silt** - 1276.152* **Clay** - 17.758***BD** + 1.115*$\mathbf{BD}^2$ – 669.248* $\mathbf{Sand}^2$ + 2479.904* $\mathbf{Clay}^2$ + 941.681* $\mathbf{Silt}^2$ + 14.792***BD*Sand**

Dep Var: alfa N: 18 Multiple R: 0.882 Squared multiple R: 0.778
Adjusted squared multiple R: 0.580 Standard error of estimate: 0.171

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	671.129	263.02	0	.	2.552	0.031
CLAY	-1276.152	498.868	-75.618	0	-2.558	0.031
BD	-17.758	14.831	-9.287	0	-1.197	0.262
BDSQR	1.115	3.683	2.27	0	0.303	0.769
SANDSQR	-669.248	261.267	-247.246	0	-2.562	0.031
CLAYSQR	2479.904	792.446	8.642	0.003	3.129	0.012
SILTSQR	941.681	378.819	26.502	0	2.486	0.035
BD*SAND	14.792	5.674	7.666	0.003	2.607	0.028

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.917	8	0.115	3.935	0.028
Residual	0.262	9	0.029		

Durbin-Watson D-Statistic 1.907
First Order Autocorrelation -0.084

<u>n &PSD</u>

Mode l
n = 2.764 - 0.855* **Silt** + 1.390* **Clay** - 0.598***BD**

Dep Var: N N: 18 Multiple R: 0.418 Squared multiple R: 0.174
Adjusted squared multiple R: 0.0 Standard error of estimate: 0.221

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	2.764	0.789	0	.	3.505	0.003
SILT	-0.855	2.561	-0.159	0.258	-0.334	0.744
CLAY	1.39	6.49	0.098	0.279	0.214	0.833
BD	-0.598	0.419	-0.374	0.86	-1.427	0.176

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.144	3	0.048	0.985	0.428
Residual	0.681	14	0.049		

Durbin-Watson D Statistic 1.569
First Order Autocorrelation 0.199

Model
n = -102.401 + 180.496* **Sand** + 35.003* **Clay** + 11.987***BD** - 72.496* $\textbf{Sand}^{2}$ -267.303* $\textbf{Clay}^{2}$ + 156.226* $\textbf{Silt}^{2}$ - 14.103***BD* Sand**

N: 18 Multiple R: 0.793 Squared multiple R: 0.630
Adjusted squared multiple R: 0.370 Standard error of estimate: 0.175

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P (2 Tail)
CONSTANT	-102.401	275.011	0	.	-0.372	0.717
BD	11.987	4.992	7.493	0.004	2.401	0.037
SANDSQR	-72.496	266.167	-32.015	0	-0.272	0.791
CLAYSQR	-267.303	788.612	-1.114	0.003	-0.339	0.742
BDSAND	-14.103	5.772	-8.736	0.003	-2.443	0.035
SAND	180.496	540.951	44.971	0	0.334	0.746
CLAY	35.003	36.618	2.479	0.006	0.956	0.362
SILTSQR	156.226	388.094	5.256	0	0.403	0.696

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.52	7	0.074	2.428	0.099
Residual	0.306	10	0.031		

Durbin-Watson D Statistic 2.630
First Order Autocorrelation -0.318

Theta S & PSD

Model
Theta S = 0.999 **-** 0.018* **Silt** + 0.043* **Clay -** 0.376***BD**

Dep Var: THETAS N: 18 Multiple R: 1.000 Squared multiple R: 0.999
Adjusted squared multiple R: 0.999 Standard error of estimate: 0.001

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P (2 Tail)
CONSTANT	0.999	0.005	0.0	.	194.938	0.0
SILT	-0.018	0.017	-0.014	0.258	-1.078	0.299
CLAY	0.043	0.042	0.013	0.279	1.029	0.321
BD	-0.376	0.003	-0.997	0.86	-138.379	0.0

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.046	3	0.015	7455.762	0.000
Residual	0.000	14	0		

Theta R & PSD

Model

Theta R = -0.160 + 0.094* **Sand** + 0.438* **Silt** + 0.055***BD**

Dep Var: TR N: 18 Multiple R: 0.664 Squared multiple R: 0.441
Adjusted squared multiple R: 0.321 Standard error of estimate: 0.021

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.16	0.608	0	.	-0.264	0.796
Sand	0.094	0.618	0.202	0.023	0.152	0.881
Silt	0.438	0.835	0.706	0.022	0.524	0.608
BD	0.055	0.04	0.296	0.86	1.373	0.191

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.005	3	0.002	3.677	0.038
Residual	0.006	14	0		

Durbin-Watson D Statistic 1.609
First Order Autocorrelation 0.140

Model
Theta R = 0.009 + 0.272***BD** - 17.315* **Clay** ^{2} - 0.264***BD* Sand**

Dep Var: THETAR N: 18 Multiple R: 0.715 Squared multiple R: 0.512
Adjusted squared multiple R: 0.407 Standard error of estimate: 0.020

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.009	0.08	0	.	0.115	0.91
BD	0.272	0.085	1.471	0.166	3.213	0.006
BD*SAND	-0.264	0.107	-1.415	0.107	-2.472	0.027
CLAYSQR	-17.315	11.586	-0.623	0.201	-1.494	0.157

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.006	3	0.002	4.888	0.016
Residual	0.005	14	0		

Durbin-Watson D Statistic 1.101
First Order Autocorrelation 0.398

Alpha & gradation indices D_{60} and D_{10}

Model
a = 0.398 - 0.006***D60**- 0.849***D10**

Dep Var: ALFA   N: 18   Multiple R: 0.259   Squared multiple R: 0.067
Adjusted squared multiple R: 0.0   Standard error of estimate: 0.271

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P (2 Tail)
CONSTANT	0.398	0.143	0	.	2.778	0.014
DT	-0.849	1.047	-0.223	0.822	-0.811	0.43
DS	-0.006	0.023	-0.067	0.822	-0.244	0.81

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.079	2	0.039	0.538	0.595
Residual	1.1	15	0.073		

Model
a = 1.064 - 0.250***D60** - 10.033***D10** - 0.044***D60**^{2} + 17.898***D10**^{2} + 3.451***D60xD10**

Dep Var: ALFA   N: 18   Multiple R: 0.716   Squared multiple R: 0.513
Adjusted squared multiple R: 0.310   Standard error of estimate: 0.219

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.064	0.274	0	.	3.886	0.002
DT	-10.033	3.681	-2.636	0.043	-2.725	0.018
DS	-0.25	0.111	-3.018	0.022	-2.245	0.044
DTSQR	17.898	9.544	1.579	0.057	1.875	0.085
DSSQR	-0.044	0.014	-6.044	0.011	-3.114	0.009
DTDS	3.451	1.116	9.398	0.004	3.093	0.009

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.605	5	0.121	2.531	0.087
Residual	0.574	12	0.048		

Durbin-Watson D Statistic   2.245
First Order Autocorrelation -0.150

n & gradation indices D_{60} and D_{10}

Model
n = 1.555 - 0.034***D60 +** 0.586***D10**

Dep Var: N   N: 18   Multiple R: 0.448   Squared multiple R: 0.201
Adjusted squared multiple R: 0.094   Standard error of estimate: 0.210

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.555	0.111	0	.	14.02	0
DT	0.586	0.811	0.184	0.822	0.723	0.481
DS	-0.034	0.018	-0.493	0.822	-1.937	0.072

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.165	2	0.083	1.881	0.187
Residual	0.66	15	0.044		

Durbin-Watson D Statistic 1.772
First Order Autocorrelation 0.087

Model
n = 1.719 - 2.153***D10 +** 0.005***D60**^{2}**+** 9.373***D10**^{2} - 0.407***D60xD10**

Dep Var: N N: 18 Multiple R: 0.537 Squared multiple R: 0.289
Adjusted squared multiple R: 0.070 Standard error of estimate: 0.213

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.719	0.231	0	.	7.427	0
DT	-2.153	3.426	-0.676	0.047	-0.628	0.541
DTSQR	9.373	9.257	0.989	0.057	1.013	0.33
DSSQR	0.005	0.011	0.849	0.016	0.46	0.653
DTDS	-0.407	0.598	-1.326	0.014	-0.681	0.508

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.238	4	0.06	1.318	0.315
Residual	0.587	13	0.045		

Durbin-Watson D Statistic 2.002
First Order Autocorrelation -0.015

Theta S & gradation indices D_{60} and D_{10}

Model
Theta S = 0.264 - 0.012***D60** + 0.174***D10**

Dep Var: TS N: 18 Multiple R: 0.651 Squared multiple R: 0.424
Adjusted squared multiple R: 0.348 Standard error of estimate: 0.042

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.264	0.022	0	.	11.908	0
DT	0.174	0.162	0.232	0.822	1.074	0.3
DS	-0.012	0.004	-0.715	0.822	-3.307	0.005

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.02	2	0.01	5.531	0.016
Residual	0.026	15	0.002		

Durbin-Watson D Statistic 2.100
First Order Autocorrelation -0.066

Model
theta S = 0.383 -0.053***D60** - 1.206***D10** - 0.001***D60**^{2} + 3.311***D10**^{2} + 0.260***D60*D10**

Dep Var: TS N: 18 Multiple R: 0.882 Squared multiple R: 0.778
Adjusted squared multiple R: 0.685 Standard error of estimate: 0.029

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.383	0.037	0.0	.	10.491	0.000
DT	-1.206	0.491	-1.605	0.043	-2.455	0.03
DS	-0.053	0.015	-3.234	0.022	-3.561	0.004
DTSQR	3.311	1.273	1.48	0.057	2.601	0.023
DSSQR	-0.001	0.002	-0.772	0.011	-0.589	0.567
DTDS	0.26	0.149	3.583	0.004	1.745	0.107

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.036	5	0.007	8.398	0.001
Residual	0.01	12	0.001		

Durbin-Watson D Statistic 2.382
First Order Autocorrelation -0.273

Theta R & gradation indices D_{60} and D_{10}

Model
Theta R = 0.088 + 0.004***D60** - 0.227***D10**

Dep Var: TR N: 18 Multiple R: 0.630 Squared multiple R: 0.397
Adjusted squared multiple R: 0.316 Standard error of estimate: 0.021

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.088	0.011	0	.	7.861	0
DT	-0.227	0.082	-0.615	0.822	-2.779	0.014
DS	0.004	0.002	0.553	0.822	2.499	0.025

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.004	2	0.002	4.93	0.023
Residual	0.007	15	0		

Durbin-Watson D Statistic 1.132
First Order Autocorrelation 0.403

Model
Theta R = 0.065 **+** 0.016***D60+** 0.039***D10 +** 0.001***D60^2** - 0.441***D10^2**- 0.123***D60*D10**

Dep Var: TR N: 18 Multiple R: 0.673 Squared multiple R: 0.453
Adjusted squared multiple R: 0.226 Standard error of estimate: 0.022

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.065	0.028	0	.	2.323	0.039
DT	0.039	0.378	0.105	0.043	0.103	0.92
DS	0.016	0.011	1.955	0.022	1.372	0.195
DTSQR	-0.441	0.979	-0.402	0.057	-0.45	0.661
DSSQR	0.001	0.001	1.909	0.011	0.928	0.372
DTDS	-0.123	0.114	-3.465	0.004	-1.076	0.303

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.005	5	0.001	1.99	0.153
Residual	0.006	12	0.001		

Durbin-Watson D Statistic 1.636
First Order Autocorrelation 0.159

Alpha & gradation number CGN and FGN

Model

$\alpha = -0.021 + 0.035*CGN + 0.135*FGN$

Dep Var: ALFA N: 18 Multiple R: 0.267 Squared multiple R: 0.071
Adjusted squared multiple R: 0.0 Standard error of estimate: 0.270

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.021	1.074	0	.	-0.019	0.985
CGN	0.035	0.361	0.042	0.325	0.097	0.924
FGN	0.135	0.254	0.231	0.325	0.53	0.604

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.084	2	0.042	0.576	0.574
Residual	1.095	15	0.073		

Durbin-Watson D Statistic 1.937
First Order Autocorrelation 0.002

Model

$\alpha = 4.497 - 4.867*CGN + 7.277*FGN + 1.179*CGN^2 + 1.408*FGN^2 - 2.962*CGN \times FGN$

Dep Var: ALFA N: 18 Multiple R: 0.425 Squared multiple R: 0.181
Adjusted squared multiple R: 0.0 Standard error of estimate: 0.284

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	4.497	13.071	0	.	0.344	0.737
CGN	-4.867	9.426	-5.89	0.001	-0.516	0.615
FGN	7.277	8.102	12.488	0	0.898	0.387
CGNSQ	1.179	1.774	9.887	0	0.664	0.519
FGNSQ	1.408	1.206	6.765	0.002	1.167	0.266
CFGN	-2.962	2.962	-22.494	0	-1	0.337

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.213	5	0.043	0.529	0.75
Residual	0.966	12	0.081		

Durbin-Watson D Statistic 1.287
First Order Autocorrelation 0.322

n & gradation number CGN and FGN

Model
n = 0.688 + 0.215*CGN + 0.069*FGN

Dep Var: N   N: 18   Multiple R: 0.436   Squared multiple R: 0.190
Adjusted squared multiple R: 0.082   Standard error of estimate: 0.211

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.688	0.84	0	.	0.819	0.425
CGN	0.215	0.282	0.311	0.325	0.762	0.458
FGN	0.069	0.199	0.143	0.325	0.35	0.732

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.157	2	0.078	1.757	0.206
Residual	0.669	15	0.045		

Durbin-Watson D Statistic   1.501
First Order Autocorrelation   0.223

Model
n = 1.544 -1.134*CGN + 2.695*FGN + 0.390*CGN^2 + 0.669*FGN^2 - 1.202*CGN x FGN

Dep Var: N   N: 18   Multiple R: 0.488   Squared multiple R: 0.238
Adjusted squared multiple R: 0.0   Standard error of estimate: 0.229

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.544	10.544	0	.	0.146	0.886
CGN	-1.134	7.604	-1.641	0.001	-0.149	0.884
FGN	2.695	6.536	5.529	0	0.412	0.687
CGNSQ	0.39	1.431	3.906	0	0.272	0.79
FGNSQ	0.669	0.973	3.846	0.002	0.688	0.505
CFGN	-1.202	2.389	-10.914	0	-0.503	0.624

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.197	5	0.039	0.75	0.602
Residual	0.629	12	0.052		

Durbin-Watson D Statistic   1.857
First Order Autocorrelation   0.047

<u>Theta S & gradation number CGN and FGN</u>

Model
Theta S = -0.039 + 0.068*CGN + 0.043*FGN

<u>Dep Var: Theta S</u>   N: 18   Multiple R: 0.753   Squared multiple R: 0.566
Adjusted squared multiple R: 0.508   Standard error of estimate: 0.036

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.039	0.145	0	.	-0.266	0.794
CGN	0.068	0.049	0.417	0.325	1.397	0.183
FGN	0.043	0.034	0.372	0.325	1.246	0.232

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.026	2	0.013	9.792	0.002
Residual	0.02	15	0.001		

Durbin-Watson D Statistic   2.533
First Order Autocorrelation -0.280

Model
Theta S = 1.271 - 0.786*CGN + 0.142*FGN + 0.148*CGN^2 + 0.065*FGN^2 - 0.091*CGN x FGN

<u>Dep Var: Theta S</u>   N: 18   Multiple R: 0.768   Squared multiple R: 0.590
Adjusted squared multiple R: 0.419   Standard error of estimate: 0.040

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.271	1.825	0	.	0.696	0.5
CGN	-0.786	1.316	-4.817	0.001	-0.597	0.562
FGN	0.142	1.131	1.238	0	0.126	0.902
CGNSQ	0.148	0.248	6.304	0	0.599	0.56
FGNSQ	0.065	0.168	1.588	0.002	0.387	0.705
CFGN	-0.091	0.414	-3.493	0	-0.22	0.83

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.027	5	0.005	3.454	0.036
Residual	0.019	12	0.002		

Durbin-Watson D Statistic   2.525
First Order Autocorrelation -0.288

Theta R & gradation number CGN and FGN

Model
Theta R = 0.077 + 0.004*CGN - 0.021*FGN

Dep Var: TR   N: 18   Multiple R: 0.322   Squared multiple R: 0.104
Adjusted squared multiple R: 0.0   Standard error of estimate: 0.026

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.077	0.102	0	.	0.752	0.464
CGN	0.004	0.034	0.054	0.325	0.126	0.902
FGN	-0.021	0.024	-0.365	0.325	-0.851	0.408

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.001	2	0.001	0.869	0.439
Residual	0.01	15	0.001		

Durbin-Watson D Statistic   1.760
First Order Autocorrelation   0.076

Model
Theta R = -1.094 + 0.944*CGN - 0.811*FGN - 0.182*CGN^2 - 0.095*FGN^2 + 0.286*CGN x FGN

Dep Var: TR   N: 18   Multiple R: 0.442   Squared multiple R: 0.195
Adjusted squared multiple R: 0.0   Standard error of estimate: 0.027

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-1.094	1.254	0	.	-0.872	0.4
CGN	0.944	0.904	11.803	0.001	1.044	0.317
FGN	-0.811	0.777	-14.383	0	-1.044	0.317
CGNSQ	-0.182	0.17	-15.767	0	-1.069	0.306
FGNSQ	-0.095	0.116	-4.713	0.002	-0.82	0.428
CFGN	0.286	0.284	22.445	0	1.007	0.334

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.002	5	0	0.583	0.713
Residual	0.009	12	0.001		

Durbin-Watson D Statistic   1.877
First Order Autocorrelation   0.020

Appendix G

Linear and non-Linear Regression for Brooks and Corey parameters with particle size distribution, gradation indices, and gradation numbers

a_c and PSD

In the next three models below, sand, silt, and clay are excluded each in turn from the model:

Model
a_c = 0.436 **-** 10.830***Sand -** 3.559***Cla**y + 5.335***BD**

Dep Var: AC N: 18 Multiple R: 0.456 Squared multiple R: 0.208
Adjusted squared multiple R: 0.038 Standard error of estimate: 2.214

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P (2 Tail)
CONSTANT	0.436	28.691	0	.	0.015	0.988
SD	-10.83	25.668	-0.263	0.145	-0.422	0.679
CL	-3.559	87.75	-0.025	0.154	-0.041	0.968
BD	5.335	4.202	0.325	0.861	1.27	0.225

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	18.037	3	6.012	1.227	0.337
Residual	68.629	14	4.902		

Durbin-Watson D Statistic 1.961
First Order Autocorrelation 0.007

MODEL
a_c = - 10.394 + 7.319***Clay +** 10.800***Silt +** 5.337***BD**

Dep Var: AC N: 18 Multiple R: 0.456 Squared multiple R: 0.208
Adjusted squared multiple R: 0.038 Standard error of estimate: 2.214

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-10.394	7.914	0	.	-1.313	0.21
CL	7.319	65.057	0.051	0.279	0.112	0.912
BD	5.337	4.203	0.326	0.861	1.27	0.225
SL	10.8	25.692	0.197	0.258	0.42	0.681

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	18.031	3	6.01	1.226	0.337
Residual	68.636	14	4.903		

Durbin-Watson D Statistic 1.961
First Order Autocorrelation 0.007

Model
$\mathbf{a_c} = -2.800 + 3.106*\mathbf{Silt} - 7.601*\mathbf{Sand} + 5.341*\mathbf{BD}$

Dep Var: AC   N: 18   Multiple R: 0.456   Squared multiple R: 0.208
Adjusted squared multiple R: 0.038   Standard error of estimate: 2.214

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-2.8	64.222	0	.	-0.044	0.966
BD	5.341	4.204	0.326	0.86	1.27	0.225
SL	3.106	88.133	0.057	0.022	0.035	0.972
SD	-7.601	65.279	-0.185	0.022	-0.116	0.909

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	18.035	3	6.012	1.226	0.337
Residual	68.631	14	4.902		

Durbin-Watson D Statistic   1.960
First Order Autocorrelation   0.007

Model
$\mathbf{a_c} = 13425.675 - 16961.379*\mathbf{Sand} - 10896.403*\mathbf{Silt} - 5671.317*\mathbf{Clay} + 610.254*\mathbf{BD} + 3785.301*\mathbf{Sand}^2 - 55507.301*\mathbf{Silt}^2 - 13779.648*\mathbf{Clay}^2 + 54.551*\mathbf{BD}^2 - 848.026*\mathbf{BD*Sand} - 2813.088*\mathbf{BD*Clay}$

Dep Var: AC   N: 18   Multiple R: 0.960   Squared multiple R: 0.922
Adjusted squared multiple R: 0.810   Standard error of estimate: 0.984

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	13425.675	8929.328	0	.	1.504	0.176
SD	-16961.379	9873.476	-412.351	0	-1.718	0.13
SL	-10896.403	8791.36	-198.483	0	-1.239	0.255
CL	-5671.317	8975.895	-39.228	0	-0.632	0.548
BD	610.254	318.557	37.228	0	1.916	0.097
SDQ	3785.301	2516.384	163.115	0	1.504	0.176
SLQ	-5507.301	3782.062	-18.103	0	-1.456	0.189
CLQ	-13779.648	6896.899	-5.587	0.001	-1.998	0.086
BDQ	54.551	27.538	12.961	0	1.981	0.088
BDSD	-848.026	331.497	-51.259	0	-2.558	0.038
BDCL	-2813.088	1360.822	-38.52	0	-2.067	0.078

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	79.888	10	7.989	8.25	0.005
Residual	6.778	7	0.968		

n_c and PSD

In the next three models below, sand, silt, and clay are excluded each in turn from the model:

Model
n_c = 1.592 + 0.837***Sand** - 0.625***Clay** - 0.982***BD**

Dep Var: NC   N: 18   Multiple R: 0.818   Squared multiple R: 0.670
Adjusted squared multiple R: 0.599   Standard error of estimate: 0.123

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.592	1.588	0	.	1.002	0.333
SD	0.837	1.421	0.237	0.145	0.589	0.565
CL	-0.625	4.857	-0.05	0.154	-0.129	0.899
BD	-0.982	0.233	-0.699	0.861	-4.222	0.001

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.426	3	0.142	9.454	0.001
Residual	0.21	14	0.015		

Durbin-Watson D Statistic   2.537

Model
$\mathbf{n_c}$ = 2.429 - 1.461***Clay** – 0.837***Silt** – 0.982***BD**

Dep Var: NC   N: 18   Multiple R: 0.818   Squared multiple R: 0.669
Adjusted squared multiple R: 0.599   Standard error of estimate: 0.123

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	2.429	0.438	0.0	-	5.544	0
CL	-1.461	3.601	-0.118	0.279	-0.406	0.691
BD	-0.982	0.233	-0.699	0.861	-4.221	0.001
SL	-0.837	1.422	-0.178	0.258	-0.588	0.566

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.426	3	0.142	9.453	0.001
Residual	0.21	14	0.015		

Durbin-Watson D Statistic   2.537
First Order Autocorrelation -0.421

Model
$\mathbf{n_c}$ = 0.957 + 1.472***Sand** + 0.639***Silt** – 0.982***BD**

Dep Var: NC   N: 18   Multiple R: 0.818   Squared multiple R: 0.670
Adjusted squared multiple R: 0.599   Standard error of estimate: 0.123

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.957	3.555	0	.	0.269	0.792
BD	-0.982	0.233	-0.699	0.86	-4.22	0.001
SL	0.639	4.878	0.136	0.022	0.131	0.898
SD	1.472	3.613	0.418	0.022	0.407	0.69

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.426	3	0.142	9.454	0.001
Residual	0.21	14	0.015		

Durbin-Watson D Statistic   2.537
First Order Autocorrelation -0.421

a_c and gradation indices (D_{60} and D_{10})

Model

$a_c = 1.805 + 0.103*D60 - 6.790*D10$

Dep Var: AC   N: 18   Multiple R: 0.197   Squared multiple R: 0.039
Adjusted squared multiple R: 0.0   Standard error of estimate: 2.357

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	1.805	1.246	0.0	-	1.448	0.168
DT	-6.79	9.112	-0.208	0.822	-0.745	0.468
DS	0.103	0.198	0.145	0.822	0.519	0.611

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	3.366	2	1.683	0.303	0.743
Residual	83.3	15	5.553		

Durbin-Watson D Statistic   1.773
First Order Autocorrelation   0.107

Model

$a_c = -0.873 + 2.115*D60 + 14.390*D10 + 0.106*D60^2 - 17.354*D10^2 - 15.069*D60*D10$

Dep Var: AC   N: 18   Multiple R: 0.485   Squared multiple R: 0.235
Adjusted squared multiple R: 0.0   Standard error of estimate: 2.350

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P (2 Tail)
CONSTANT	-0.873	2.943	0.0	-	-0.297	0.772
DT	14.39	39.553	0.441	0.043	0.364	0.722
DS	2.115	1.195	2.982	0.022	1.77	0.102
DTSQR	-17.354	102.543	-0.179	0.057	-0.169	0.868
DSSQR	0.106	0.15	1.71	0.011	0.703	0.495
DTDS	-15.069	11.985	-4.787	0.004	-1.257	0.233

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	20.406	5	4.081	0.739	0.609
Residual	66.26	12	5.522		

Durbin-Watson D Statistic   2.155
First Order Autocorrelation -0.093

n_c and gradation indices (D_{60} and D_{10})

Model

$n_c = 0.364 - 0.036 \cdot D60 + 0.915 \cdot D10$

Dep Var: NC N: 18 Multiple R: 0.549 Squared multiple R: 0.301
Adjusted squared multiple R: 0.208 Standard error of estimate: 0.172

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.364	0.091	0.0	-	3.995	0.001
DT	0.915	0.666	0.327	0.822	1.375	0.189
DS	-0.036	0.014	-0.6	0.822	-2.521	0.023

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.192	2	0.096	3.237	0.068
Residual	0.444	15	0.03		

Durbin-Watson D Statistic 2.238
First Order Autocorrelation -0.254

Model

$n_c = 0.708 - 0.142 \cdot D60 - 3.240 \cdot DT - 0.003 \cdot D60^2 + 10.331 \cdot D10^2 + 0.669 \cdot D60 \cdot D10$

Dep Var: NC N: 18 Multiple R: 0.711 Squared multiple R: 0.505
Adjusted squared multiple R: 0.299 Standard error of estimate: 0.162

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.708	0.203	0	.	3.493	0.004
DT	-3.24	2.726	-1.159	0.043	-1.189	0.258
DS	-0.142	0.082	-2.337	0.022	-1.725	0.11
DTSQR	10.331	7.066	1.241	0.057	1.462	0.169
DSSQR	-0.003	0.01	-0.527	0.011	-0.27	0.792
DTDS	0.669	0.826	2.479	0.004	0.81	0.434

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.322	5	0.064	2.453	0.094
Residual	0.315	12	0.026		

Durbin-Watson D Statistic 2.813
First Order Autocorrelation -0.563

a_c and gradation number CGN & FGN

Model

a_c = -0.999 + 1.033*CGN - 1.339*FGN

Dep Var: AC   N: 18   Multiple R: 0.170   Squared multiple R: 0.029
Adjusted squared multiple R: 0.0   Standard error of estimate: 2.369

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.999	9.419	0	.	-0.106	0.917
CGN	1.033	3.163	0.146	0.325	0.327	0.748
FGN	-1.339	2.23	-0.268	0.325	-0.6	0.557

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	2.501	2	1.25	0.223	0.803
Residual	84.166	15	5.611		

Durbin-Watson D Statistic   1.765
First Order Autocorrelation   0.108

Model

a_c = -8.520 -4.310*CGN + 30.702*FGN + 3.008*CGN^2 + 8.199*FGN^2 - 14.509*CGN x FGN

Dep Var: AC   N: 18   Multiple R: 0.339   Squared multiple R: 0.115
Adjusted squared multiple R: 0.0   Standard error of estimate: 2.529

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-8.52	116.489	0	.	-0.073	0.943
CGN	-4.31	84.009	-0.608	0.001	-0.051	0.96
FGN	30.702	72.208	6.146	0	0.425	0.678
CGNSQ	3.008	15.812	2.943	0	0.19	0.852
FGNSQ	8.199	10.75	4.595	0.002	0.763	0.46
CFGN	-14.509	26.396	-12.852	0	-0.55	0.593

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	9.935	5	1.987	0.311	0.897
Residual	76.731	12	6.394		

Durbin-Watson D Statistic   1.937
First Order Autocorrelation   0.023

n_c and gradation number CGN & FGN

Model

n_c = -0.284 + 0.129 *CGN + 0.179 *FGN

Dep Var: NC N: 18 Multiple R: 0.604 Squared multiple R: 0.364
Adjusted squared multiple R: 0.280 Standard error of estimate: 0.164

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.284	0.653	0	.	-0.435	0.67
CGN	0.129	0.219	0.212	0.325	0.587	0.566
FGN	0.179	0.155	0.417	0.325	1.155	0.266

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.232	2	0.116	4.299	0.033
Residual	0.404	15	0.027		

Durbin-Watson D Statistic 2.325
First Order Autocorrelation -0.269

Model

n_c = 6.431 - 3.812*CGN - 0.756*FGN + 0.603*CGN^2 + 0.012*FGN^2 + 0.154*CGN x FGN

Dep Var: NC N: 18 Multiple R: 0.649 Squared multiple R: 0.422
Adjusted squared multiple R: 0.181 Standard error of estimate: 0.175

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	6.431	8.066	0	.	0.797	0.441
CGN	-3.812	5.817	-6.28	0.001	-0.655	0.525
FGN	-0.756	5	-1.765	0	-0.151	0.882
CGNSQ	0.603	1.095	6.884	0	0.551	0.592
FGNSQ	0.012	0.744	0.08	0.002	0.016	0.987
CFGN	0.154	1.828	1.595	0	0.084	0.934

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.268	5	0.054	1.75	0.198
Residual	0.368	12	0.031		

Durbin-Watson D Statistic 2.118
First Order Autocorrelation -0.157

Appendix H

Linear and non-Linear Regression for Fredlund and Xing parameters with particle size distribution, gradation indices, and gradation numbers

a_f and PSD

Model

a_f = - 6.955 - 18.046***Sand** + 4.371***Silt** + 12.549***BD** **(BD = bulk density)**

Dep Var: AF   N: 18   Multiple R: 0.467   Squared multiple R: 0.218
Adjusted squared multiple R: 0.051   Standard error of estimate: 4.878

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-6.955	141.182	0.0	-	-0.049	0.961
SD	-18.046	143.489	-0.198	0.023	-0.126	0.902
SL	4.371	193.749	0.036	0.022	0.023	0.982
BD	12.549	9.259	0.345	0.86	1.355	0.197

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	93.015	3	31.005	1.303	0.312
Residual	333.071	14	23.791		

Durbin-Watson D Statistic   2.078
First Order Autocorrelation -0.050

Model

a_f = -352.900 + 5880.153***Clay** + 466.563***BD** + 1023.602***Sand**^{2} -1577.359***Silt**^{2} - 8635.957***Clay**^{2} + 154.391***BD**^{2} - 1118.018***BD*Sand** - 2972.789***BD*Clay**

Dep Var: AF   N: 17   Multiple R: 0.957   Squared multiple R: 0.915
Adjusted squared multiple R: 0.831   Standard error of estimate: 2.121

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-352.9	370.299	0.0	.	-0.953	0.368
CL	5880.153	2897.259	17.261	0.0	2.03	0.077
BD	466.563	373.689	11.874	0.0	1.249	0.247
SDQ	1023.602	351.532	17.516	0.0	2.912	0.02
SLQ	-1577.359	832.759	-2.24	0.008	-1.894	0.095
CLQ	-8635.957	2831.801	-1.554	0.041	-3.05	0.016
BDQ	154.391	46.173	15.374	0.001	3.344	0.01
BDSD	-1118.018	370.895	-30.514	0.0	-3.014	0.017
BDCL	-2972.789	1492.679	-17.282	0.0	-1.992	0.082

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	388.929	8	48.616	10.807	0.001
Residual	35.99	8	4.499		

Durbin-Watson D Statistic 2.636
First Order Autocorrelation -0.320

<u>h_r and PSD</u>

Model

h_r = - 439.426 **+** 391.528***Sand +** 586.174***Silt +** 26.338***BD**

Dep Var: HR N: 18 Multiple R: 0.540 Squared multiple R: 0.291
Adjusted squared multiple R: 0.140 Standard error of estimate: 11.382

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-439.426	329.449	0	.	-1.334	0.204
SD	391.528	334.831	1.752	0.023	1.169	0.262
SL	586.174	452.112	1.965	0.022	1.297	0.216
BD	26.338	21.607	0.296	0.86	1.219	0.243

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	745.684	3	248.561	1.919	0.173
Residual	1813.642	14	129.546		

Durbin-Watson D Statistic 1.893
First Order Autocorrelation 0.026

Model

h_r = -16957.844 + 29913.633***Silt** + 54074.753***Clay** + 2680.515***BD** + 18333.244***$Sand^2$** - 27891.967* **$Silt^2$** - 55489.594***$Clay^2$** + 311.442***BD^2** - 4007.585***BD*Sand** - 13780.133***BD*Clay**

Dep Var: HR N: 18 Multiple R: 0.817 Squared multiple R: 0.668
Adjusted squared multiple R: 0.294 Standard error of estimate: 10.308

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-16957.844	40141.304	0	.	-0.422	0.684
SL	29913.633	74813.268	100.262	0	0.4	0.7
CL	54074.753	100886.33	68.777	0	0.536	0.607
BD	2680.515	3942.184	30.089	0	0.68	0.516
SDQ	18333.244	40374.994	145.38	0	0.454	0.662
SLQ	-27891.967	59526.15	-16.849	0	-0.469	0.652
CLQ	-55489.594	113991.62	-4.151	0.001	-0.487	0.639
BDQ	311.442	227.693	13.617	0	1.368	0.209
BDSD	-4007.585	4110.069	-44.579	0	-0.975	0.358
BDCL	-13780.133	16921.233	-34.729	0	-0.814	0.439

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	1709.219	9	189.913	1.787	0.213
Residual	850.107	8	106.263		

Durbin-Watson D Statistic 2.272
First Order Autocorrelation -0.168

m_f and PSD

Model
m_f = 2.729 - 2.533***Silt** -0.853***Clay** - 1.085***BD**

Dep Var: MF N: 18 Multiple R: 0.786 Squared multiple R: 0.617
Adjusted squared multiple R: 0.535 Standard error of estimate: 0.186

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	2.729	0.664	0.0	-	4.107	0.001
SL	-2.533	2.158	-0.382	0.258	-1.174	0.26
CL	-0.853	5.468	-0.049	0.279	-0.156	0.878
BD	-1.085	0.353	-0.548	0.86	-3.076	0.008

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.779	3	0.26	7.52	0.003
Residual	0.484	14	0.035		

Durbin-Watson D Statistic 1.828
First Order Autocorrelation -0.038

n_f and PSD

Model

n_f = - 87.487 + 50.125***Sand** + 90.296***Silt** + 20.677***BD**

Dep Var: NF   N: 18   Multiple R: 0.491   Squared multiple R: 0.241
Adjusted squared multiple R: 0.078   Standard error of estimate: 6.641

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-87.487	192.216	0.0	-	-0.455	0.656
SD	50.125	195.356	0.398	0.023	0.257	0.801
SL	90.296	263.783	0.537	0.022	0.342	0.737
BD	20.677	12.607	0.412	0.86	1.64	0.123

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	196.064	3	65.355	1.482	0.262
Residual	617.382	14	44.099		

Durbin-Watson D Statistic   1.276
First Order Autocorrelation   0.341

Model

n_f = 46688.085 - 78043.667***Sand** - 19827.491***Silt** + 2861.115***BD** + 31665.996***Sand**^{2} - 45537.825***Silt**^{2} - 102480.886***Clay**^{2} + 54.414***BD**^{2} - 3133.604***BD*Sand** - 11762.812***BD*Clay**

Dep Var: NF   N: 17   Multiple R: 0.782   Squared multiple R: 0.612
Adjusted squared multiple R: 0.112   Standard error of estimate: 6.679

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	46688.085	39599.774	0	.	1.179	0.277
SD	-78043.667	65371.381	-554.979	0	-1.194	0.271
SL	-19827.491	18646.111	-104.188	0	-1.063	0.323
BD	2861.115	2557.143	52.934	0	1.119	0.3
SDQ	31665.996	26161.1	393.92	0	1.21	0.265
SLQ	-45537.825	38566.697	-47.004	0	-1.181	0.276
CLQ	-102480.89	73863.86	-13.386	0.001	-1.387	0.208
BDQ	54.414	147.527	3.939	0	0.369	0.723
BDSD	-3133.604	2666.465	-62.171	0	-1.175	0.278
BDCL	-11762.812	10967.643	-49.711	0	-1.073	0.319

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	491.846	9	54.65	1.225	0.403
Residual	312.242	7	44.606		

Durbin-Watson D Statistic 2.052
First Order Autocorrelation -0.028

a_f and gradation indices (D_{60} and D_{10})

Model

$\mathbf{a_f}$ = 3.135 - 13.185***D10** + 0.219***D60**

Dep Var: AF N: 18 Multiple R: 0.176 Squared multiple R: 0.031
Adjusted squared multiple R: 0.0 Standard error of estimate: 5.246

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	3.135	2.775	0	.	1.13	0.276
DT	-13.185	20.286	-0.182	0.822	-0.65	0.526
DS	0.219	0.441	0.139	0.822	0.496	0.627

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	13.273	2	6.636	0.241	0.789
Residual	412.813	15	27.521		

Model

$\mathbf{a_f} = -2.885 + 34.214*\mathbf{D10} + 4.669*\mathbf{D60} - 42.835*\mathbf{D10}^2 + 0.212*\mathbf{D60}^2 - 32.202*\mathbf{D10*D60}$

Dep Var: AF N: 18 Multiple R: 0.482 Squared multiple R: 0.232
Adjusted squared multiple R: 0.0 Standard error of estimate: 5.221

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-2.885	6.539	0	.	-0.441	0.667
DT	34.214	87.876	0.473	0.043	0.389	0.704
DS	4.669	2.654	2.969	0.022	1.759	0.104
DTQ	-42.835	227.825	-0.199	0.057	-0.188	0.854
DSQ	0.212	0.334	1.546	0.011	0.634	0.538
DTDS	-32.202	26.628	-4.614	0.004	-1.209	0.25

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	99.017	5	19.803	0.727	0.617
Residual	327.069	12	27.256		

Durbin-Watson D Statistic 2.252
First Order Autocorrelation -0.151

h_r and gradation indices (D_{60} and D_{10})

Model
h_r = 13.728 - 24.081***D10** + 0.202***D60**

Dep Var: HR N: 18 Multiple R: 0.123 Squared multiple R: 0.015
Adjusted squared multiple R: 0.0 Standard error of estimate: 12.963

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	13.728	6.856	0	.	2.002	0.064
DT	-24.081	50.125	-0.136	0.822	-0.48	0.638
DS	0.202	1.089	0.052	0.822	0.185	0.855

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	38.847	2	19.423	0.116	0.892
Residual	2520.48	15	168.032		

Durbin-Watson D Statistic 1.693
First Order Autocorrelation 0.123

Model
h_r = - 8.797 + 215.863***D10** + 11.774***D60** - 428.641***$D10^2$** + 0.790***$D60^2$** - 96.776***D10*D60**

Dep Var: HR N: 18 Multiple R: 0.509 Squared multiple R: 0.259
Adjusted squared multiple R: 0.0 Standard error of estimate: 12.569

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-8.797	15.743	0	.	-0.559	0.587
DT	215.863	211.563	1.217	0.043	1.02	0.328
DS	11.774	6.39	3.055	0.022	1.843	0.09
DTQ	-428.641	548.496	-0.812	0.057	-0.781	0.45
DSQ	0.79	0.804	2.352	0.011	0.982	0.345
DTDS	-96.776	64.109	-5.658	0.004	-1.51	0.157

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	663.559	5	132.712	0.84	0.546
Residual	1895.767	12	157.981		

Durbin-Watson D Statistic 1.992
First Order Autocorrelation -0.030

m_f and gradation indices (D_{60} and D_{10})

Model
m_f = 0.198 + 2.411***D10** - 0.065***D60**

Dep Var: MF N: 18 Multiple R: 0.747 Squared multiple R: 0.558
Adjusted squared multiple R: 0.499 Standard error of estimate: 0.193

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.198	0.102	0	.	1.943	0.071
DT	2.411	0.746	0.612	0.822	3.231	0.006
DS	-0.065	0.016	-0.759	0.822	-4.005	0.001

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.705	2	0.352	9.461	0.002
Residual	0.559	15	0.037		

Durbin-Watson D Statistic 1.434
First Order Autocorrelation 0.238

Model
m_f = 0.318 + 1.351***D10** -0.113***D60** + 2.966***$D10^2$** + 0.005***$D60^2$**

Dep Var: MF N: 18 Multiple R: 0.773 Squared multiple R: 0.597
Adjusted squared multiple R: 0.473 Standard error of estimate: 0.198

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	0.318	0.202	0	.	1.574	0.139
DT	1.351	2.869	0.343	0.058	0.471	0.646
DS	-0.113	0.055	-1.324	0.074	-2.042	0.062
DTQ	2.966	8.349	0.253	0.061	0.355	0.728
DSQ	0.005	0.005	0.614	0.075	0.958	0.356

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.754	4	0.189	4.817	0.013
Residual	0.509	13	0.039		

Durbin-Watson D Statistic 1.286
First Order Autocorrelation 0.296

n_f and gradation indices (D_{60} and D_{10})

Model

$n_f = 4.454 - 14.174 * \mathbf{D10} + 1.200 * \mathbf{D60}$

Dep Var: NF N: 18 Multiple R: 0.509 Squared multiple R: 0.259
Adjusted squared multiple R: 0.160 Standard error of estimate: 6.339

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	4.454	3.353	0	.	1.328	0.204
DT	-14.174	24.513	-0.142	0.822	-0.578	0.572
DS	1.2	0.533	0.552	0.822	2.252	0.04

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	210.66	2	105.33	2.621	0.106
Residual	602.785	15	40.186		

Durbin-Watson D Statistic 1.353
First Order Autocorrelation 0.314

Model

n_f **=** -1.636 **+** 66.995***D10 +** 4.018***D60 -**132.595***D10**^{2}+ 0.503***D60**^{2} - 39.665***D10*D60**

Dep Var: NF   N: 18   Multiple R: 0.581   Squared multiple R: 0.338
Adjusted squared multiple R: 0.062   Standard error of estimate: 6.701

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-1.636	8.392	0	.	-0.195	0.849
DT	66.995	112.784	0.67	0.043	0.594	0.564
DS	4.018	3.406	1.849	0.022	1.179	0.261
DTQ	-132.595	292.401	-0.445	0.057	-0.453	0.658
DSQ	0.503	0.429	2.656	0.011	1.173	0.264
DTDS	-39.665	34.176	-4.113	0.004	-1.161	0.268

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	274.684	5	54.937	1.224	0.356
Residual	538.761	12	44.897		

Durbin-Watson D Statistic   1.574
First Order Autocorrelation   0.203

a_f and gradation number CGN & FGN

Model

a_f = -4.189 + 2.871***CGN** - 3.604***FGN**

Dep Var: AF   N: 18   Multiple R: 0.204   Squared multiple R: 0.042
Adjusted squared multiple R: 0.0   Standard error of estimate: 5.218

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-4.189	20.749	0	.	-0.202	0.843
CGN	2.871	6.966	0.183	0.325	0.412	0.686
FGN	-3.604	4.913	-0.325	0.325	-0.734	0.474

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	17.706	2	8.853	0.325	0.727
Residual	408.38	15	27.225		

Durbin-Watson D Statistic   1.883
First Order Autocorrelation   0.052

Model

$\mathbf{a_f}$ = 7.870 - 30.0***CGN** + 79.167***FGN** + 10.511***CGN**^{2} + 19.729***FGN**^{2} - 36.646***CGN** x **FGN**

Dep Var: AF   N: 18   Multiple R: 0.353   Squared multiple R: 0.125
Adjusted squared multiple R: 0.0   Standard error of estimate: 5.575

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	7.87	256.815	0	.	0.031	0.976
CGN	-30	185.208	-1.91	0.001	-0.162	0.874
FGN	79.167	159.191	7.148	0	0.497	0.628
CGNSQ	10.511	34.858	4.638	0	0.302	0.768
FGNSQ	19.729	23.701	4.987	0.002	0.832	0.421
CFGN	-36.646	58.192	-14.64	0	-0.63	0.541

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	53.145	5	10.629	0.342	0.878
Residual	372.941	12	31.078		

Durbin-Watson D Statistic   2.008
First Order Autocorrelation -0.010

n_f and gradation number CGN & FGN

Model

$\mathbf{n_f}$ = 21.653 - 2.766***CGN** - 5.126***FGN**

Dep Var: NF   N: 18   Multiple R: 0.446   Squared multiple R: 0.199
Adjusted squared multiple R: 0.092   Standard error of estimate: 6.592

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	21.653	26.214	0	.	0.826	0.422
CGN	-2.766	8.801	-0.127	0.325	-0.314	0.758
FGN	-5.126	6.207	-0.335	0.325	-0.826	0.422

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	161.562	2	80.781	1.859	0.19
Residual	651.883	15	43.459		

Durbin-Watson D Statistic   1.540
First Order Autocorrelation   0.210

Model

$\mathbf{n_f}$ = -243.818 + 209.641***CGN** - 203.247***FGN** - 38.388***CGN**^{2} - 4.062***FGN**^{2} + 55.604 ***CGN** x **FGN**

<u>Dep Var: NF</u> N: 18 Multiple R: 0.643 Squared multiple R: 0.414
Adjusted squared multiple R: 0.169 Standard error of estimate: 6.305

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-243.818	290.455	0	.	-0.839	0.418
CGN	209.641	209.468	9.66	0.001	1.001	0.337
FGN	-203.247	180.044	-13.281	0	-1.129	0.281
CGNSQ	-38.388	39.425	-12.259	0	-0.974	0.349
FGNSQ	-4.062	26.805	-0.743	0.002	-0.152	0.882
CFGN	55.604	65.815	16.076	0	0.845	0.415

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	336.404	5	67.281	1.692	0.211
Residual	477.041	12	39.753		

Durbin-Watson D Statistic 1.827
First Order Autocorrelation 0.062

<u>$\mathbf{m_f}$ and gradation number CGN & FGN</u>

Model

$\mathbf{m_f}$ = -0.871 + 0.305***CGN** + 0.109***FGN**

<u>Dep Var: MF</u> N: 18 Multiple R: 0.515 Squared multiple R: 0.266
Adjusted squared multiple R: 0.168 Standard error of estimate: 0.249

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-0.871	0.989	0	.	-0.881	0.392
CGN	0.305	0.332	0.357	0.325	0.92	0.372
FGN	0.109	0.234	0.18	0.325	0.464	0.649

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.335	2	0.168	2.712	0.099
Residual	0.928	15	0.062		

Durbin-Watson D Statistic 2.014
First Order Autocorrelation -0.059

Model

$\mathbf{m_f}$ = 5.912 - 4.935***CGN** + 4.055***FGN** + 0.974***CGN**^{2} + 0.361***FGN**^{2} - 1.348***CGN** x **FGN**

Dep Var: MF   N: 18   Multiple R: 0.544   Squared multiple R: 0.296
Adjusted squared multiple R: 0.002   Standard error of estimate: 0.272

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	5.912	12.544	0	.	0.471	0.646
CGN	-4.935	9.047	-5.77	0.001	-0.545	0.595
FGN	4.055	7.776	6.723	0	0.521	0.612
CGNSQ	0.974	1.703	7.897	0	0.572	0.578
FGNSQ	0.361	1.158	1.678	0.002	0.312	0.76
CFGN	-1.348	2.842	-9.888	0	-0.474	0.644

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	0.373	5	0.075	1.007	0.455
Residual	0.89	12	0.074		

Durbin-Watson D Statistic   2.067
First Order Autocorrelation -0.086

h_r and gradation number CGN & FGN

Model

$\mathbf{h_r}$ = 7.633 + 2.349***CGN** - 4.291***FGN**

Dep Var: HR   N: 18   Multiple R: 0.113   Squared multiple R: 0.013
Adjusted squared multiple R: 0.0   Standard error of estimate: 12.978

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	7.633	51.607	0	.	0.148	0.884
CGN	2.349	17.327	0.061	0.325	0.136	0.894
FGN	-4.291	12.219	-0.158	0.325	-0.351	0.73

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	32.91	2	16.455	0.098	0.907
Residual	2526.416	15	168.428		

Durbin-Watson D Statistic   1.679
First Order Autocorrelation   0.126

Model

$\mathbf{h_r}$ = -300.842 + 135.324***CGN** + 210.770***FGN** - 11.963*$\mathbf{CGN^2}$ + 24.338*$\mathbf{FGN^2}$ - 70.121***CGN** x **FGN**

Dep Var: HR   N: 18   Multiple R: 0.313   Squared multiple R: 0.098
Adjusted squared multiple R: 0.0   Standard error of estimate: 13.869

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	-300.842	638.884	0	.	-0.471	0.646
CGN	135.324	460.745	3.515	0.001	0.294	0.774
FGN	210.77	396.023	7.764	0	0.532	0.604
CGNSQ	-11.963	86.718	-2.154	0	-0.138	0.893
FGNSQ	24.338	58.961	2.51	0.002	0.413	0.687
CFGN	-70.121	144.766	-11.43	0	-0.484	0.637

Analysis of Variance

Source	Sum-of-Squares	DF	Mean Square	F-Ratio	P
Regression	251.293	5	50.259	0.261	0.926
Residual	2308.034	12	192.336		

Durbin-Watson D Statistic   1.909