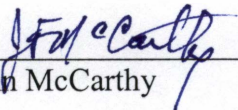
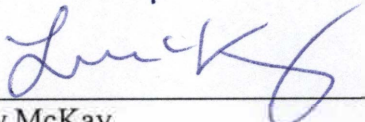


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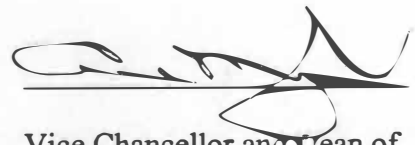
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Ed Perfect, Major Professor

We have read this thesis and
recommend its acceptance:


John McCarthy
Larry McKay

Acceptance for the Council:


Vice Chancellor and Dean of
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Thesis
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**DETERMINATION OF AN APPROPRIATE GEOMETRICAL MODEL
FOR SOIL AGGREGATES BASED UPON SPECIFIC SURFACE AREA
SCALING**

**A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville**

**Jeremy E. Lawson
May 2005**

DEDICATION

I'd like to dedicate this work to all of the relatives I've lost while attending the University of Tennessee, Knoxville. To my great-uncle Kyle Midkiff, Christmas (2004) was just not the same without your company, and I'm sure no others will be. To my great-uncle Wilburn Triplett Jr., a magnificent man and teacher, argued by many as West Virginia's greatest high school math teacher, your calm and polite nature will be missed. To my grandmother Wilmarene Midkiff, one of the greatest Marshall University supporters of all time, I will always cherish the time I spent with you especially the times we cheered The Herd on to victory, your love and support will never be forgotten. And finally to my grandfather Robert "Ed" Lawson, as good a man as any, a better man than most, I will always admire your integrity and your beliefs, there could not possibly have been a better role-model for me than you. It was a privilege and an honor to know each and every one of you, thanks.

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ABSTRACT

The appropriate geometrical form of soil aggregates is important for modeling soil hydraulic and mechanical properties. To investigate this topic, specific surface area (SSA) measurements were conducted on soil aggregates obtained from two sites. Differing long-term agricultural practices at the two sites resulted in nine distinct soil treatments. Each of the soil treatments was fractionated into five size classes and the SSA of each class was measured using the nitrogen adsorption technique. The measured data were then compared to simulated SSA results. To accomplish this, six geometrical models were developed, using either Euclidean or fractal geometry, to predict the SSA scaling as a function of size. These models predict that as aggregate size increases, the SSA either remains constant (with a scaling exponent of zero) or decreases (with an integer exponent of minus one or non-integer exponent of between 0 and -1). The determination of an appropriate model did not rely solely on SSA scaling. Other physical properties such as particle- and pore-size distributions were measured on the same treatments in order to more finely discern between the different models. The presence or absence of these properties had major implications as to which geometrical model was most appropriate. By comparing the SSA scaling data with the particle- and pore-size distribution measurements it was apparent that the most appropriate geometrical model for soil aggregates is a pore-solid fractal. This study gives support to the idea that soil aggregates are fractal in nature.

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LIST OF SYMBOLS AND ABBREVIATIONS

α	An Equation Constant
β	Scaling Exponent
ρ_s	Particle Density
σ	Surface Tension of Water
ψ	Measured Water Potential
$\propto$	Proportional to Symbol
∞	Infinity
A_{cs}	Cross-Sectional Area of the Adsorbate
b	Scaling Ratio Between Consecutive Model Structures
C	BET Constant
CT	Conventional Till
d	Euclidean Dimension
(d)	Diameter of a Sphere
D	Fractal Dimension
D_m	Mass Fractal Dimension
D_p	Pore Fractal Dimension
D_{ps}	Pore-Solid Fractal Dimension
D_s	Surface Fractal Dimension
i	Iteration Level
I	Intercept (SSA Determination)
j	Upper Limit of Iterative Steps
L	Macroscopic Width of a Sphere
m	Mass
M	Molecular Weight of the Adsorbate
m_t	Total Mass
N	Number of Specified Objects
N	Avogadro's Number (SSA Determination)
N_j	Number of Specified Objects at the Upper Limit of Iteration
NT	No Till
N_w	Number of Replication Sites Present in the Pore-Solid Fractal Model
N_x	Number of Pores Present in the Pore-Solid Fractal Model
N_y	Number of Solids Present in the Pore-Solid Fractal Model
P/P_0	Partial Pressure
s	Slope
SA	Surface Area
SA_i	Surface Area per Iteration Level

SA_t	Total Surface Area
SEM	Scanning Electron Microscope
SSA	Specific Surface Area
TC	Total Carbon
TOC	Total Organic Carbon
V	Volume
V_i	Volume per Iteration Level
V_t	Total Volume
w	Replication Sites in the Pore-Solid Fractal Model
W	Mass of Gas Adsorbed at a Relative Partial Pressure
W_m	Mass of Adsorbate Constituting a Monolayer of Surface Coverage
x	Pores in the Pore-Solid Fractal Model
y	Solids in the Pore-Solid Fractal Model
z	An Increasing Integer Value

1.0 INTRODUCTION

Specific surface area (SSA) can be defined as a measure of the number of areal units needed to cover the surface of a figure divided by its mass. This standard definition, which has been used for centuries, assumes application to basic Euclidean objects such as circles, spheres, cubes, etc. The equations used to determine specific surface area work well for these objects but rarely do naturally occurring materials have these basic shapes. In order to determine the specific surface area of non-Euclidean materials new equations have been developed thanks largely to the work of Mandelbrot (1982) and his ideas for a new branch of mathematics – fractal geometry.

According to Mandelbrot (1989), fractal geometry can be considered as a new geometric language that is geared towards the study of assorted mathematical and natural objects that are not smooth, but are rough and fragmented to the same degree at all scales. This statement describes one of the most important characteristics of fractals, that of scale invariance. Scale invariance is a term used to describe objects that are indistinguishable at various magnifications. Scale invariance is without doubt present in natural phenomena. Without some sort of scale for reference it may be impossible to distinguish if a photograph covers a range of several millimeters or several meters (Turcotte, 1997). For instance, a mountain is composed of large rocks, which are composed of smaller rocks, which are composed of even smaller rocks. Without a reference it would be very difficult to determine scale. This phenomenon is also present in soil aggregates.

A soil aggregate is an assemblage of primary soil particles joined together by flocculation and cementation. Flocculation is a term used to describe the electrostatic attraction of oppositely charged clay particles. Under the right conditions clay particles will join together and form small aggregates. However, these particles are not stable and can be easily dispersed. For an aggregate to remain together there needs to be a cementing agent present. The most important cementing agent is called humus (Hillel, 1998). As a plant dies there is an increase in microbial activity which leads to its decomposition. During decomposition humic cements are produced by microbial

organisms (Metting, 1993). Like clay, humus is a charged particle and during flocculation humic material is combined with clay particles to form stable aggregates.

The formation of a soil aggregate has been heavily debated and the two most commonly accepted theories are in direct contrast of one another. One theory states that microaggregates are formed within macroaggregates. The macroaggregates are highly unstable and disintegrate into smaller microaggregates and primary particles. This idea was first suggested by Oades (1984) and has been supported by many researchers such as Beare et al. (1994), Jastrow (1996), Gale (1997), Angers et al. (1997), and Six et al. (1998). The second theory is based on the idea that primary particles and microaggregates are built up into progressively larger macroaggregates. This theory was originally posed by Tisdall and Oades in 1982. Oades and Waters (1991) support this theory in soils where organic matter is the dominant gluing agent. Regardless of the actual formation of a soil aggregate it is apparent that there is a hierarchical arrangement of primary particles and microaggregates that are combined together to form a larger macroaggregates (Figure 1). This hierarchical structure has led many researchers to conclude that soil aggregates are fractal.

The objective of this study was to examine the specific surface area scaling of Euclidean and fractal models in relation to specific surface area measurements performed on soil aggregates from different size fractions. The data obtained from the SSA analysis was combined with particle- and pore size distribution data to aid in the determination of an accurate geometrical model to be used for describing soil aggregates. The combination of these analyses has led to a determination of whether or not soil aggregates can be considered as fractal entities, or if they obey the laws of Euclidean geometry. This could be a valuable and important step for future work as this may become a starting point for mathematical modeling of soil structure.

1.1 Literature Review

Pfeifer, Avnir, and co-workers (Pfeifer and Avnir, 1983; Avnir et al. 1983; Avnir et al. 1984; Pfeifer, 1984; Pfeifer et al. 1984; Avnir et al. 1985; Pfeifer and Obert, 1989; Farin and Avnir, 1989; Avnir, 1989) are considered the pioneers of applying fractal geometry to natural materials. They have shown that at a molecular-size range the

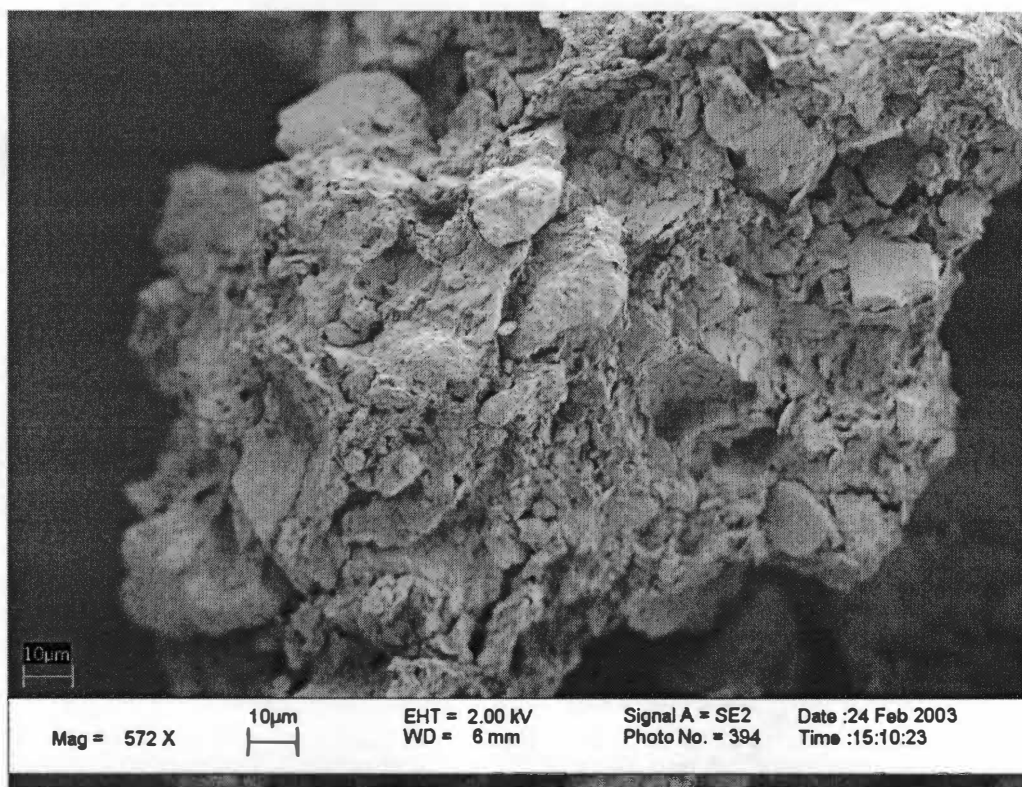


Figure 1: SEM image of a soil aggregate taken at a magnification of 572x. Notice how it appears as if smaller particles and microaggregates are joined together to create a larger aggregate.

surfaces of most materials are fractal (Avnir et al. 1984) with surface fractal dimensions (D_s) ranging from $2 \leq D_s < 3$. D_s values that are around 2 indicate a smooth surface and D_s values that are near 3 indicate an “extreme irregularity of the surface.” Based on their work they have concluded that the specific surface area of soils (as well as several other materials) scales as $SSA \propto L^{D_s-3}$, where L represents the macroscopic width of the soil aggregate/particle.

The equation $SSA \propto L^{D_s-3}$ has been used by many researchers (e.g., Anderson et al. 1998; Pernyeszi and Dekany, 2003; Okuda et al. 1995; Van Dammê et al. 1988) as the model of choice to determine the fractal dimensions of their materials. Avnir et al. (1984) used data from a paper written by Love and Whittaker (1954) that analyzed the specific surface area, using BET gas adsorption, of different types and size classes of

agricultural limestone and determined a surface fractal dimension for each material (Figure 2). They obtained their fractal dimensions by plotting data points on a log-log scale and calculating a best fit line through the data. The slope of this line and the value 3 are summed to get the fractal dimension. Table 1, presented by Farin and Avnir (1989) lists many different types of materials with their calculated fractal dimensions based upon specific surface area measurements derived from the Pfeifer-Avnir equation. The equation $SSA \propto L^{Ds-3}$ was definitely applicable for surface fractals (see Section 2.3). However, the question of whether or not any given material is actually a surface fractal must then be posed. This research will look in depth at soil aggregates in an attempt to determine if they are fractal, and if so what type of fractal they truly are.

The approach used in this study is novel in that the soil aggregates were fractionated into different size classes and specific surface area measurements were performed on each fraction in an attempt to derive a scaling relationship. Papers written by Mayer (1994a, 1994b) and Keil et al. (1994) have measured the specific surface areas

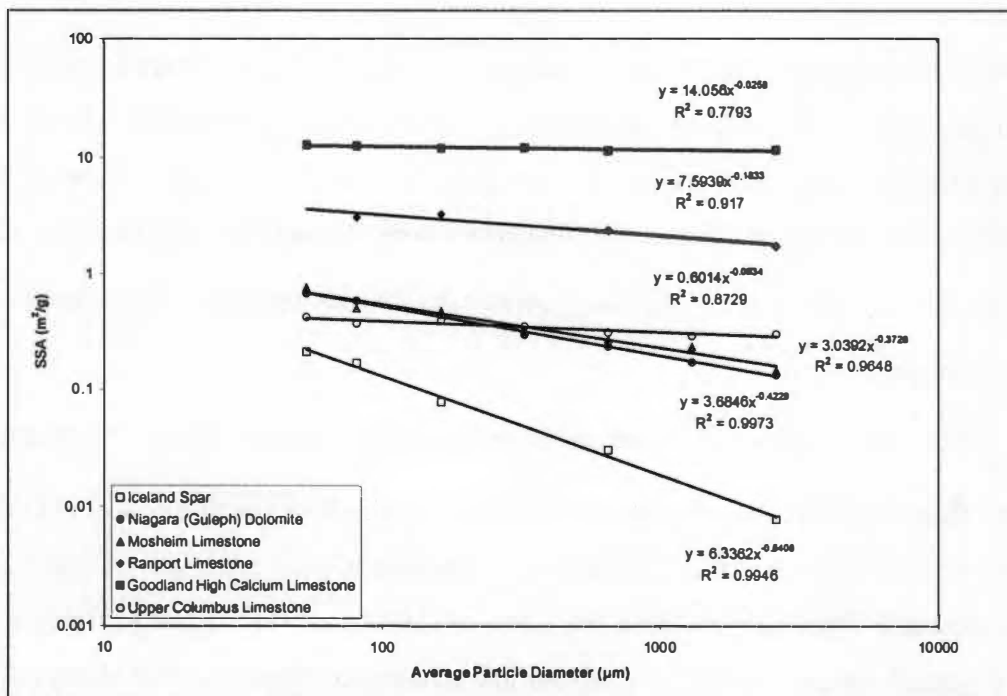


Figure 2: Surface fractal dimension determination using various types of agricultural limestone (Love and Whittaker, 1954).

Table 1: SSA scaling data presented by Farin and Avnir (1989). The exponent value, or slope, was determined by using the Pfeifer-Avnir equation.

Material	Exponent	D _s value ⁺
Silica-60 (Woelm)	0.04	3.04
Halimeda skeletal carbonate (green algae)	0.02	3.02
Silica-60 (Woelm)	0.00	3.00
Alumina (merck)	-0.02	2.98
Cobalt ion-exchanged zeolite X	-0.03	2.97
Upper Columbus dolomite	-0.09	2.91
Fungia skeletal carbonate (coral)	-0.27	2.73
Igneous rock (from shoal)	-0.27	2.73
Cobalt phthalocyanine loaded zeolite X	-0.29	2.71
Soil (mainly kaolinite)	-0.29	2.71
Clypeaster skeletal carbonate (echinoid)	-0.31	2.69
5 types of shaly rocks	-0.40	2.60
Niagra dolomite	-0.42	2.58
α-FeOOH	-0.43	2.57
Coal mine dust	-0.48	2.52
5 charcoals	-0.50	2.50
Syncrude coke	-0.52	2.48
Syncrude coke	-0.53	2.47
B(eta)-Copper phthalocyanine pigments	-0.55	2.45
Hybla alkali feldspar	-0.64	2.36
Lead Corning glass	-0.65	2.35
Coal mine dust	-0.67	2.33
Soil (feldspar, quartz limonite)	-0.67	2.33
Iceland spar	-0.84	2.16
Snowit (fine Belgian Glass sand)	-0.85	2.15
Madagascar quartz	-0.86	2.14
Vitreous silica	-0.97	2.03
Alkylammonium montmorillonite	-0.97	2.03
Alkyldiammonium montmorillonite	-0.97	2.03
Aerosil (Degussa)	-0.98	2.02
Alkyldiammonium hectorite	-1.02	1.98
Periclase	-1.05	1.95

⁺D_s = exponent + 3

of different sized fractions of marine sediments but their research was not concerned with the determination of a fractal dimension or with fractals in general. The author's analysis of SSA data from Keil et al. (1994) gave scaling exponent values between -0.7033 and -0.2806 with R^2 values between 0.8269 and 0.9483. When the Pfeifer-Avnir equation was invoked, surface fractal dimensions of between 2.2967 and 2.7194 were obtained. Avnir et al. (1984) did analyze data from a paper written by Cohen and Knight (1947) that measured the specific surface area of soil particles. However, the specific surface area measurements in that paper were conducted on primary particles and not aggregates. No papers were found that dealt with the determination of specific surface area on different sized fractions of soil aggregates where the researchers were also looking for a fractal dimension. Furthermore, different models have been developed in an attempt to determine whether or not soil aggregates are fractal in nature and if they are, what kind of fractal are they?

2.0 GEOMETRICAL MODELS

Six geometrical models have been developed in order to determine whether or not soil aggregates are actually fractal. The first two models deal with Euclidean spheres in two different arrangements, either as single spheres of various sizes or as an accumulation of identical spheres arranged into aggregates. The third model describes the behavior of a surface fractal aggregate at different sizes. A surface fractal is an object whose surface boundary or perimeter increases by some sort of power law distribution at increasing iteration levels. This model was based on the Koch snowflake, with modifications so that it could be constructed in three-dimensional space, and was constructed of different sized spheres. The fourth model describes the behavior of a mass fractal aggregate whose mass decreases and surface area increases at increasing iteration levels. This model was based on the Menger sponge that was modified so that the figure was constructed of spheres and not cubes. The fifth model developed was that for a pore fractal aggregate. A pore fractal is essentially the inverse of a Menger sponge whose pores are now solids and solids now pores. This model was also constructed using spheres. The sixth and final model was that of the pore-solid fractal aggregate. This model was developed by Niemark (1989) and was further expanded by Perrier et al., (1999). Unlike the previous models this model takes into account and quantifies both the pore and solid space within the object.

2.1 Euclidean Solids

Euclidean geometry has been around since Euclid compiled all previously known mathematical knowledge and wrote *The Elements* nearly two thousand years ago. This work has been the basis for the teaching of geometry ever since. The following has been devised to confirm the scaling of surface area, volume, and mass for Euclidean spheres constructed with different diameters (Figure 3). The macroscopic width of each sphere is equal to the diameter (d) and will be referred to as L.

1. Four sizes of Euclidean spheres were used with diameters of 1, 3, 9, and 27.
2. The surface area (SA) of each sphere was calculated by using the equation,

$$SA = 4 \cdot \pi \cdot \left(\frac{L}{2}\right)^2, \text{ where } L \text{ is the diameter of the sphere.}$$

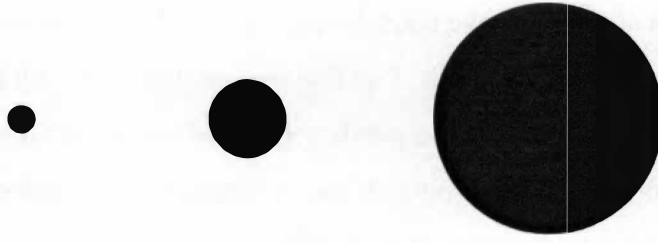


Figure 3: Cross-sectional view of Euclidean solid spheres constructed with L values of 1 (left), 3 (center), and 9 (right). Black represents solids.

3. The volume (V) of each sphere was calculated by using the equation,

$$V = \frac{4}{3} \cdot \pi \cdot \left(\frac{L}{2}\right)^3.$$

4. The mass (m) of each sphere was calculated by rearranging the equation $\rho_s = \frac{m}{V}$,

where ρ_s equaled the particle density of the spheres, to give $m = \rho_s \cdot V$; m can

then be solved by the equation $m = \frac{4}{3} \cdot \pi \cdot \left(\frac{L}{2}\right)^3 \cdot \rho_s$ if ρ_s is assumed to be equal

for all of the spheres.

5. By completing these steps Figures 4 and 5 were generated.
6. By observing the exponents given by the two graphs it is apparent that SA scales as L^2 and m scales as L^3 . These values are expected since SA is a squared function, and m is a cubed function since it was equal to V .
7. By dividing the SA by m Figure 6 was produced. SA/ m is referred to as the specific surface area (SSA).
8. Since SA scales as L^2 and m scales as L^3 , dividing the two quantities should result in the scaling relation $SA/m \propto L^{-1}$, which was shown by Figure 6.

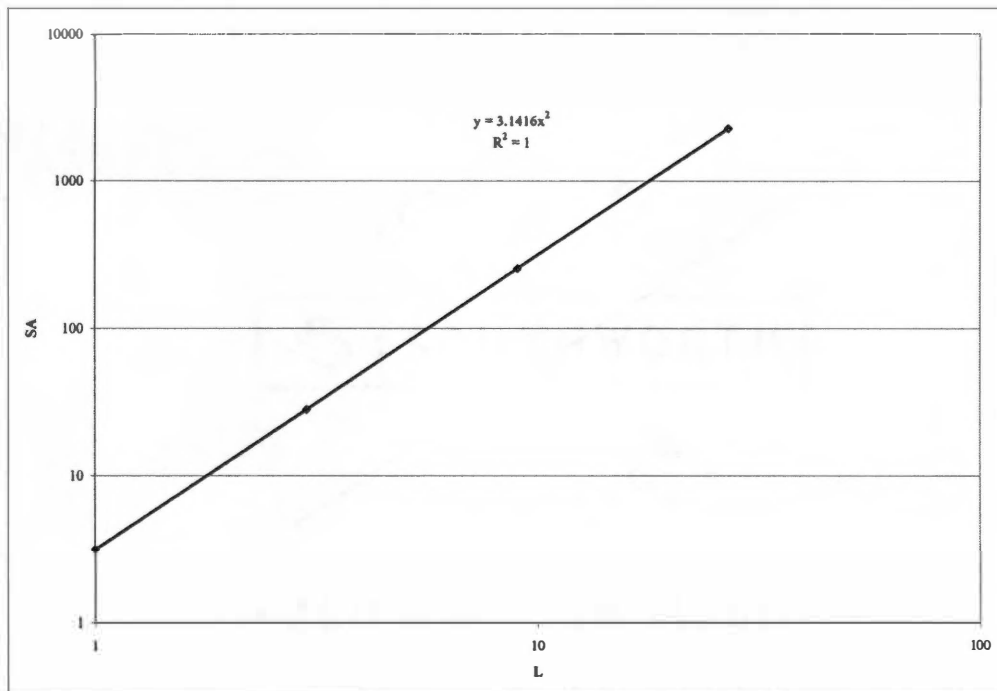


Figure 4: SA scaling behavior of Euclidean spheres constructed with various diameters.

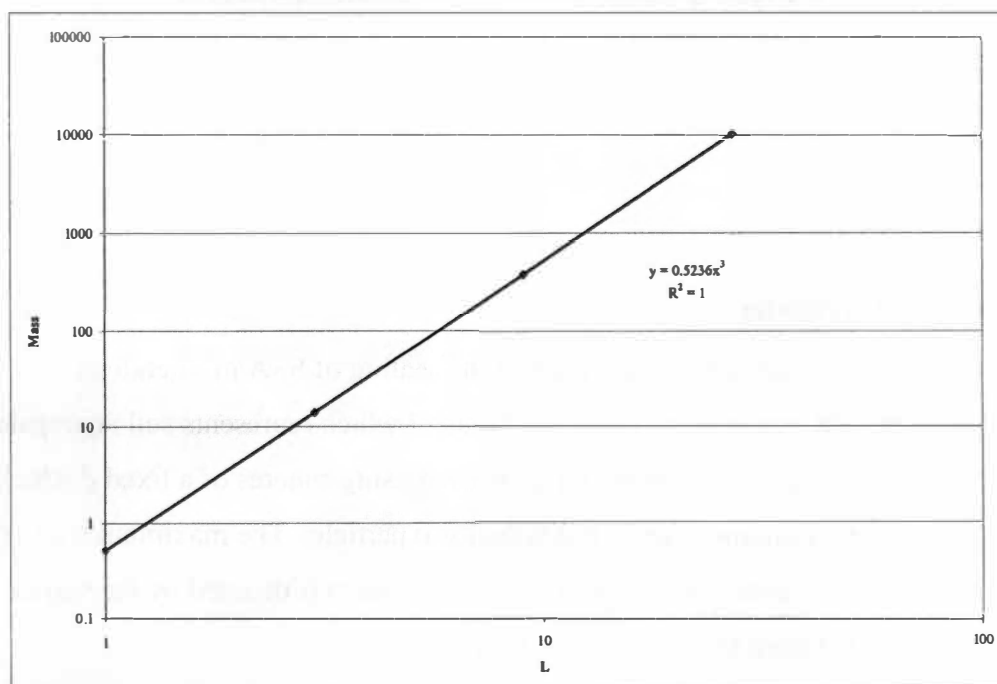


Figure 5: The scaling behavior of the m of Euclidean spheres constructed with various diameters.

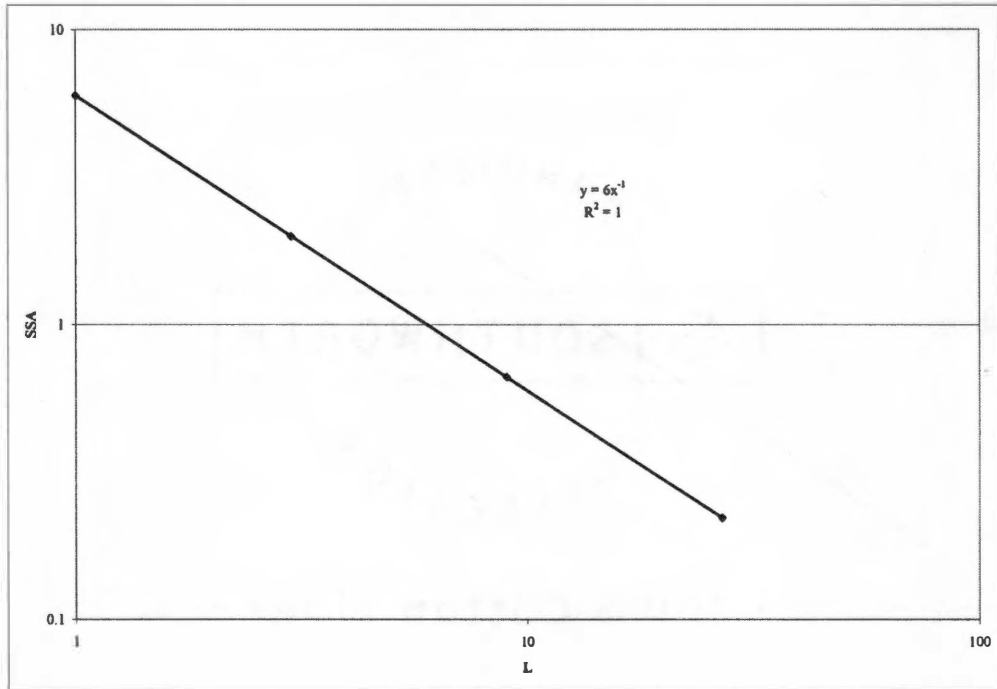


Figure 6: The scaling behavior of SSA when L is increased for solid Euclidean spheres.

9. To conclude the scaling relations for solid Euclidean spheres are:

- $SA \propto L^2$
- $V \propto L^3$
- $m \propto L^3$
- $SSA \propto L^{-1}$

2.2 Euclidean Aggregates

The following has been devised to test the scaling of SSA in Euclidean aggregates. This test was constructed using Figure 7 which represents soil aggregates of different sizes. The aggregates were all constructed using spheres of a fixed d which will be used as the minimum d for an individual soil particle. The maximum width (L) of the constructed aggregates differs by a factor of 3 which is denoted by the variable b which is the ratio between the increasing sizes of L .

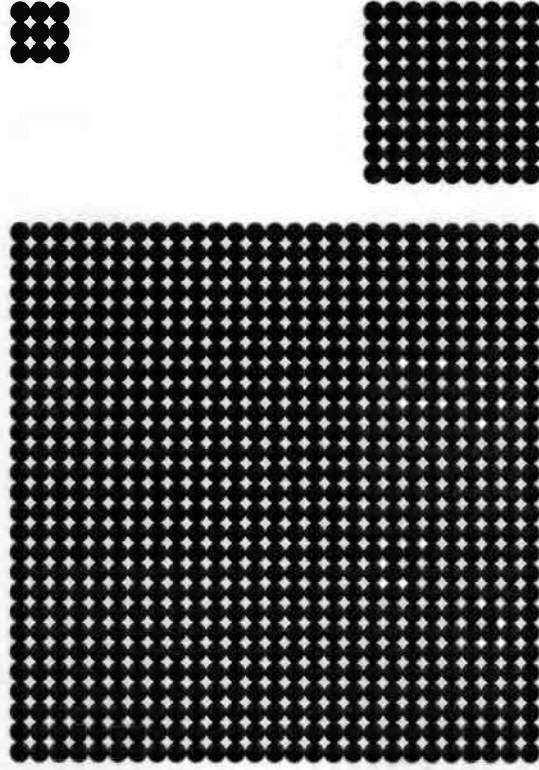


Figure 7: Cross-sectional view of a Euclidean aggregate with a cubic arrangement of spheres with L values of 3 (top left), 9 (top right), and 27 (bottom). The diameter of each sphere is equal to 1 and black represents solids.

1. Four values of L were calculated using the formula $L = \left(\frac{1}{b}\right)^{-i}$, where i is the iteration step between each arrangement.
2. The number of spheres (N) in each arrangement was calculated by cubing the value obtained for L , $N = \left[\left(\frac{1}{b}\right)^{-i}\right]^3$.
3. The d of each sphere was then set at a constant value which represents the minimum diameter that the spheres can obtain, $d = \frac{1}{b}$.
4. The SA of a single sphere was then calculated by the equation, $SA = 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2$.

5. The total surface area (SA_t) of each aggregate was calculated by multiplying SA

by N, $SA_t = 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \cdot \left[\left(\frac{1}{b}\right)^{-i}\right]^3$. Since d is a constant, $SA_t \propto \left[\left(\frac{1}{b}\right)^{-i}\right]^3$ or

$$SA_t \propto L^3.$$

6. The volume, V, of a single sphere was then calculated by the equation,

$$V = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3.$$

7. The total volume of spheres (V_t) in each aggregate was calculated by multiplying

V by N, $V_t = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \left[\left(\frac{1}{b}\right)^{-i}\right]^3$.

8. If particle density is held constant then m can be determined by the same method as volume. The m of a single sphere was calculated by the equation,

$$m = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \rho_s.$$

9. The total mass (m_t) of each aggregate was calculated by multiplying m by N,

$$m_t = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \rho_s \cdot \left[\left(\frac{1}{b}\right)^{-i}\right]^3.$$

10. By completing these steps Figures 8 and 9 were generated.

11. By observing the exponents given by the two graphs it is apparent that SA_t and m_t scale as L^3 . For m_t this result was expected since m_t and V_t were determined using the same equations. However, the SA_t of a Euclidean figure should have intuitively scaled as L^2 not as L^3 . This discrepancy may be explained by noting that the spheres were compacted in a cubic arrangement. By compacting the spheres in this manner the arrangement has a greater influence on SA than the individual spheres themselves.

12. The SSA was determined by dividing the SA_t by m_t which produced Figure 10.

13. Since the exponents of SA_t and m_t were the same, SSA was a constant.

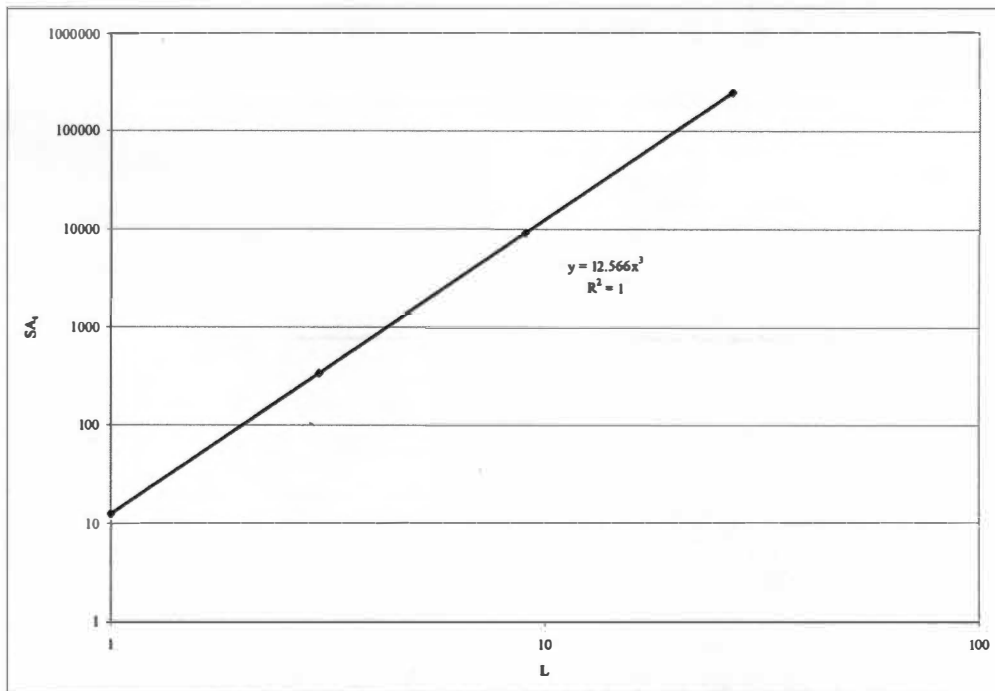


Figure 8: SA_i scaling behavior of a Euclidean cubic aggregate constructed with spheres when L is increased.

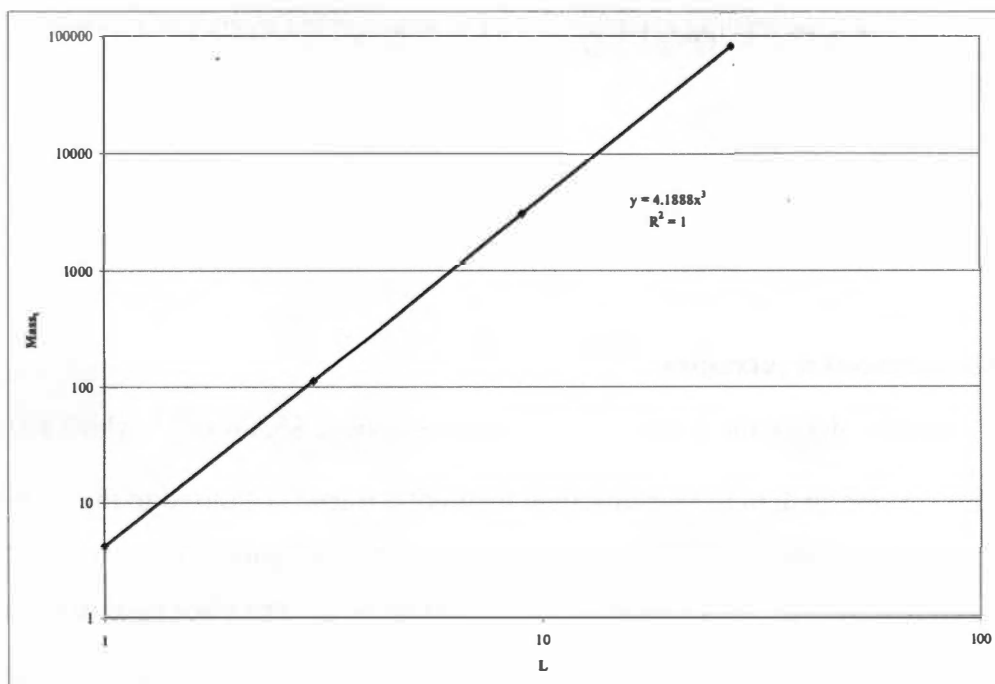


Figure 9: The scaling behavior of the m_t of a Euclidean cubic aggregate constructed with spheres when L is increased.

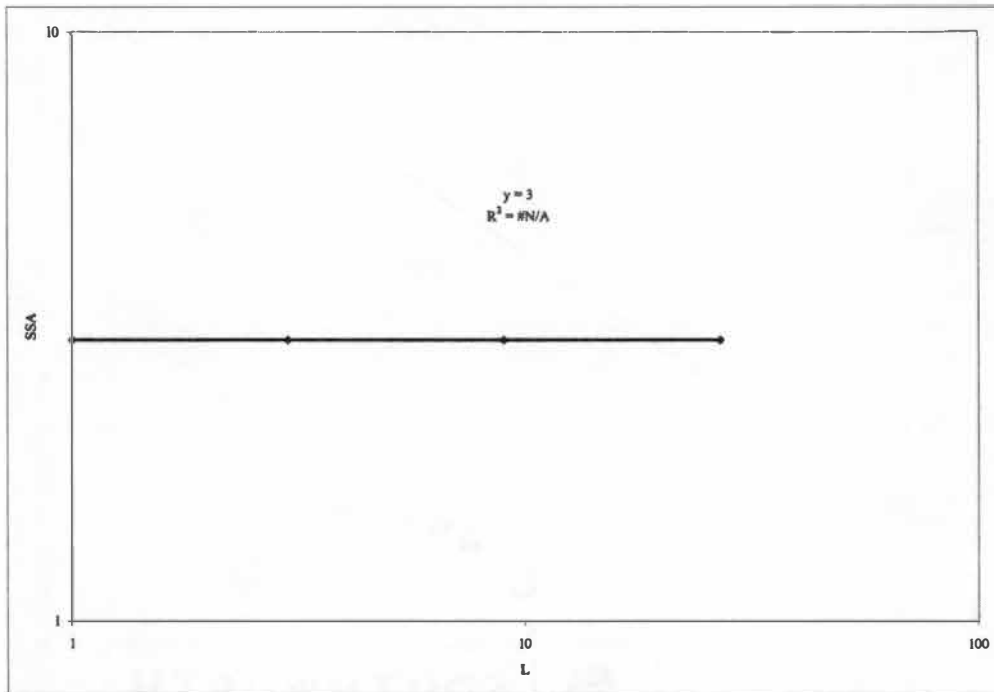


Figure 10: The scaling behavior of SSA when L is increased for a Euclidean cubic aggregate made of spheres.

14. To conclude the scaling relations for a Euclidean cubic aggregate made of spheres:

- $SA_t \propto L^3$
- $V_t \propto L^3$
- $m_t \propto L^3$
- $SSA \propto L^0$

2.3 Surface Fractal Aggregates

In order to derive the Pfeifer-Avnir (1983) equation, $SSA \propto L^{D_s-3}$, which states that SSA is proportional to the macroscopic width of a fractal (L) raised to the power of the surface fractal dimension (D_s) minus 3, surface fractals (Figure 11) were created, each having the same D_s value but with varying values of L. The steps used to test the equation are as follows:

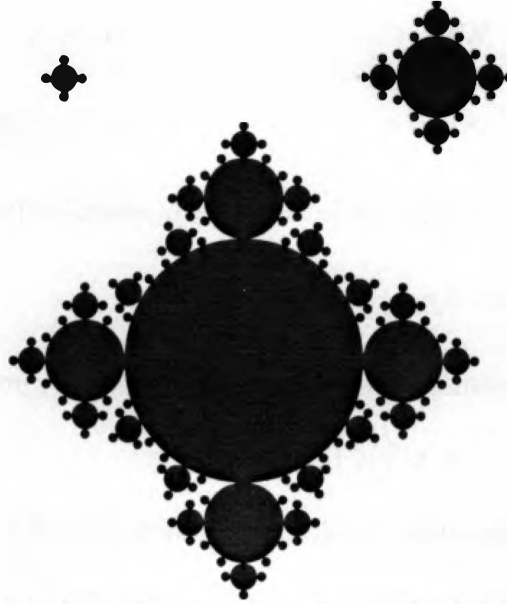


Figure 11: Cross-sectional view of surface fractal aggregates with L values of $3\sqrt{2}$ (top left), $9\sqrt{2}$ (top right), and $27\sqrt{2}$ (bottom). Black represents solids.

1. It was determined through basic geometric relationships that the maximum dimension that the surface fractal could have was proportional to $\sqrt{2}$ (for a 45-45-90 degree triangle the lengths of each side follow the law of 1:1: $\sqrt{2}$). So, $L = b^z \cdot \sqrt{2}$, where z is an increasing integer value and b is the ratio between the largest L values per surface fractal. (For this test b was set at 3).
2. d was calculated to a finite iteration level (j) (d represents the width of a fixed tile and for these calculations it represents the lower limit that the fractal can be iterated to). d can be calculated by the equation, $d = \left(\frac{1}{b^i}\right)$. For this test $j=10$, i.e. $1 \leq i \leq 10$.
3. For this test D_s was set at $\log(13)/\log(3) = 2.3347$.

4. N was calculated for each i. It should be noted that the surface fractal behaves differently at $i = 1$. When $i = 1$, six spheres are added to the figure, when $i > 1$, N

is multiplied by 13. At $i = 1$, $N = \left(\frac{1}{b^i}\right)^{-D_s} \cdot 6$. For $i > 1$, $N = \left(\frac{1}{b^i}\right)^{-D_s} \cdot 13$.

5. The SA is calculated to the i-th level for each sphere by the equation,

$$SA = 4\pi \left(\frac{d}{2}\right)^2, \text{ where } d = \left(\frac{1}{b^i}\right)/2.$$

6. The SA for each iteration level (SA_i) was calculated by multiplying N by the SA per sphere, $SA_i = N \cdot 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2$.

7. The SA_t for the figure was calculated by summing the SA for each iteration level,

$$SA_t = \sum_{i=1}^{b^j} N \cdot 4 \cdot \pi \cdot \left[\left(\frac{1}{b^i}\right)/2\right]^2.$$

8. The V of each sphere was calculated to the j-th level by using the equation,

$$V = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3.$$

9. The V for each iteration level (V_i) was calculated by multiplying N by the V per

sphere, $V_i = N \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3$.

10. The V_t for the figure was calculated by summing the V for each iteration level,

$$V_t = \sum_{i=0}^{b^j} N \cdot \frac{4}{3} \cdot \pi \cdot \left[\left(\frac{1}{b^i}\right)/2\right]^3.$$

11. If particle density is held constant then m can be determined by the same method

as the volume, $m = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3$.

12. The total m (m_t) can be calculated by using the same equation as that used to

calculate V_t , $m_t = \sum_{i=0}^{b^j} N \cdot \frac{4}{3} \cdot \pi \cdot \left[\left(\frac{1}{b^i}\right)/2\right]^3 \cdot \rho_s$.

13. By finishing these steps Figures 12 and 13 were generated.

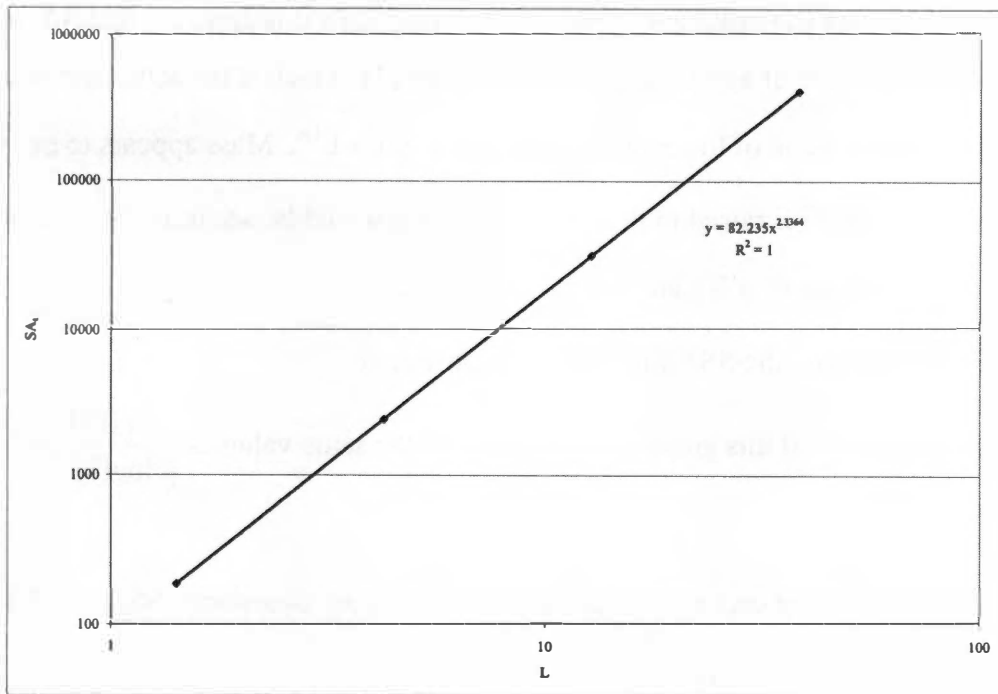


Figure 12: SA_t scaling behavior of a surface fractal when L is increased.

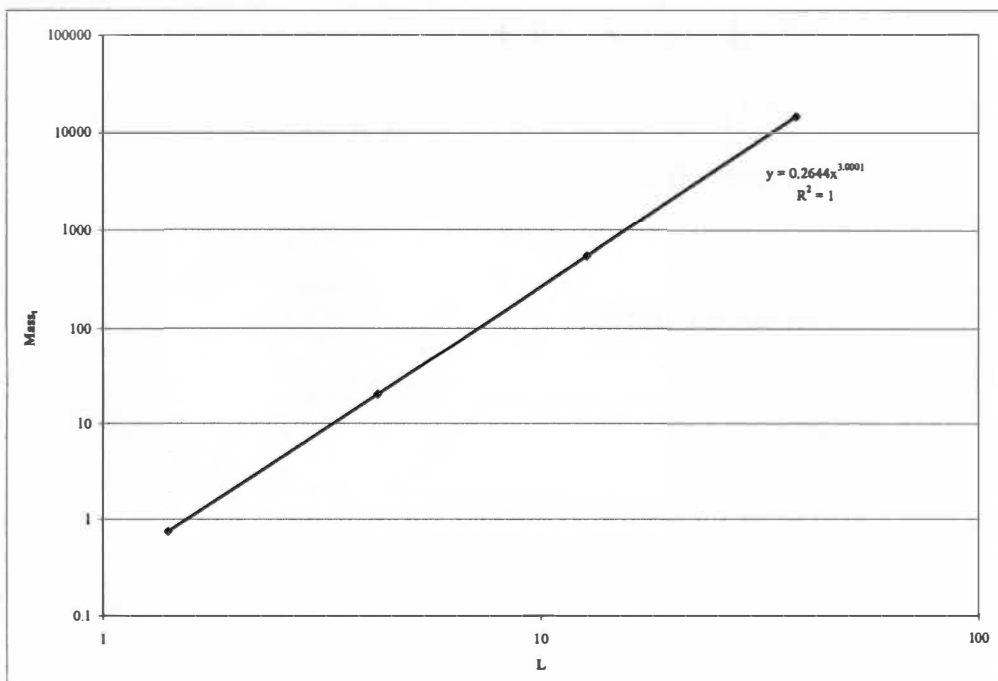


Figure 13: The scaling behavior of m_t of a surface fractal when L is increased.

14. By observing the exponents given by the two graphs it is apparent that SA_t scales with a D_s value of approximately $\log(13)/\log(3)$, which is the actual surface fractal dimension of the construction. Thus, $SA \propto L^{D_s}$. Mass appears to be proportional to L raised to the value of 3. This would be accurate for a surface fractal because $m_t \propto V_t$, and $V_t \propto L^3$, so $m_t \propto L^3$.

15. By determining the SSA Figure 14 was produced.

16. The exponent of this graph is approximately the same value as $\left[\frac{\log(13)}{\log(3)} \right] - 3$, or $D_s - 3$.

17. This relationship can also be stated by the following equations: $SSA \propto L^{D_s}/L^3 \propto L^{D_s-3}$.

18. The Pfeifer-Avnir equation can also be derived by the following equations:

$$N \propto (L/d)^{D_s}$$

$$SA_t \propto N, d^2 \propto (L/d)^{D_s} d^2$$

For a constant tile size (d) and a variable L :

$$SA_t \propto L^{D_s} \text{ (Figure 12)}$$

For variable tile sizes (d) and a fixed L :

$$SA_t \propto d^{2-D_s} \text{ (Figure 15)}.$$

19. To conclude for surface fractals:

- $SA_t \propto L^{D_s}$
- $V_t \propto L^3$
- $m_t \propto L^3$
- $SSA \propto L^{D_s-3}$

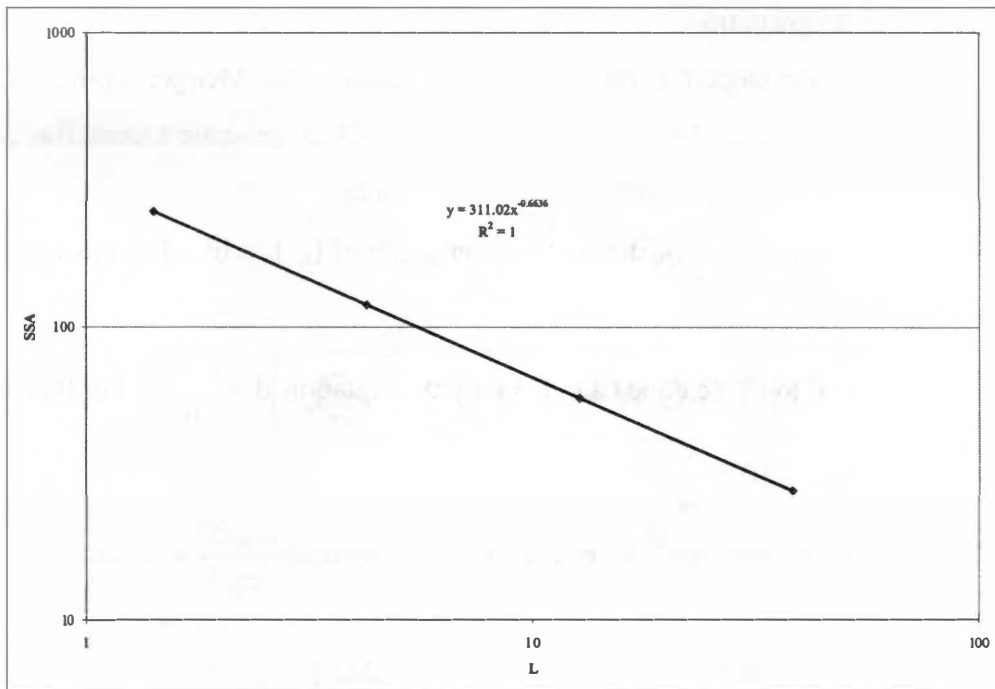


Figure 14: The scaling behavior of SSA when L is increased for a surface fractal.

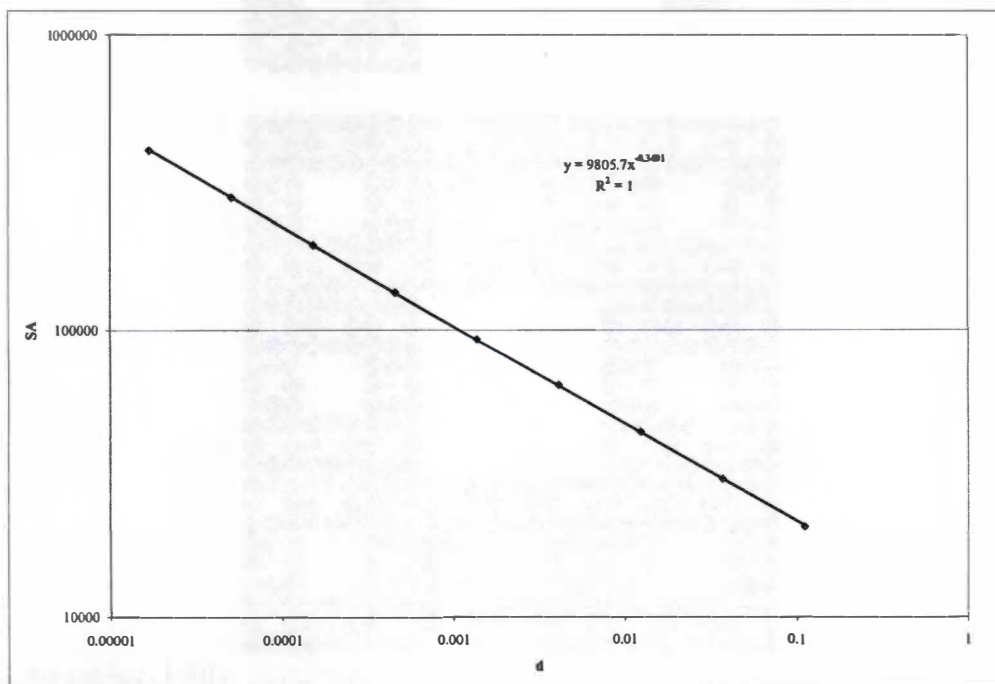


Figure 15: SA scaling behavior of a surface fractal using variable tile sizes (d) and a fixed L.

2.4 Mass Fractal Aggregates

This test was developed using mass fractals, based on the Menger sponge model, that were constructed (Figure 16) using various values of L to generate a mass fractal aggregate for surface area, mass, and specific surface area.

1. A Menger sponge was constructed to a set width of L , $L = b^z$. For this test b was set at three.
2. d is calculated to j . d can be calculated by the equation $d = \left(\frac{1}{b^i} \right)$. For this test $j=10$, i.e., $1 \leq i \leq 10$.
3. For this test the mass fractal dimension, D_m , was set at $\frac{\log 20}{\log 3} = 2.7268$.

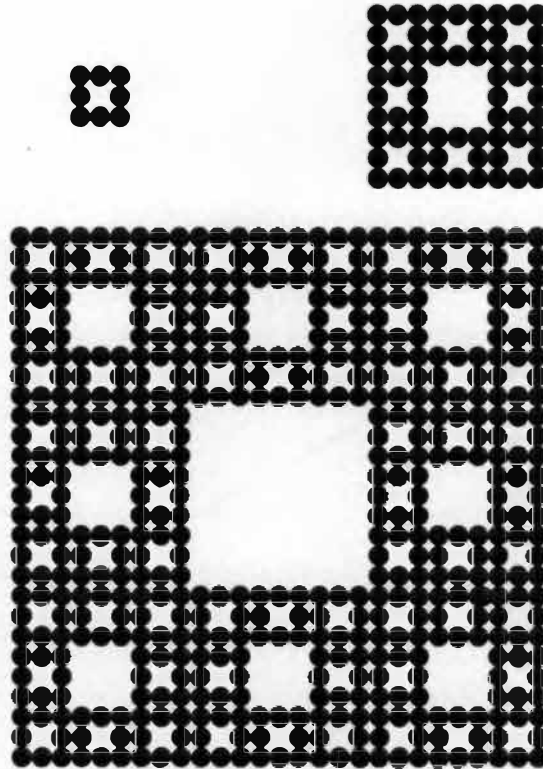


Figure 16: Cross-sectional view of a Menger sponge constructed with L values of 3 (top left), 9 (top right), and 27 (bottom). The diameter of each sphere equals 1 and black represents solids.

4. N was calculated for each iteration level using the equation, $N = d^{-D}$.
5. The SA_i for each iteration level was then calculated to the j -th level by using the equation, $SA_i = N_j \cdot 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2$. N_j is the number of spheres at the highest iteration level.
6. The V of each sphere is then calculated to the j -th level by using the equation, $V = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3$.
7. The V_t was then calculated by multiplying N_j by the V per sphere, $V_t = N_j \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3$.
8. m was calculated by multiplying the V by the ρ_s which was held constant.
9. The m_t can be calculated by using the same equation used to calculate V_t , $m_t = N_j \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \rho_s$.
10. By completing these steps figures 17 and 18 were produced.
11. By observing the exponents given by the two graphs it was apparent that the D_m value for the SA_t scaling was approximately $\frac{\log(20)}{\log(3)} = 2.7268$, which is the mass fractal dimension of a Menger Sponge. Thus, $SA_t \propto L^{D_m}$. The exponent for the mass scaling also had a value of approximately $\frac{\log(20)}{\log(3)} = 2.7268$. So m scales proportionally to L^{D_m} .
12. By determining the SSA figure 19 was produced. Thus, $SSA \propto L^0$.

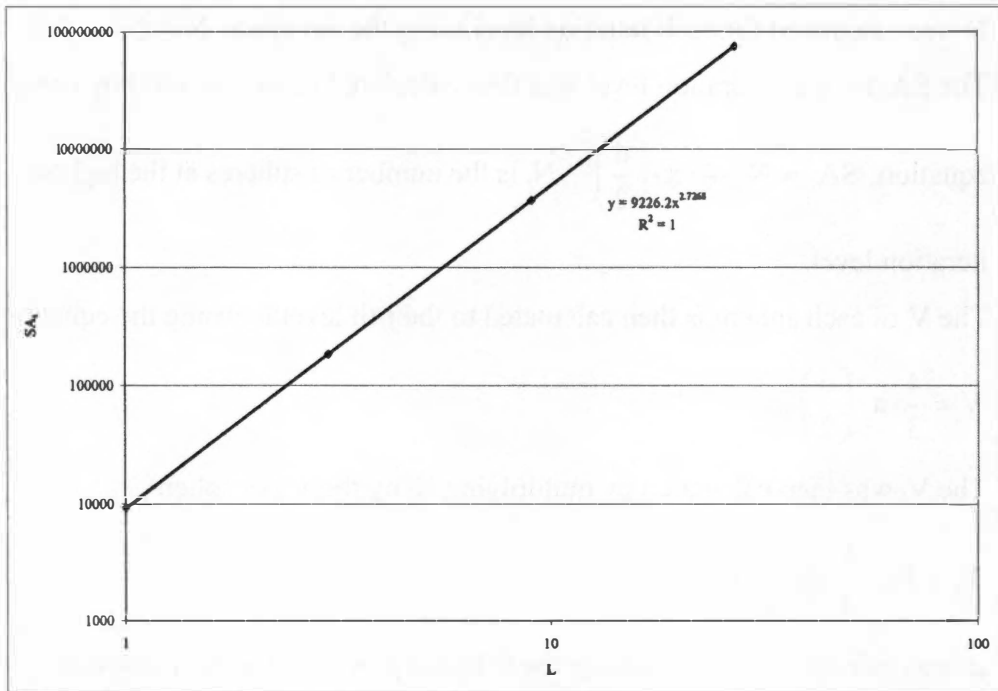


Figure 17: The SA_t scaling behavior of a mass fractal when L is increased.

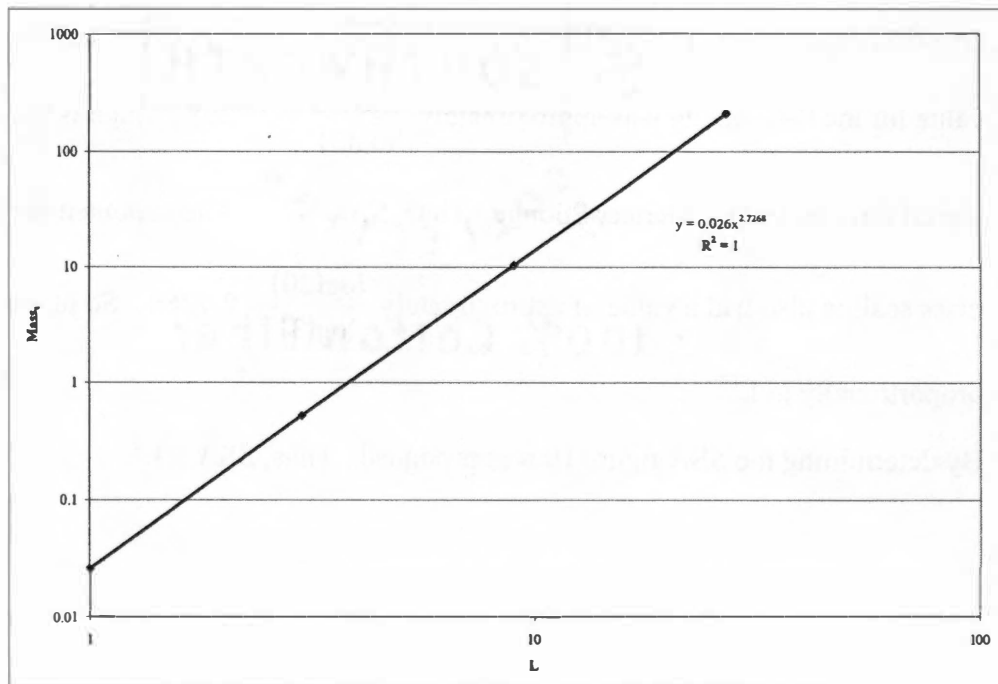


Figure 18: The m_t scaling behavior of a mass fractal when L is increased.

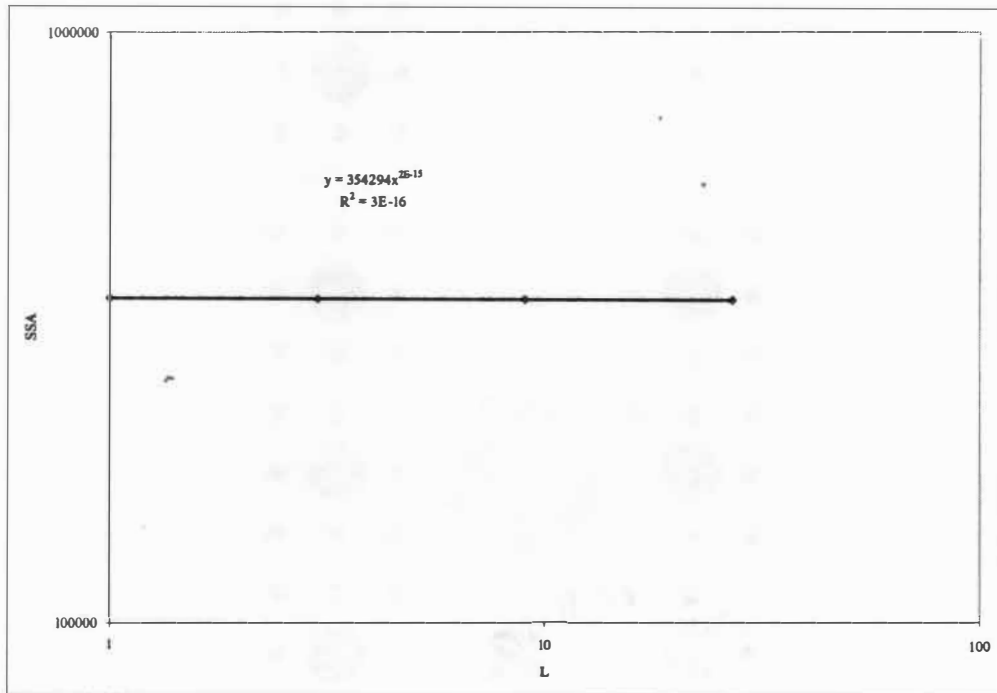


Figure 19: The SSA scaling behavior of a mass fractal when L is increased.

13. To summarize for mass fractals:

- $SA_t \propto L^{D_m}$
- $V_t \propto L^3$
- $m_t \propto L^{D_m}$
- $SSA \propto L^0$

2.5 Pore Fractal Aggregates

This test was developed using pore fractals, based on the Menger sponge, that were constructed (Figure 20) using various values for L to generate a pore fractal model for SA, m, and SSA.

1. A Menger sponge pore fractal was constructed to a set width of L, where $L = b^z$. For this test b was set at 3.

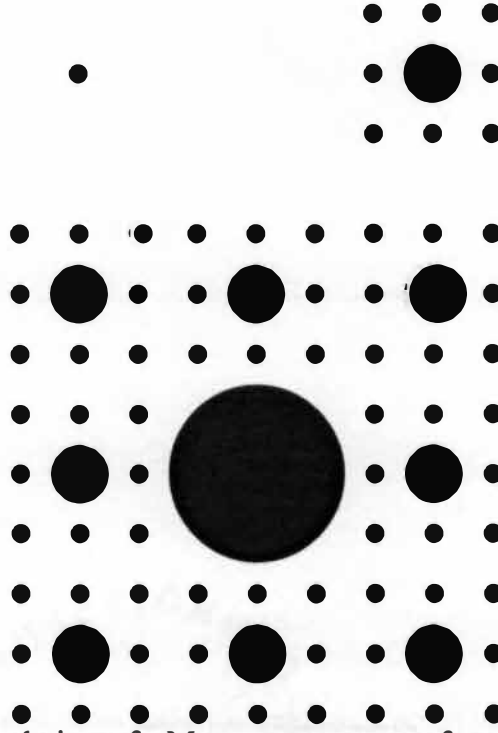


Figure 20: Cross-sectional view of a Menger sponge pore fractal constructed with L values of 3 (top left), 9 (top right), and 27 (bottom). Black represents solids.

2. d is calculated to j . d can be calculated by the equation $d = \left(\frac{1}{b^i} \right)$. For this test

$j=10$, i.e., $1 \leq i \leq 10$.

3. For this test the pore fractal dimension, D_p , was set at $\frac{\log(20)}{\log(3)} = 2.7268$.

4. N was calculated for each iteration level using the equation, $N = \left(\frac{1}{b^{i-1}} \right)^{-D_p} \cdot 7$.

5. The SA is calculated to the j -th level for each sphere by the equation,

$$SA = 4 \cdot \pi \cdot \left(\frac{d}{2} \right)^2, \text{ where } d = \left(\frac{1}{b^i} \right).$$

6. The SA_i was then calculated using the following equation, $SA_i = N_j \cdot 4 \cdot \pi \cdot \left(\frac{d}{2} \right)^2$.

7. The SA_t was calculated using the equation, $SA_t = \sum_{i=1}^{b^j} N \cdot 4 \cdot \pi \cdot \left[\left(\frac{1}{b^i} \right) / 2 \right]^2$.
8. The V of each sphere was then calculated to the j -th level by using the equation,

$$V = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2} \right)^3.$$
9. The V_i was calculated using the equation, $V_i = N \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2} \right)^3$.
10. The V_t was then calculated using the equation, $V_t = \sum_{i=1}^{b^j} N \cdot \frac{4}{3} \cdot \pi \cdot \left[\left(\frac{1}{b^i} \right) / 2 \right]^3$.
11. m was calculated by multiplying the V by the ρ_s which was held constant.
12. m_t was calculated using basically the same equation used to calculate V_t ,

$$m_t = \sum_{i=1}^{b^j} N \cdot \frac{4}{3} \cdot \pi \cdot \left[\left(\frac{1}{b^i} \right) / 2 \right]^3 \cdot \rho_s.$$
13. By finishing the steps above figures 21 and 22 were generated.
14. By observing the exponents given by figures 21 and 22 it was apparent that the D_p value for the SA_t scaling was approximately $\frac{\log(20)}{\log(3)} = 2.7268$, which is the pore fractal dimension of a Menger sponge. Thus, $SA_t \propto L^{D_p}$. m_t is proportional to the value of L^3 . (Even though the graph gives a value of 3.0093, m does scale as L^3 within the limit of $1 \leq i \leq \infty$.) This is correct for a pore fractal because $m_t \propto V_t$, and $V_t \propto L^3$, so $m_t \propto L^3$.
15. By determining the SSA Figure 23 was produced.
16. The exponent of Figure 23 is approximately the same value as $\left[\frac{\log(13)}{\log(3)} \right] - 3$, or $D_p - 3$.
17. This relationship can also be stated by the following equations: $SA_t/m_t \propto L^{D_p/L^3} \propto L^{D_p-3}$.

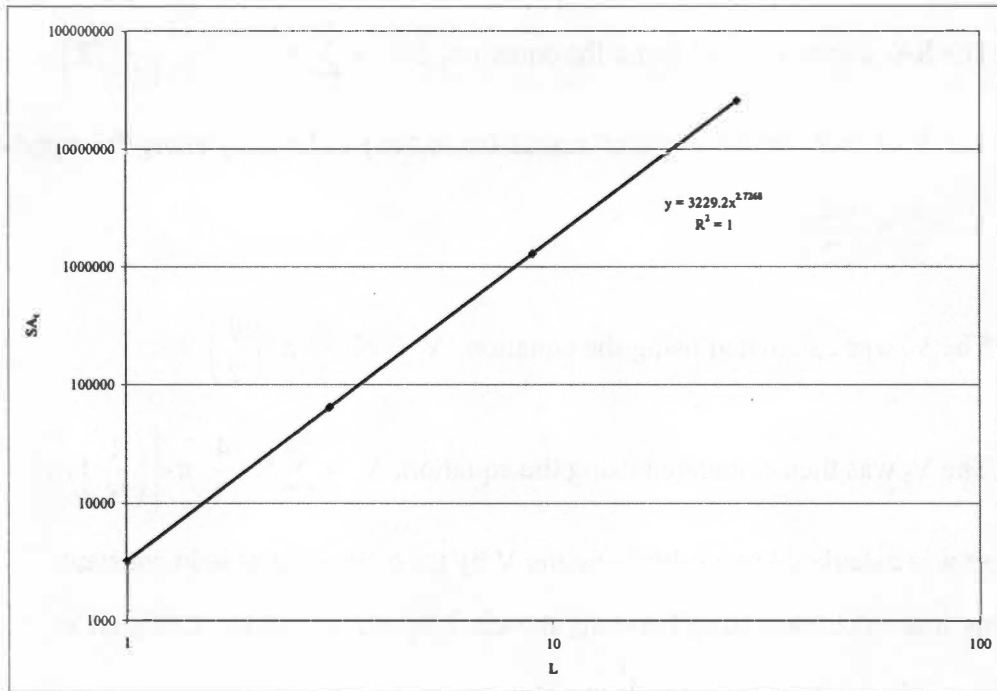


Figure 21: SA_t scaling behavior of a pore fractal when L is increased.

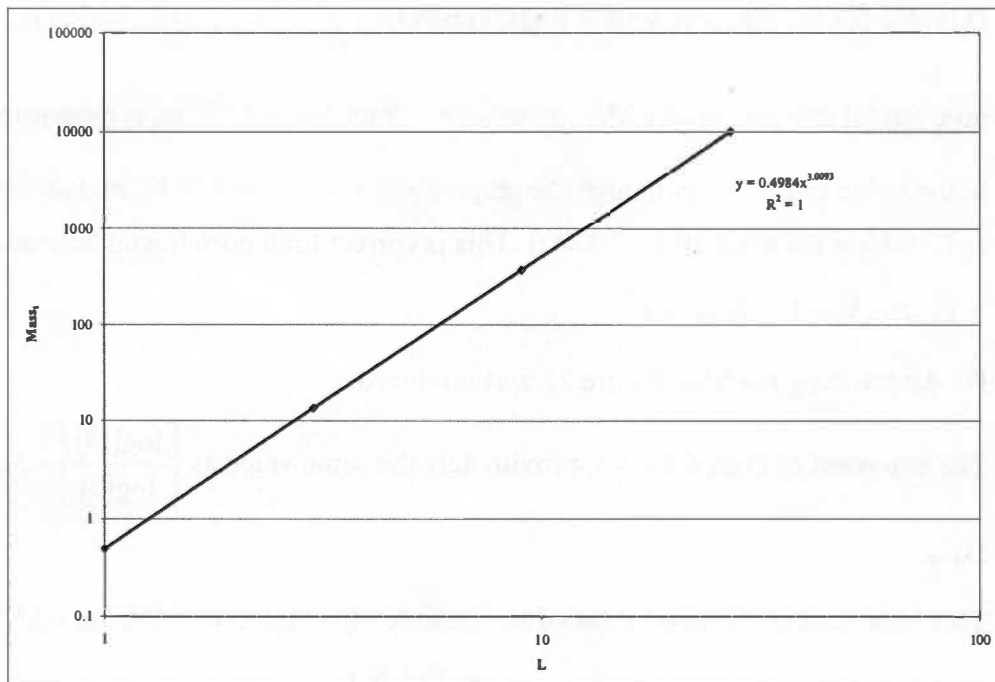


Figure 22: m_t scaling behavior of a pore fractal when L is increased.

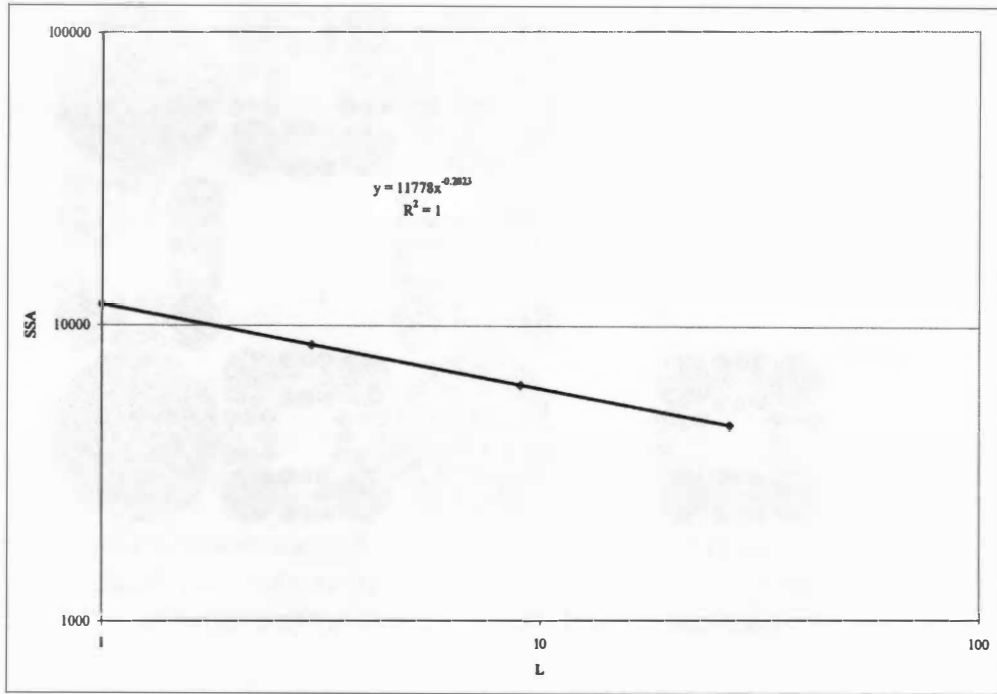


Figure 23: SSA scaling behavior of a pore fractal when L is increased.

18. To summarize for pore fractals:

- $SA_t \propto L^{D_p}$
- $V_t \propto L^3$
- $m_t \propto L^3$
- $SSA \propto L^{D_p-3}$

2.6 Pore-Solid Fractal Aggregates

The pore-solid fractal model is basically a combination of a pore fractal and a mass fractal. Unlike the pore fractal and mass fractal, however, it contains size distributions of both pores and solids within the same structure.

1. The model was based upon a three-dimensional representation of Figure 24, in which the numbers of pores, solids, and generators were fixed to have a fractal dimension greater than 2.

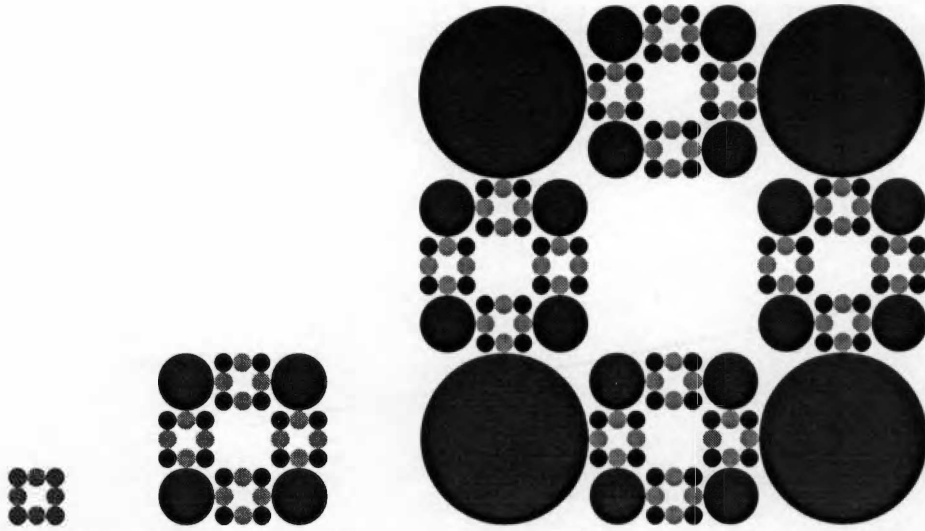


Figure 24: Cross-sectional view of a pore-solid aggregate constructed with L values of 3 (left), 9 (middle), and 27 (right). The black spheres represent solids, the gray spheres represent iteration sites (generators), and the white space represents pores.

2. The fractal dimension was calculated by the equation, $D_{ps} = 3 + \frac{\log(1-x-y)}{\log(n)}$,

where D_{ps} is the pore-solid fractal dimension, x is the proportion of pores, y is the proportion of solids, and n is the inverse similarity ratio which was equal to 3 (Perrier et al. 1999).

3. d was calculated based upon j .

4. The number of pores present within the model, N_x , was calculated using the

equation, $N_x = \frac{x}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$, where w is the number of generation sites.

5. The number of solids present within the model, N_y , was calculated using the

equation, $N_y = \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.

6. The number of generation sites present within the model, N_w , was calculated

using the equation, $N_w = \frac{w}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.

7. The SA for each sphere was calculated using the equation, $SA = 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2$.
8. The SA_i was calculated using the equation, $SA_i = 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \cdot \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.
9. The SA_t was calculated by the equation, $SA_t = \sum_{i=0}^j 4 \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \cdot \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.
10. The V of a single sphere was calculated by the equation, $V = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3$.
11. The V_i was calculated using the equation, $V_i = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.
12. The V_t was calculated by the equation, $V_t = \sum_{i=0}^j \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}$.
13. The m of a single sphere was calculated by the equation, $m = \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \rho_s$,

where ρ_s is assumed to be constant.

14. The m_t was calculated by the equation,

$$m_t = \sum_{i=0}^j \frac{4}{3} \cdot \pi \cdot \left(\frac{d}{2}\right)^3 \cdot \rho_s \cdot \frac{y}{w} \cdot L^{D_{ps}} \cdot \left(\frac{1}{b^i}\right)^{-D_{ps}}.$$

15. After performing these calculations figures 25, 26, and 27 were generated.
16. By observing these graphs it is apparent that SA_t scales as $L^{D_{ps}}$, m_t scales as L^3 , and the SSA scales as $L^{D_{ps}-3}$.
17. The D_{ps} values considered here are limited to values greater than 2. Different relations are present when D_{ps} values are less than 2 (Perrier et al. 1999).
18. To summarize for pore-solid fractals:

- $SA_t \propto L^{D_{ps}}$
- $V_t \propto L^3$
- $m_t \propto L^3$
- $SSA \propto L^{D_{ps}-3}$

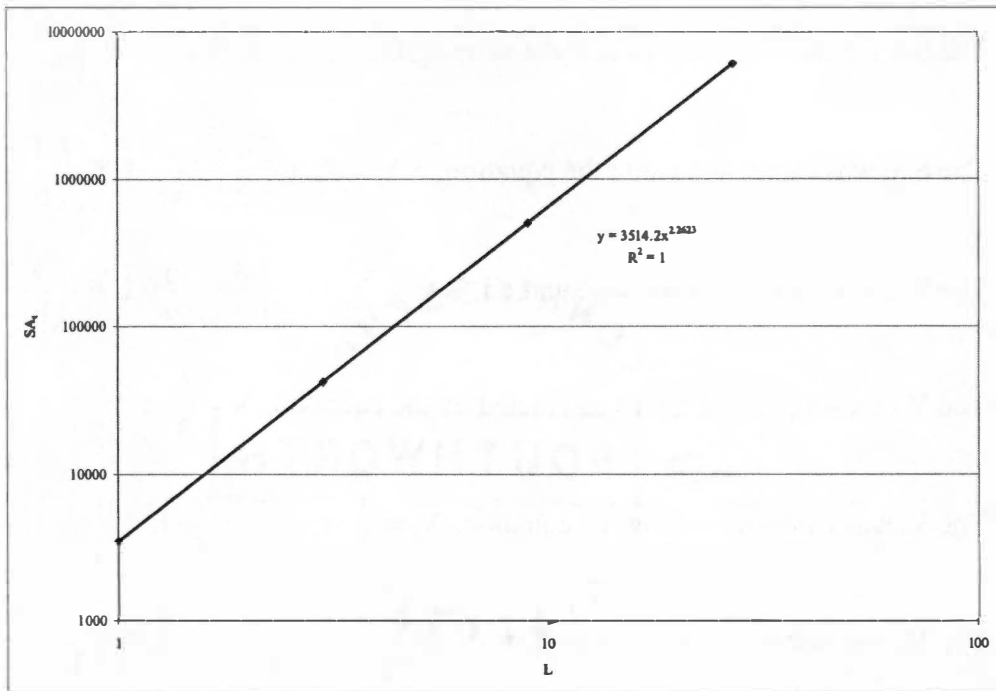


Figure 25: SA_t scaling behavior of a pore-solid fractal.

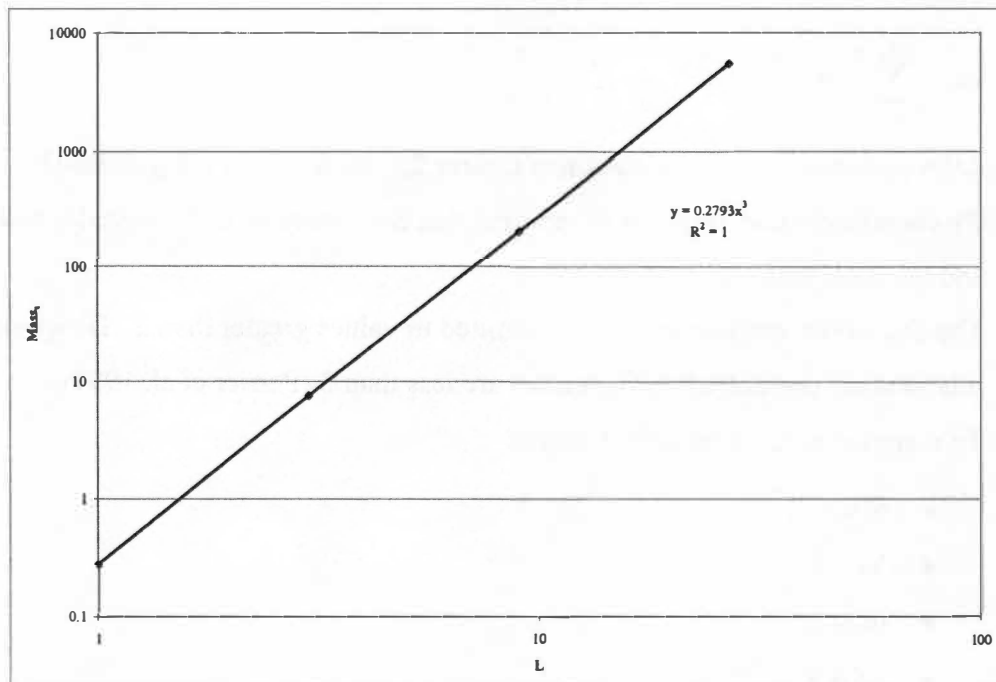


Figure 26: m_t scaling behavior of a pore-solid fractal.

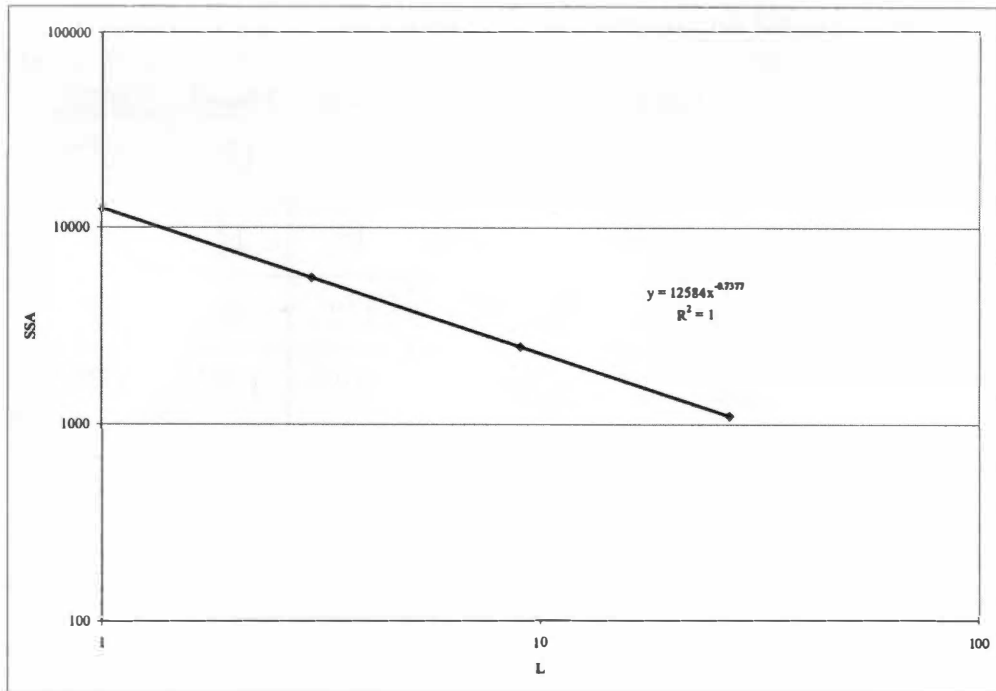


Figure 27: SSA scaling behavior of a pore-solid fractal.

The scaling relationships for all models are summarized in Table 2. For $2 \leq D \leq 3$ the exponent (β) from the $SA/m \propto L^\beta$ relations are classified in Table 3. Table 3 suggests that regardless of what exponent is generated from the specific surface area data there will still be an uncertainty regarding which model is actually correct. To determine between the various models further experimentation was performed. Figure 28 is a flow chart that describes what steps were taken depending on the value of the exponent that was determined by measuring SSA as a function of L.

Table 2: Scaling relations for all geometrical models.

	Euclidean Solids	Euclidean Aggregates	Surface Fractal	Mass Fractal	Pore Fractal	Pore-Solid Fractal
$SA \propto$	L^2	L^3	L^{D_s}	L^{D_m}	L^{D_p}	$L^{D_{ps}^*}$
$V \propto$	L^3	L^3	L^3	L^3	L^3	L^3
$m \propto$	L^3	L^3	L^3	L^{D_m}	L^3	L^3
$SA/m \propto$	L^{-1}	L^0	L^{D_s-3}	L^0	L^{D_p-3}	$L^{D_{ps}-3^*}$

* $D_{ps} > 2$

Table 3: Summary of exponents for each geometrical model.

Exponent	Model		
$\beta = 0$	Mass Fractal	Euclidean Aggregates	----
$0 < \beta < -1$	Surface Fractal	Pore Fractal	Pore-Solid Fractal
$\beta = -1$	Euclidean Solid	----	----

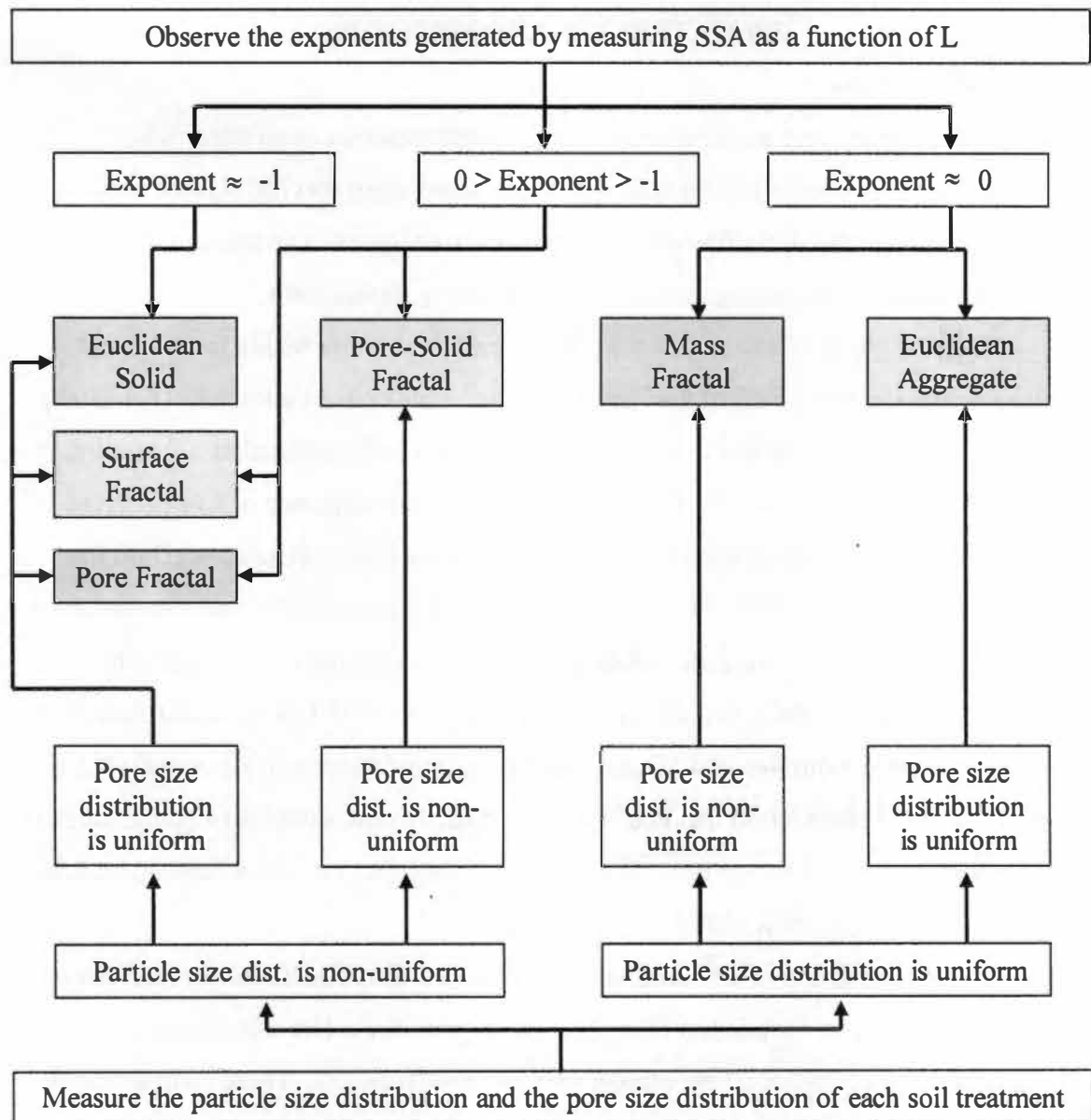


Figure 28: A flow chart showing experimentation plan. A method to distinguish between a surface fractal and a pore fractal is unknown if distinguishable at all (models are shown in gray).

3.0 MATERIALS AND METHODS

3.1 Soil Descriptions

Soil samples were acquired from two different localities in an attempt to establish a scaling relationship for soil aggregates based upon specific surface area measurements. A total of 9 different treatments were analyzed in an attempt to see how, and to what degree, soil management affects the scaling relationship.

The first group of soil samples were obtained from a site within the National Environmental Research Park at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, IL. The soil at this site was a silty clay loam and classified as a fine-silty, mixed, mesic Aquic Argiudolls. The site contains a chronosequence of five different agricultural activities that range from current agricultural usage, denoted AgD, to the original remnant prairie, RRD. The three other soil samples, which at one time were all used for agricultural practices, are currently being restored to their original prairie origins. They range from agricultural practices ceasing in 1978 (24 years of restoration at the time of collection) denoted 5D, to 1984 (19 years of restoration) denoted 11D, to 1993 (10 years of restoration) denoted N3D. Six to eight core samples (4.8cm diameter) were collected from a depth of 0 to 15cm for each treatment. Further details about this site can be found in Jastrow (1987, 1996, 1998).

The second group of soil samples were obtained from the Kentucky Agricultural Experiment Station, at Spindeltop Farm near Lexington, KY. The soil at this site was a silty loam and classified as a fine, mixed, mesic Typic Paleudalf. These samples came from two tillage treatments, conventional till (CT) and no till (NT), that had been exposed to two different nitrogen treatments, 300 lbs/acre ($3.36 \times 10^{-2} \text{ kg/m}^2$) of nitrogen applied and 0 pounds of nitrogen per acre, which resulted in four different management practices: CT300, CT0N, NT300, and NT0N. The soil was collected using a flat shovel approximately 8 inches across which was inserted into the soil to a depth of approximately four inches. The soil was placed into a sample bag and immediately sealed to retain the natural moisture level. Additional information about this site is given in Karathanasis (1991), Perfect et al. (1997), Six et al. (1999), Perfect et al. (2004). Figure 29 is an outline of how the soils were treated for experimentation in this study.

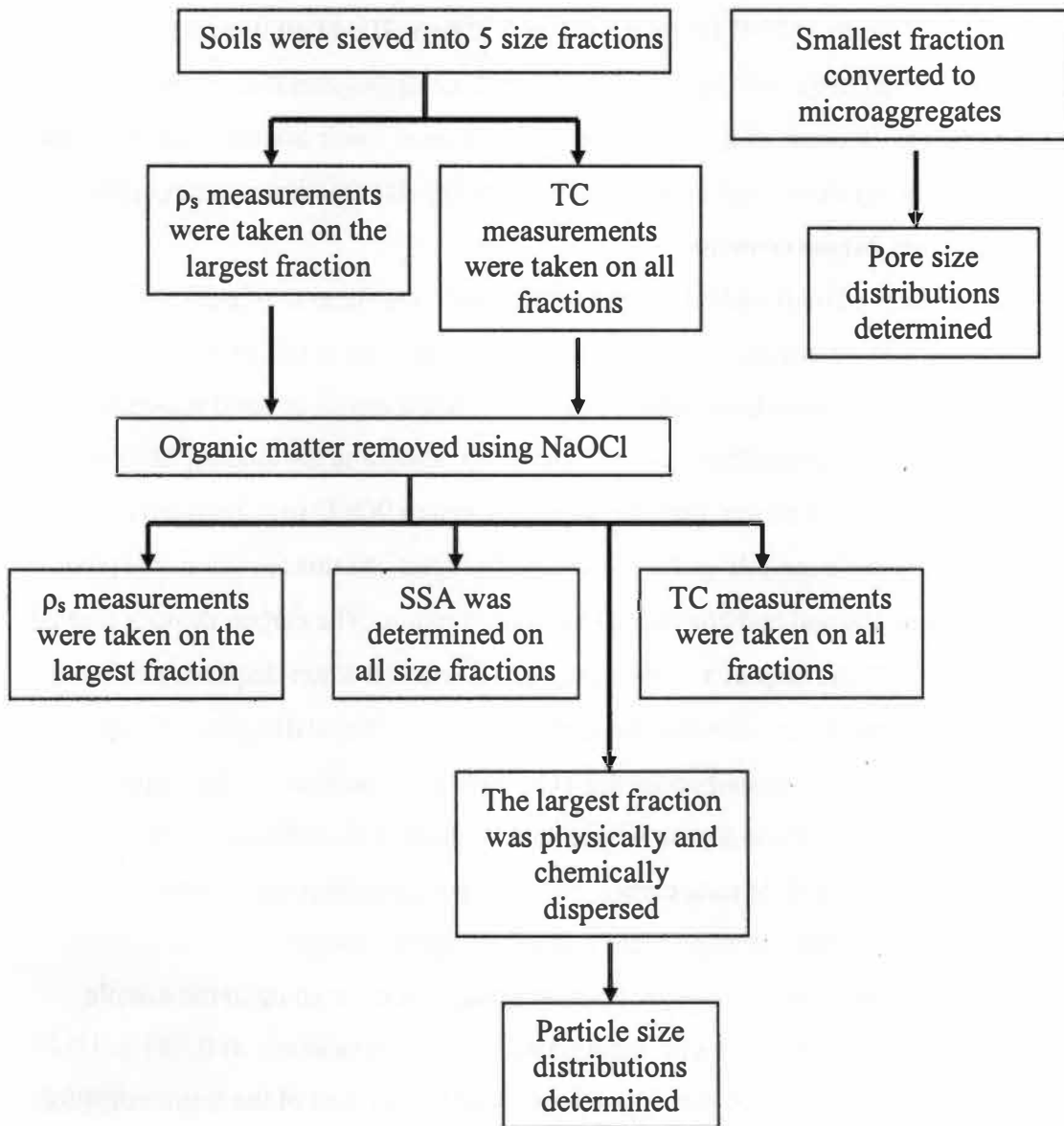


Figure 29: Flowchart showing how samples were treated before experimentation.

3.2 Aggregate Fractionation

In order to perform specific surface area measurements each of the nine soil treatments were air dried and divided into 5 different size fractions using a Fritsch analysette 3Pro sieve shaker. The sieve shaker was set at an amplitude of 2mm and was shaken for 3 minutes. The soil was sieved into 5 different size fractions: 2.0-4.0mm, 1.0-2.0mm, 0.5-1.0mm, 0.25-0.5mm, and 0.106-0.25mm. Based on this method of fractionation, the different size fractions contained both aggregates and any coarse primary particles. Because of the large size fractions used it was assumed that the mass contribution of any primary particles present within any size fraction was negligible.

3.3 Total Carbon Measurements

The amount of total carbon present within each size fraction of each soil was measured using a PC-controlled total organic carbon analyzer Model TOC-V CSH which contains a solid sample module, SSM-5000A, for analysis of solid materials, developed by the Shimadzu Corporation. In order to determine the amount of total carbon within each soil fraction, the sample was heated to 900⁰C in a small oven housed within the solid sample module in the presence of oxygen. At this temperature carbon was released from the soil and converted to carbon dioxide. The carbon dioxide flowed through a tube, with the help of a carrier gas, until it reached a non-dispersive infrared (DNIR) gas analyzer, which detected the carbon dioxide. The NDIR gas analyzer released a signal that was picked up by the TOC-Control V software. The software converts the NDIR signal into a peak whose area could then be calculated. The area is proportional to the amount of total carbon that was present within the sample.

In order to use the calculated area a standardization curve was developed. For this analysis a known concentration of fructose syrup was injected upon the sample boats. The fructose was diluted with distilled water to concentrations of 0.024 and 0.24 mgC/ μ L solution. Appendix A provides a more detailed account of the standardization procedure followed, showing both the calibration curve along with the regression equation. By injecting different volumes of the fructose into the sample boats a mathematical relationship was developed which was used to correlate the areas given for the soils. In doing so the amount of total carbon in mg was determined. By dividing the

mg of total carbon by the sample weight the quantity of mg of total carbon per gram of soil was determined. Measurements were taken, in duplicate, before and after the removal of organic matter to not only determine the amount of carbon within the soils but also to see how much carbon had effectively been removed by the sodium hypochlorite method discussed in section 3.4.

3.4 Organic Matter Removal

To remove organic matter a solution of sodium hypochlorite (NaOCl) was used following the method described by Lavkulich and Wiens (1970). The chemical NaOCl was obtained from a 6% NaOCl concentration of Clorox® bleach. The NaOCl solution was buffered by titrating a 1N concentration of HCl until the desired pH of 9.5 was reached. 10g of each soil fraction along with 20mL of the NaOCl solution were mixed in 50mL centrifuge tubes. After the initial combination of the soil and NaOCl solution, each centrifuge tube was heated at 95°C for 15min. After heating, the tubes were then placed in a centrifuge and spun at a rate of 2000rpm's for 30min. After completion, the soil formed into a large pellet at the bottom of the centrifuge tubes with a large portion of the NaOCl solution (now a different color than the original solution) segregated above it. The free solution was then drained from each tube and new solution was added. To ensure that the entire soil was being treated the tube was inverted and placed on a sieve where the vibrations broke up the pellet and mixed the contents of the tube. This process was repeated 6 times until there was a minimal change of coloration of the NaOCl solution. Upon completion each sample was freeze-dried using a Labconco Freezone® 6 Liter Freeze Dry System at -40°C and a vacuum setting of approximately 50×10^{-3} mbar. The samples were left overnight and then mortared and pestered to break up the pellet.

3.5 Particle Density Measurements

Particle densities for each soil were measured using the pycnometer method described by Flint and Flint (2002) before and after the removal of organic matter. To determine the particle densities the following equation was used,

$$\rho_s = \frac{\rho_w \cdot (W_s - W_a)}{(W_s - W_a) - (W_{sw} - W_w)}, \text{ where } \rho_s \text{ is the particle density, } \rho_w \text{ is the density of water at the observed temperature, } W_s \text{ is the weight of the pycnometer plus the soil sample}$$

corrected to each soils oven-dry water content, W_a is the weight of the pycnometer filled with air, W_{sw} is the weight of the pycnometer filled with soil and distilled water, and W_w is the weight of the pycnometer filled with distilled water at the observed temperature.

3.6 Specific Surface Area Measurements

3.6.1 Theory and Procedure

Specific surface area measurements (SSA) were obtained using a Quantachrome NOVA-1000 gas sorption analyzer using nitrogen gas. This instrument uses the Brunauer-Emmett-Teller (BET) (1938) method which is defined by the equation,

$$\frac{1}{W \cdot ((P_0/P) - 1)} = \frac{1}{W_m \cdot C} + \frac{C - 1}{W_m \cdot C} \left(\frac{P}{P_0} \right),$$

where W is the mass of gas adsorbed at a

relative pressure P/P_0 and W_m was the mass of the adsorbate constituting a monolayer of surface coverage. The term C , the BET constant, is related to the energy of adsorption in the first adsorbed layer and its value is an indication of the magnitude of the adsorbent/adsorbate interactions.

A standard multipoint BET protocol was used and data points were collected at various partial pressures between 0.05 and 0.35. The actual relative pressure was plotted against the BET transform, $\frac{1}{W \cdot (P_0/P)}$. In doing so the slope (s), $\frac{C - 1}{W_m \cdot C}$, and the y-

intercept (I), $\frac{1}{W_m \cdot C}$, were determined. After the slope and intercept were found W_m

was calculated by the equation, $W_m = \frac{1}{s + I}$. Once W_m was determined the total surface

area (SA_t) was obtained using the equation, $SA_t = \frac{W_m \cdot N \cdot A_{cs}}{M}$, where N is Avodagro's

number (6.023×10^{23} molecules/mol), A_{cs} is the cross-sectional area of the adsorbate (16.2×10^{-20} m²/molecule for N₂), and M is the molecular weight of the adsorbate (28.01348 g/mol for N₂). The specific surface area (SSA) of the sample was then

determined by dividing the SA_t by the mass of the sample (m), $SSA = \frac{SA_t}{m}$

(Quantachrome Corporation Instruction Manual for the NOVA-1000 gas sorption analyzer).

The soil samples were prepared for SSA analysis following Pennell's (2002) method.

1. Organic matter was removed using the NaOCl method described in section 3.4.
2. The soil was dried for one hour at 105°C to remove any atmospheric water that may have absorbed onto the soil.
3. Approximately one gram of soil was transferred into a glass sample holder.
4. The sample was outgassed with nitrogen (Pennell suggests helium in his methodology) at a temperature of 105°C for a minimum of twelve hours.
5. The soil's mass and density measurements were inputted into the instrument's computer.
6. Thirteen relative pressures were programmed into the instrument at evenly spaced increments between 0.0500 and 0.3500. Each relative pressure data point was collected while the glass sample tube was submerged in liquid nitrogen.

3.6.2 Statistical Treatment of SSA Data

SSA data were statistically analyzed using a nonlinear regression procedure utilizing the Newton method in the statistical software package SAS (SAS Institute Inc., 1999). The equation $SSA = \alpha \cdot L^\beta$ was used to fit the data where α was an unknown fitting parameter that was equivalent to the y-intercept, L was the size of the aggregate, and β was a scaling factor that was equal to D (fractal dimension) – d (Euclidean dimension).

3.6.3 Measurements Based Upon Particle Size Distributions

Specific surface area was also determined using an x-ray disc centrifuge (see section 3.7). Following Allen's (1997) method the relative percentage of mass was multiplied by the mean particle size between two sequential sizes. The relative percentage was obtained from the cumulative percentages given by the instrument. The products for each size were summed. This value was then multiplied by 6 which was a shape coefficient determined by dividing the surface area of a sphere by its volume. This quantity was divided by the soil's particle density to obtain the specific surface area of the soil.

3.7 Particle Size Distribution Measurements

Particle size distribution measurements were conducted using an x-ray disc centrifuge (XDC) developed by the Brookhaven Institute as described in Allen (1997). To obtain the particle size distributions the following procedure was followed using the largest size fraction (2.0-4.0mm) of each of the 9 soils after the removal of organic matter. Organic matter was removed (see section 3.4) because it tends to act as a glue combining smaller particles and aggregates into larger aggregates (Jastrow, 1996). The soils were then chemically and physically dispersed (described later in this section) in order to break down the soil aggregates into their constituent primary particles.

The XDC is a device that uses a centrifuge to speed up the process of settling sediment out of solution. The instrument uses Stoke's Law to determine the size of the particles in suspension at various times and spin rates. This instrument can only be used for particles that have a diameter of less than 50 μ m. It is difficult to get accurate measurements of particles this small using other methods, such as the hydrometer, due to convective forces that will not allow silt and clay sized particles to settle out of suspension. By using a centrifuge, small particles can be accurately analyzed. To obtain particles less than 50 μ m in diameter the following method was followed. Each soil was mortared and pested until the soil was in powder form. 15g of the powdered soil was placed in a beaker. Then 0.75g of the chemical dispersion agent, Na-hexametaphosphate, was added, followed by 150mL of distilled water. The solution was stirred. These masses and volumes were chosen because in order to get accurate readings with the XDC the particles must be present in concentrations of 0.5 to 5.0% by volume.

The soils were then physically dispersed via ultrasonification using a Branson Digital Sonifier. The soil solution was sonified at 30% power (60W) for 150s. To obtain the amount of energy introduced into the solution the following method was used,

$$\text{Ultrasonic Energy} = \frac{(60\text{W}) \cdot (150\text{s})}{150\text{mL}} = 60 \frac{\text{W} \cdot \text{s}}{\text{mL}} = 60 \frac{\frac{\text{m}^2 \cdot \text{kg} \cdot \text{s}}{\text{s}^3}}{\text{mL}} = 60 \frac{\frac{\text{m}^2 \cdot \text{kg}}{\text{s}^2}}{\text{mL}} = 60 \frac{\text{J}}{\text{mL}}$$

(Gregorich et al. 1988). At this point the soils were dispersed into primary particles. After dispersion the soils were wet sieved through a 53 μ m sieve using distilled water.

The soil particles that passed through the sieve were transferred into a plastic bottle for particle size analysis

The plastic bottles were physically shaken to suspend all of the deposited particles and 25mL were pipetted into the centrifuge of the XDC. The samples were mixed again in the centrifuge. The XDC was ran twice at different speeds and times to obtain a suite of particle sizes. The first run was at a spin rate of 1000 rpm's for 5min and the second run was at a spin rate of 7000 rpm's for a duration of 80min. The resultant data were merged into one complete particle size distribution for an entire suite of sizes for each soil. To determine a scaling factor for this data the method described in section 3.6.2 was followed, where L now stood for particle size.

3.8 Water Retention Measurements

Pore size distributions were inferred from water retention curves for each soil, before the removal of organic matter, using a WP4 Dew Point PotentialMeter (Decagon Devices, Inc., Pullman, WA) as described by Scanlon et al. (2002). The WP4 was used to measure the water potential (ψ , MPa) for each soil. Water potential can be determined using the Kelvin equation, $\psi = \left(\frac{R \cdot T}{V_w} \right) \cdot \ln(A_w)$ where R is the ideal gas constant (8.314 J/mol K), T is the temperature (K), V_w is the molar volume of water ($1.8 \times 10^{-5} \text{ m}^3/\text{mol}$), and A_w is water activity.

For the determination of the water retention curve, microaggregates (250-53 μm) of each soil class were used. Microaggregates were created by Julie Jastrow (Argonne National Laboratory) on bulk soils stored at the Univ. of Tennessee. Data was obtained by Jie (Joe) Zhuang (Univ. of Tennessee) and was analyzed by the author. Between 1g and 3g of soil from each class was weighed and placed in a sample cup. The soil was then wetted to saturation by capillarity using filter paper that was in contact with the soil aggregates and a reservoir of distilled water. The level of the distilled water and the soil aggregates were kept at an equal level so pressure gradients would not influence the wetting of the soils. After removal of the filter paper from the sample cups the sample was allowed to slowly air dry and measurements were taken using the WP4. Samples were weighed after each water potential measurement (Perfect et al. 2004). After

completion of the analysis the soils were placed in an oven and heated to 105°C for 24hr so the mass water content at each water potential measurement could be obtained.

To obtain a pore size distribution the measured water contents for each soil were plotted against their water potentials and a polynomial trend line was plotted through the data. The water content at 0 water potential, the point where the aggregates experienced complete saturation, was obtained by extrapolation from the y-intercept of the trend line. By now dividing the water content at each measured water potential by the water content at 0 water potential, the degree of saturation was obtained for each measured point. The measured water potentials were then plotted against their degree of saturation. A best-fit line was fitted to the data with the slope intercepting the y-axis at a value of unity.

The next step was to transform the water potentials into measurements of length. This was accomplished using the Young-Laplace equation, $\psi = -\frac{2 \cdot \sigma \cdot \cos(\alpha)}{r}$, where ψ is the measured water potential (MPa), σ is the surface tension of water (kg/s²), α is the contact angle, and r is the radius of the pore (m) (Pellicier et al.2000). The equation was then rearranged to solve for r , $r = -\frac{2 \cdot \sigma}{\psi}$ (the cosine of the contact angle was assumed to be unity). The accuracy of the WP4 instrument begins to decline below a water potential value of -1 MPa. Due to this limitation a maximum pore size was determined by inserting $\psi = -1\text{MPa}$ into the equation. The maximum pore size that could accurately be

determined by this method was, $d = \frac{4 \cdot \left(72.75 \frac{\text{mN}}{\text{m}} \right)}{1\text{MPa}} = \frac{0.2910 \frac{\text{N}}{\text{m}}}{1 \times 10^6 \frac{\text{N}}{\text{m}^2}} = 2.910 \times 10^{-7} \text{ m}$, or a

diameter of 0.2910μm. The WP4 instrument cannot operate accurately at water potentials greater than 40MPa. This limit represents a minimum pore size of 0.0073μm.

To finally obtain a pore size distribution, a series of water potentials between 1 and 40 MPa's were divided by the maximum pore size to obtain a suite of pore diameters. The polynomial trend line equation obtained from plotting the measured water potentials by the degree of saturation was then applied to these water potentials, which resulted in cumulative percentages for the fractions less than d_{max} . Finally, the

pore diameters were plotted against their cumulative percentages to obtain the pore size distributions for each soil. To determine a scaling factor for this data the method described in section 3.6.2 was followed, where L now stood for pore size.

4.0 RESULTS AND DISCUSSION

4.1 Total Carbon

Total carbon (TC) measurements were measured using a PC-controlled total organic carbon analyzer Model TOC-V CSH which contains a solid sample module, SSM-5000A, for analysis of solid materials, developed by the Shimadzu Corporation. Each of the five size classes for each soil treatment was measured in duplicate before and after the removal of organic matter. For the purposes of this report total carbon is synonymous with organic carbon because the amount of inorganic carbon found in these soils was negligible (Jastrow, 1996; Karanthanasis 1991). Tables 4 and 5 show the numerical results for the total carbon analysis and Figures 30, 31, 32, and 33 graphically illustrate the results for easier comparison.

4.1.1 *Fermilab Soils*

As shown by the data, the Fermilab soils have a higher percentage of total carbon than do the Kentucky soils with the exception of the AgD soil which happened to have TC levels comparable with the Kentucky soils. Two primary features were readily observable when looking at Figure 30. The first was the amount of total carbon seems to diminish as the aggregate size increases. This phenomenon happens in each fraction of each soil with the exception of the 0.106-0.25mm fraction for the AgD soil. It appears to contrast the findings of Tisdall and Oades (1980) who found greater concentrations of carbon in macroaggregates ($>250\mu\text{m}$) than in microaggregates ($<250\mu\text{m}$). This would also go against a hypothesis posed by Elliott (1986) who suggested that the larger aggregates should have a higher concentration of carbon because the macroaggregates were composed of microaggregates bound together by organic matter.

This discrepancy might be related to the amount of TC that may be present in small mesopores (2-50nm) (Mayer et al. 2004). Tisdall and Oades (1982) believed that in soils with a high organic matter content, primary particles bind together into microaggregates which bind together to form macroaggregates. Dexter (1988) pointed out that as larger aggregates form, larger pores must also develop. If the majority of organic matter is present within the aggregate's pore space then larger aggregates with

Table 4: Total carbon measurements for the Fermilab soils (percentages of TC present within the soil can be obtained by dividing the TC Before or TC After by 10).

Soil	Fraction	OM Before (mg C/g soil)	OM After (mg C/g soil)	% Lost
RRD	2.0-4.0mm	58.66	30.06	48.76
RRD	1.0-2.0mm	69.36	25.26	63.58
RRD	0.5-1.0mm	79.11	16.04	79.72
RRD	0.25-0.5mm	102.32	22.95	77.57
RRD	0.106-0.25mm	124.31	22.53	81.87
5D	2.0-4.0mm	42.04	15.84	62.31
5D	1.0-2.0mm	44.68	10.65	76.16
5D	0.5-1.0mm	51.81	12.29	76.28
5D	0.25-0.5mm	61.60	10.47	83.01
5D	0.106-0.25mm	70.00	13.63	80.53
11D	2.0-4.0mm	39.92	13.22	66.87
11D	1.0-2.0mm	41.67	14.43	65.37
11D	0.5-1.0mm	45.00	14.48	67.3
11D	0.25-0.5mm	58.28	12.99	77.71
11D	0.106-0.25mm	63.25	14.67	76.81
N3D	2.0-4.0mm	36.51	12.99	64.42
N3D	1.0-2.0mm	44.35	12.68	71.41
N3D	0.5-1.0mm	47.28	13.29	71.89
N3D	0.25-0.5mm	55.63	13.75	75.29
N3D	0.106-0.25mm	58.17	23.18	60.15
AgD	2.0-4.0mm	23.55	5.47	76.79
AgD	1.0-2.0mm	24.29	6.25	74.27
AgD	0.5-1.0mm	28.78	6.24	78.33
AgD	0.25-0.5mm	30.88	5.68	81.59
AgD	0.106-0.25mm	22.54	3.59	84.05

Table 5: Total carbon measurements for the Kentucky soils (percentages of TC present within the soil can be obtained by dividing the TC Before or TC After by 10).

Soil	Fraction	OM Before (mg C/g soil)	OM After (mg C/g soil)	% Lost
NT300	2.0-4.0mm	25.58	17.22	32.69
NT300	1.0-2.0mm	28.57	14.09	50.69
NT300	0.5-1.0mm	25.49	11.07	56.56
NT300	0.25-0.5mm	30.06	13.28	55.82
NT300	0.106-0.25mm	37.59	8.16	78.30
NT0N	2.0-4.0mm	17.74	9.71	45.24
NT0N	1.0-2.0mm	19.23	8.38	56.44
NT0N	0.5-1.0mm	21.51	7.24	66.34
NT0N	0.25-0.5mm	24.67	9.26	62.48
NT0N	0.106-0.25mm	23.08	5.04	78.17
CT300	2.0-4.0mm	13.79	7.35	46.71
CT300	1.0-2.0mm	13.08	10.65	18.54
CT300	0.5-1.0mm	14.31	5.72	60.04
CT300	0.25-0.5mm	15.34	5.51	64.08
CT300	0.106-0.25mm	18.38	3.56	80.60
CT0N	2.0-4.0mm	10.70	6.02	43.75
CT0N	1.0-2.0mm	10.84	5.99	44.73
CT0N	0.5-1.0mm	10.84	8.55	21.14
CT0N	0.25-0.5mm	13.16	5.63	57.23
CT0N	0.106-0.25mm	15.13	2.76	81.75

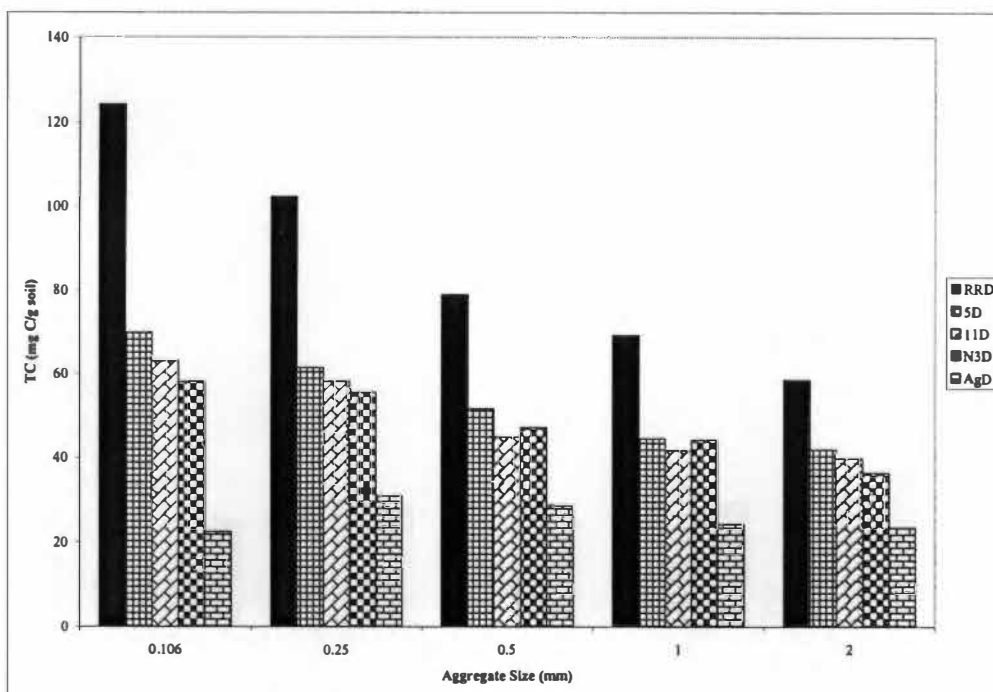


Figure 30: Total carbon measurements on the Fermilab soils before TC removal. The values for aggregate size were taken from the lowest size fraction between sieves.

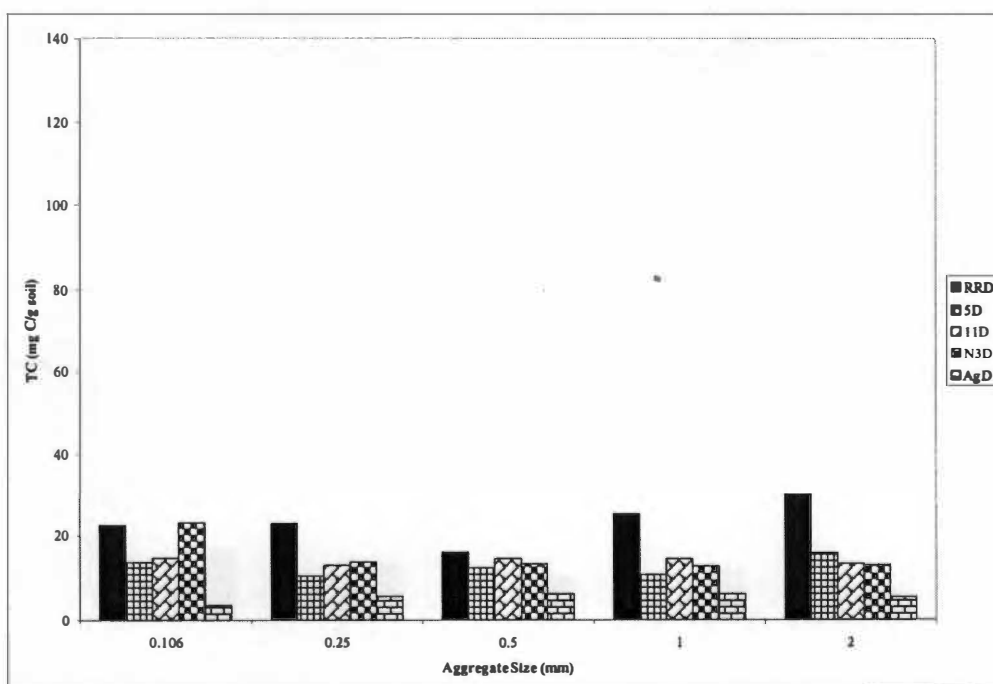


Figure 31: Total carbon measurements on the Fermilab soils after TC removal. The values for aggregate size were taken from the lowest size fraction between sieves.

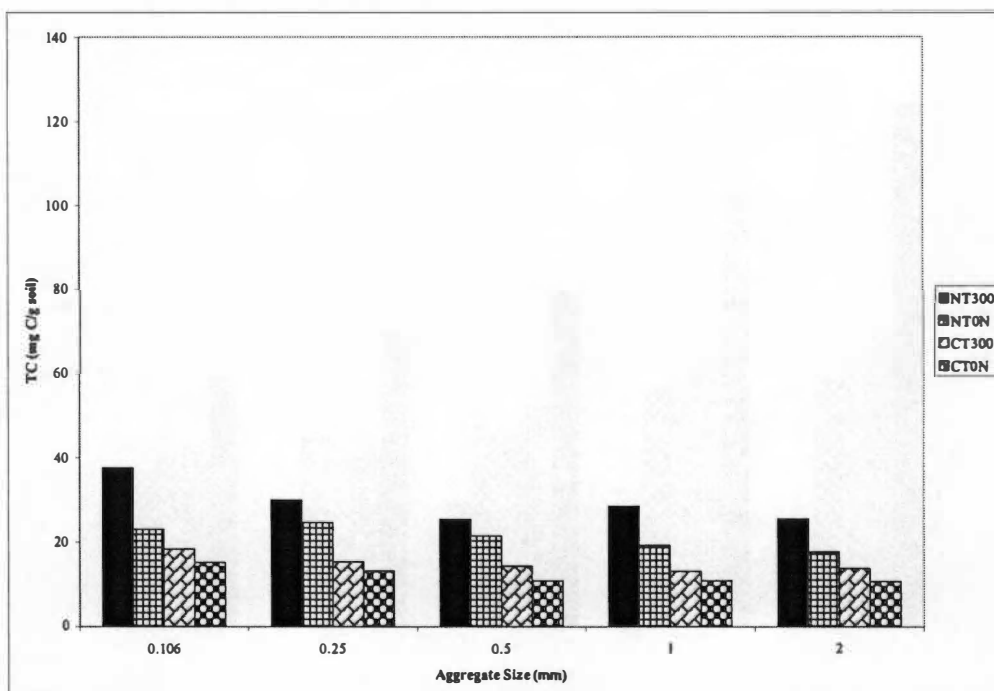


Figure 32: Total carbon measurements on the Kentucky soils before TC removal. The values for aggregate size were taken from the lowest size fraction between sieves.

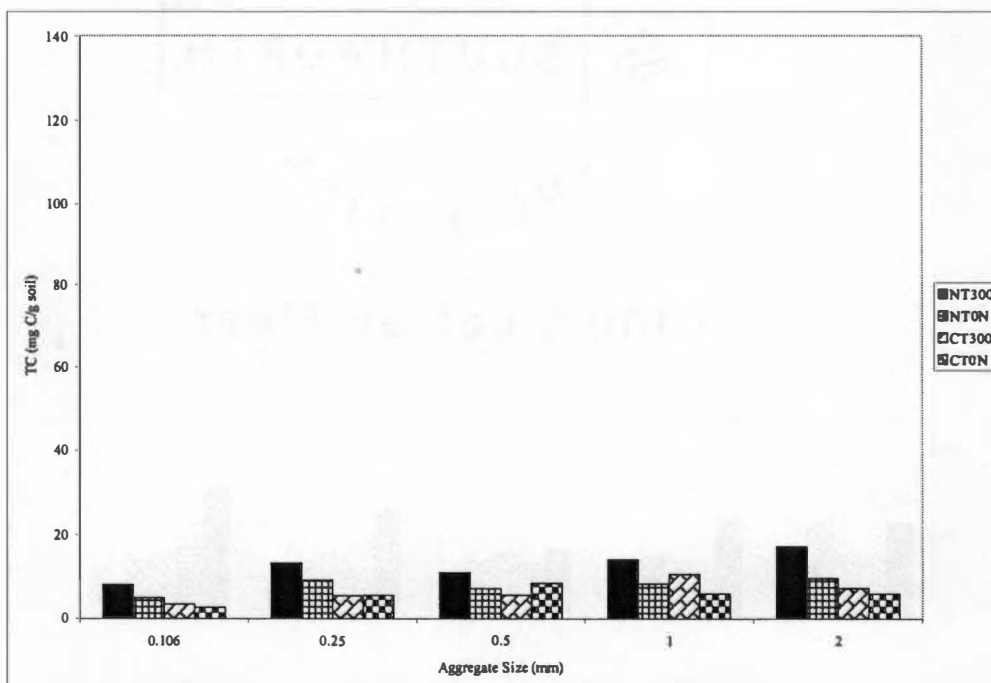


Figure 33: Total carbon measurements on the Kentucky soils after TC removal. The values for aggregate size were taken from the lowest size fraction between sieves.

larger pores should have a higher concentration of organic matter. However, this scenario does not account for degradation of the organic matter. Mayer (1994b) showed that the majority of organic matter is adsorbed to the individual mineral grains of sediment and the majority of the surface area was found to be within pores of <10nm in diameter. Zimmerman et al. (2004) pointed out that pores of this size can prohibit enzyme penetration which would begin the process of degradation. So, according to this scenario, the majority (if not all) of the organic matter present in larger pores would be destroyed and only preserved in small mesopores. If this were true then smaller aggregates with a higher percentage of mesopores (compared to larger aggregates) should have the highest percentage of TC, which was shown in the studied soils. However, Mayer et al. (2004) showed that only a small percentage of organic matter is present in pores small enough to prohibit enzyme degradation. So, while the mesopore exclusion scenario may work in theory it may not be the actual reason why there is a higher abundance of TC in the smaller aggregates.

The second feature present was that there appeared to be a TC hierarchy present between each of the five soils. The RRD soil (virgin prairie) had the highest amounts of carbon in each of the five aggregate fractions while the AgD (currently cultivated soil) had the lowest amount of carbon in each of the size fractions. The three intermediate soils (5D, 11D, and N3D) each showed this trend of decreasing carbon content as well but at a lesser degree. The intermediate soils were consistent with this hierarchical content of carbon with two exceptions occurring at the 0.5-1.0mm and the 1.0-2.0mm levels where the N3D soil had a higher percentage of carbon than that of the 11D soil. This trend suggests agricultural practices at the Fermilab site has had a detrimental effect on the amount of TC stored within soils.

4.1.2 Kentucky Soils

As discussed in 4.1.1 the Kentucky soils also show two readily observable features. There appeared to be a hierarchical arrangement based on aggregate size where the smaller aggregates had the greater concentrations of TC. This trend is present in each soil with exceptions occurring at the 0.5-1.0mm size fraction for NT300, 0.106-0.25mm size fraction for NT0N, and the 2.0-4.0mm size fraction for CT300 (Figure 32).

There is also a TC hierarchy present between each of the four soils themselves with the NT300 soil having the greatest amount of TC in each size fraction and the CT0N soil having the smallest amount of TC present in each size fraction.

The fact that the amount of TC decreases in each soil from NT300 to NT0N to CT300 to CT0N also indicates that the management of the soil has a direct impact on its ability to retain carbon. The data indicates that tillage (CT) causes a decrease in the ability of the soil to retain carbon, while the addition of nitrogen fertilizer to the soil will cause an increase in the amount of carbon stored in the soil. The effect that tillage has on carbon storability has been well documented (Adu and Oades, 1978; Beare et al. 1994a,b; Paustian et al. 1997; Six et al. 1999; Six et al. 2000a,b; Balesdent et al. 2000; Halvorson et al. 2002; etc.). There are a number of possible reasons why tillage decreases carbon content such as the destruction of soil aggregates and subsequent exposure to the atmosphere which would increase carbon decomposition (Beare et al. 1994a,b; Adu and Oades, 1978). Beare et al. (1994a,b) claimed that through tillage, crop residues are buried and mixed within the soil which would promote microbial decomposition. Soils that are not tilled allow crop residues to accumulate on the surface of the soil which would increase the possibility of aggregation. The amount of nitrogen applied to the soil also changes the amount of stored carbon. Nitrogen promotes the development of plant life. When the plants die they begin to decompose within the soil which in turn elevates the amount of carbon present within the soil.

4.1.3 TC Removal

There was a significant decrease in TC present in the soils after treatment with NaOCl, however, not all of the TC was destroyed. This method did remove up to 84% of the original TC but quantities between 0.2-3% (2-30 mg C/g soil) TC by mass remained in all samples which is slightly less than average percentage left in the soil reported by Lavkulich and Wiens (1970). In general, TC removal with NaOCl largely eliminated differences between the size fractions of each soil (Figures 31 and 33). However, differences between the management treatments remained. This suggests that the carbon pools responsible for aggregation were different from those influenced by management, with the later containing the more recalcitrant material.

4.2 Particle Density

Particle density (ρ_s), as used in this study, was defined as the mass of an oven dry soil divided by the volume of the soil particles. For this analysis the largest size fraction (2.0-4.0mm) of each soil was measured before and after the removal of organic matter. The numerical results of this analysis are shown in Table 6 and are visually illustrated in Figures 34 and 35. The particle density results before removal of organic matter show a trend in each soil of decreasing density with increasing TC concentration. This result is logical when compared to organic matter densities reported by Mayer et al. (2004) from 1.14-1.86 g/cm³. An increase in the amount of organic matter present within a soil would decrease the soil's density. After organic matter removal there were only slight increases in particle density for most of the soils which validates the previous assumption. The percentage increase in particle density upon TC removal is consistent with the findings of Mayer et al. (2004) with the exceptions of NT300, CT300 and CT0N which showed slight decreases in density.

Table 6: Particle density measurements.

Soil	Treatment	ρ_s w/OM (g/cm ³)	ρ_s wo/OM (g/cm ³)	% Change
Fermilab	RRD	2.41	2.52	4.6
Fermilab	5D	2.54	2.58	1.6
Fermilab	11D	2.46	2.61	5.9
Fermilab	N3D	2.54	2.76	8.2
Fermilab	AgD	2.56	2.58	1.0
Kentucky	NT300	2.54	2.50	-1.6
Kentucky	NT0N	2.71	2.81	3.7
Kentucky	CT300	2.74	2.73	-0.4
Kentucky	CT0N	2.76	2.74	-0.7

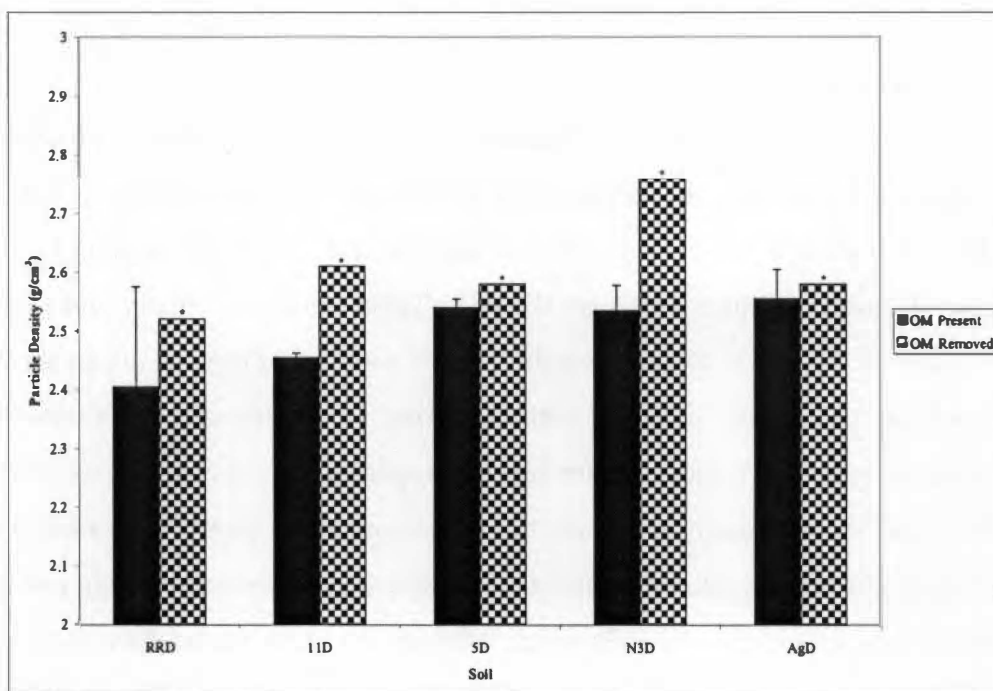


Figure 34: Particle density measurements for the Fermilab soils (error bars represent standard deviation, * represents samples for which only one density value was measured).

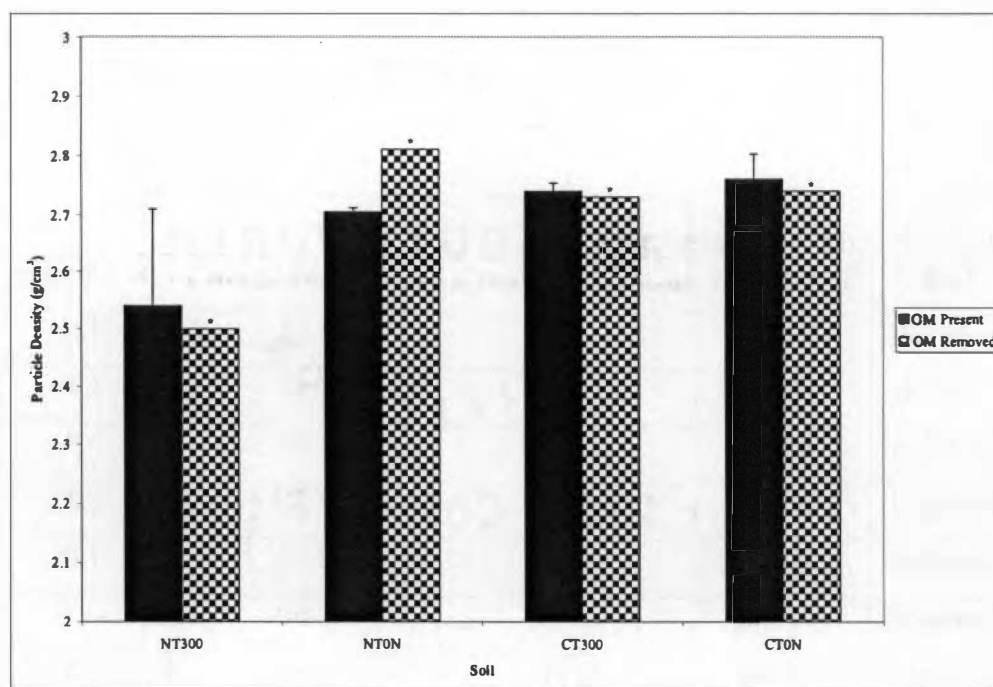


Figure 35: Particle density measurements for the Kentucky soils (error bars represent standard deviation, * represents samples for which only one density value was measured).

4.3 Specific Surface Area

4.3.1 Reproducibility

Before SSA measurements were conducted on the different size fractions the Quantachrome NOVA-1000 gas sorption analyzer was tested for reproducibility. For this procedure the $<0.25\text{mm}$ fraction from each of the four Kentucky soils was used prior to the removal of organic matter. Three samples of each soil were analyzed to determine how many sample runs were needed to obtain usable data. For each run a new sample was used and not simply the rerunning of one sample three different times. Table 7 shows the results of this analysis and Table 8 shows the statistical analysis of variance results where DF stands for degrees of freedom, and SS stands for sum of squares. Table 8 shows that the primary difference between the soils is tillage treatment (shown by the F values) and the effects of nitrogen fertilizer are significant but secondary. The interaction between tillage and nitrogen levels was not statistically significant. Figure 36 shows the SSA analysis of these soils. The standard deviations (represented by error bars) were very small for each soil indicating little variability from sample to sample. Because of this result, the SSA analysis conducted in the remainder of this study was based on only one measurement for each fraction of each soil, unless an obvious discrepancy arose.

4.3.2 Gas Sorption Results

Specific surface area measurements (SSA) were obtained using a Quantachrome NOVA-1000 gas sorption analyzer using nitrogen gas and are shown in Table 9. As SSA measurements were taken on each fraction of each soil there were three possible model outcomes (Table 3): first, SSA decreases by a scaling factor of -1 as larger aggregate sizes were analyzed; second, SSA remains constant for all aggregates in which the scaling factor would be 0; third, SSA decreases by a scaling factor in the interval between 0 and -1. If aggregates are Euclidean entities then SSA must either remain constant at 0 or decrease in size by a scaling factor of -1. However, based upon the construction of the models for this study, obtaining a scaling factor of 0 or -1 would not necessarily discredit the possibility that aggregates are fractal since a Mass fractal would scale as 0. If however, the resultant data shows a scaling factor that happens to be

Table 7: Results of the reproducibility experiment.

Treatment	Rep	SSA (m ² /g)
NT300	1	8.3722
NT300	2	8.7726
NT300	3	8.6693
NT0N	1	10.4121
NT0N	2	10.1176
NT0N	3	10.5102
CT300	1	12.1478
CT300	2	12.3178
CT300	3	12.5482
CT0N	1	14.1158
CT0N	2	14.3769
CT0N	3	14.0017

Table 8: Analysis of variance of the data in Table 7.

Source	DF	Type I SS	F Value	Pr > F
Tillage	1	42.7677	1053.80	<0.0001
Nitrogen Level	1	9.5523	235.37	<0.0001
Tillage and Nitrogen Level	1	0.0054	0.13	0.7245

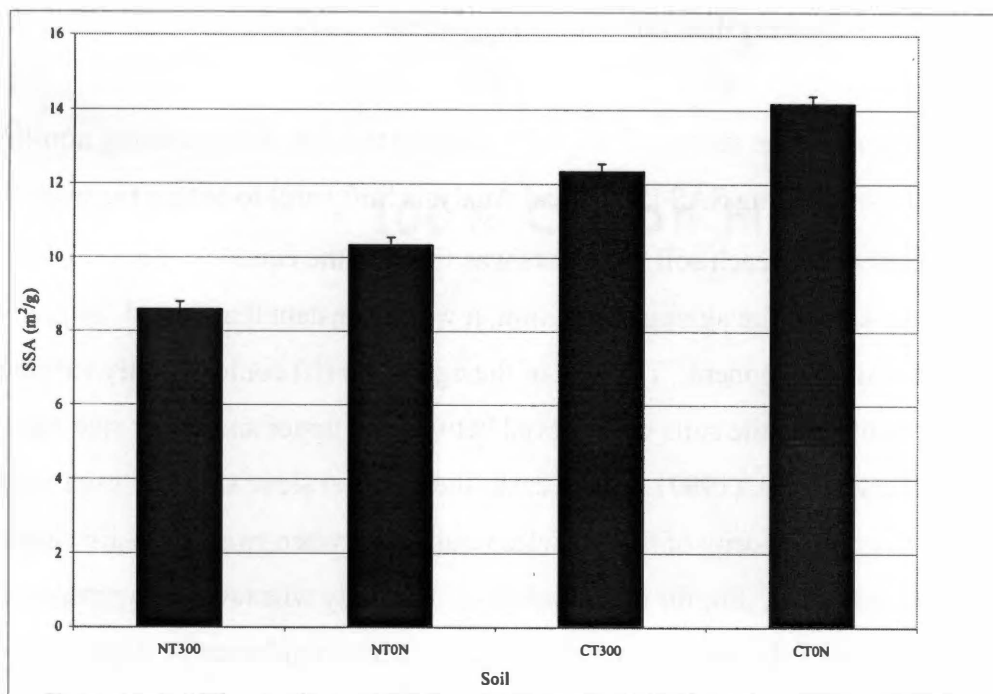


Figure 36: Mean SSA results for the <0.25mm fractions of the KY soils (standard deviations for each soil are represented by error bars).

Table 9: SSA results using N₂ gas adsorption. The size column is in units of mm and the SSA is in units of m²/g.

SIZE	RRD	5D	11D	N3D	AgD	NT300	NT0N	CT300	CT0N
2	2.19	2.88	2.62	3.10	4.77	7.28	9.13	13.75	13.71
1	2.47	4.28	3.39	3.09	4.77	6.49	14.71	17.88	17.34
0.5	4.17	3.83	3.00	3.08	4.75	11.91	13.51	14.33	16.06
0.25	3.14	3.06	3.47	3.32	3.76	7.37	8.28	11.05	11.69
0.106	2.96	3.74	2.45	2.55	2.48	10.11	11.97	13.60	13.29

between the two end points then this would support the theory that soil aggregates are in fact fractal.

After obtaining the data from the SSA analysis the data were fit using non-linear regression techniques using SAS (Statistical Analysis Software) to obtain the overall SSA scaling patterns for each soil. The data was fitted to the equation, $SSA = \alpha \cdot L^\beta$ where L was the size of the aggregate fraction, α was a constant that varied for each soil, and β was the scaling exponent. The size of the aggregate (L) could actually vary within each measurement since the soils were sieved between an upper and lower size range. According to Perfect et al. (1997) in such cases the smallest sieve size was used because it was shown that the majority of the particles retained between two sieves are closer in size to the smallest sieve. So, for the purposes of this study whenever an aggregate size is listed it was actually the smallest sized aggregate in a particular range that was analyzed (e.g. a 2mm size refers to all aggregates between 2 to 4mm in diameter).

The estimated β values were plotted as Figures 37 and 38 to show the scaling trends for each soil. Table 10 shows the results of the statistical analysis. It should be noted that the β factor presented in Table 10 does not equal 0 or -1 in any soil. This result indicates that soil aggregates are indeed not Euclidean structures. However, it should also be pointed out that only three of the soils, RRD, 5D, and NT300, are within the range of -1 to 0. The other six soils show that as aggregate size increases so does SSA. This is physically unreasonable. The β values are, however, not exact for each soil. These values are just an estimation made by the SAS software. There is actually a range of β values that are possible and the SAS software was 95% (positive and negative correlation) certain that the actual β value was found between the two extremes. Figures 39 and 40 show these ranges after they were fitted to the $\beta = D-3$ model. As has been previously mentioned as aggregate size increases the β value should be less than or equal to zero and/or greater than or equal to -1.

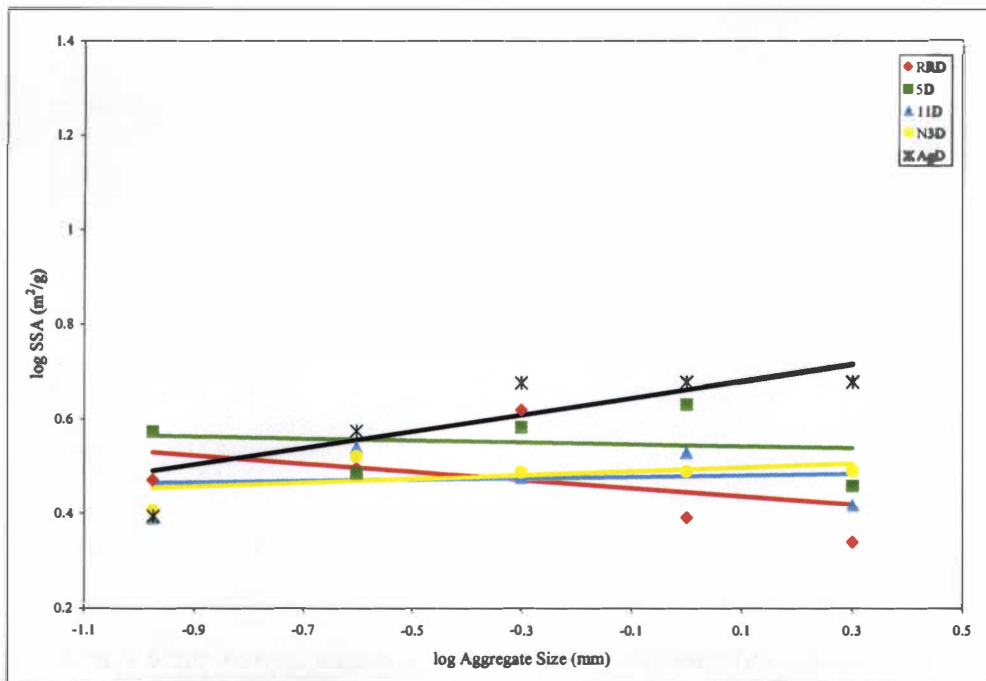


Figure 37: SSA measurements for Fermilab soil treatments. Dots represent measured data and solid lines represent the estimated scaling trends as shown in Table 10.

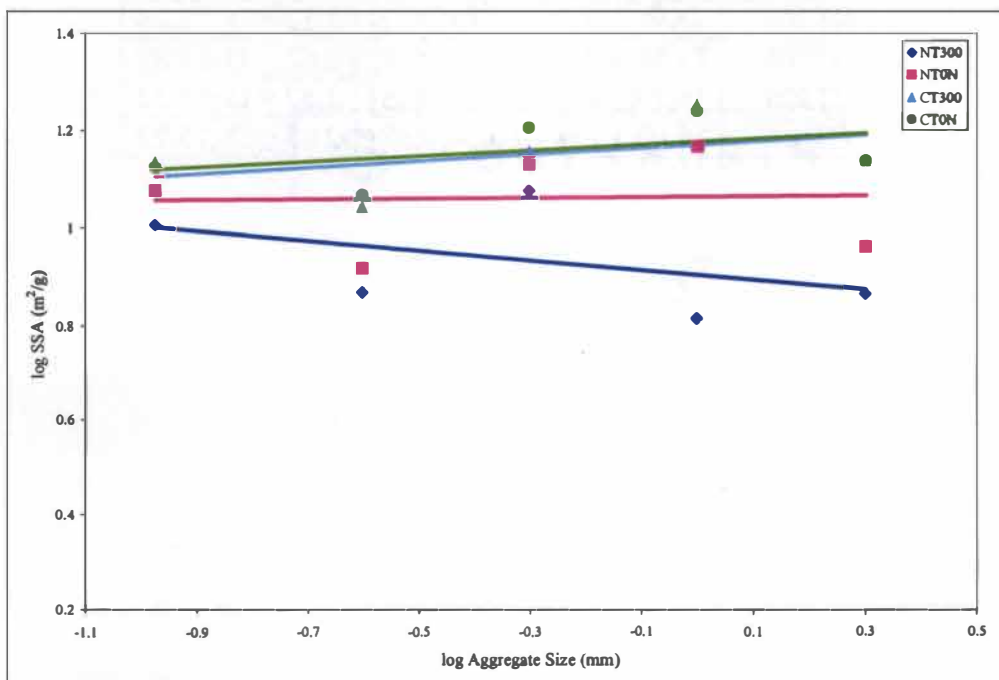


Figure 38: SSA measurements for Kentucky soil treatments. Dots represent measured data and solid lines represent the estimated scaling trends as shown in Table 10.

Table 10: SSA results and statistical analysis ([] represents approximate standard error).

Treatment	α	β	D
RRD	2.80[0.45]	-0.085[0.12]	$2.54 \leq D \leq 3.29$
5D	3.51[0.36]	-0.019[0.08]	$2.72 \leq D \leq 3.24$
11D	3.02[0.28]	0.016[0.08]	$2.77 \leq D \leq 3.26$
N3D	3.12[0.15]	0.041[0.04]	$2.91 \leq D \leq 3.17$
AgD	4.60[0.32]	0.177[0.07]	$2.97 \leq D \leq 3.39$
NT300	7.98[1.32]	-0.101[0.12]	$2.52 \leq D \leq 3.28$
NT0N	11.58[1.74]	0.007[0.12]	$2.62 \leq D \leq 3.39$
CT300	14.79[1.37]	0.067[0.08]	$2.82 \leq D \leq 3.32$
CT0N	15.02[1.27]	0.059[0.07]	$2.83 \leq D \leq 3.29$

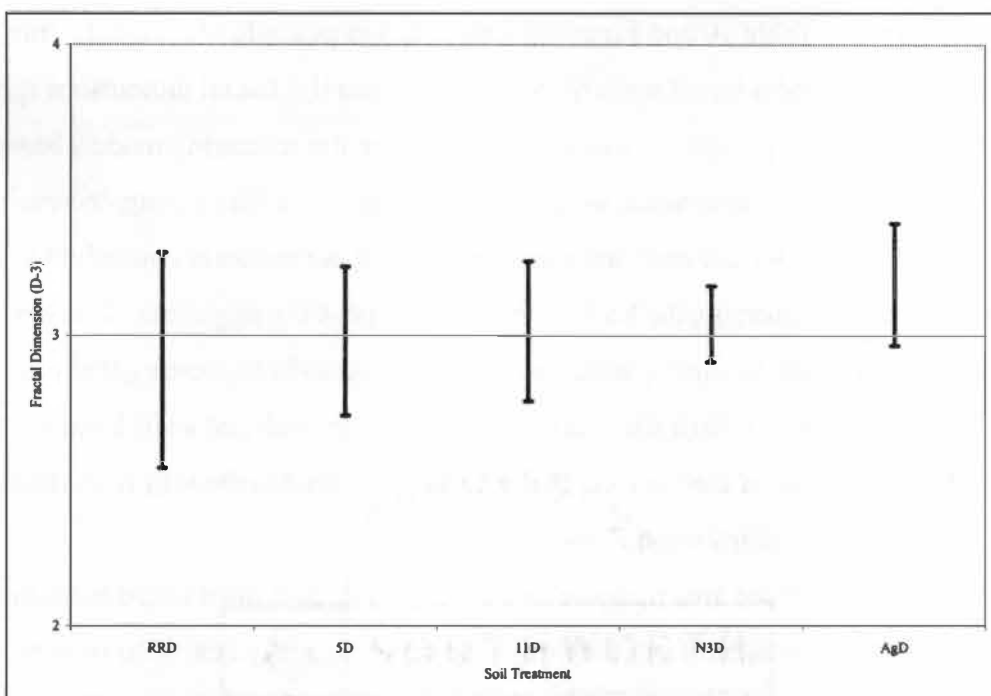


Figure 39: Range of fractal dimensions shown in Table 10 for the Fermilab soils.

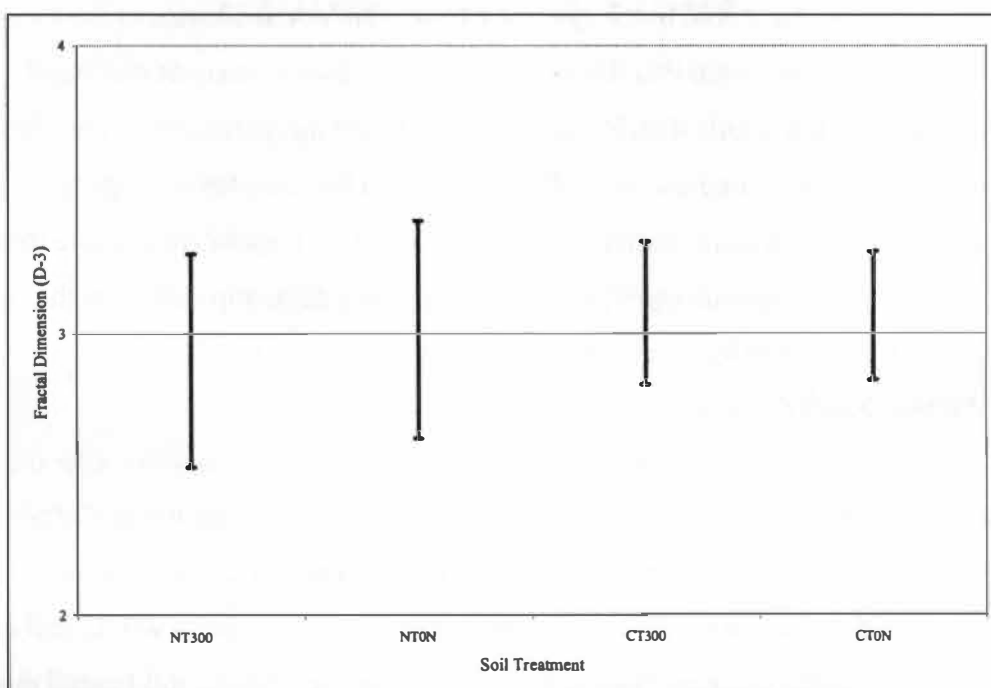


Figure 40: Range of fractal dimensions shown in Table 10 for the Kentucky soils.

Based on Table 10 and Figures 37 and 38, it is possible to eliminate only the Euclidean solid model based upon SSA scaling. Since the fractal dimensions span the $D = 3$ limit, it is not possible to discriminate between the remaining models based on these results alone. It also needs to be noted that α shows a very strong decreasing trend with increasing TC within each soil treatment. The α parameter is equivalent to the y-intercept, which represents the SSA of the smallest possible aggregate. This trend is more apparent in the Kentucky soils than the Fermilab soils suggesting that α is controlled by particle size (a silty clay loam for the Fermilab and a silt loam for Kentucky), presence of carbon (Kentucky has less residual carbon) or both (Figure 41).

4.3.3 Particle Size Distribution Results

Specific surface area measurements were also determined based upon the particle size distributions obtained from the x-ray disc centrifuge. As described in section 3.6.3 the largest aggregate size fraction of each soil treatment after organic matter removal was analyzed. Table 11 shows the results of this analysis. Both methods indicate that the Kentucky soil had on average a higher SSA than the Fermilab soil. It is apparent, with regard to the Fermilab soils, that the particle size distribution SSA measurements are close to those measured by N_2 gas. The results are not as consistent for the Kentucky soils but it should be noted that the particle size distribution analysis measured a lower SSA in the Kentucky soils than N_2 adsorption but both measurements were within an order of magnitude of one another. Within each soil the samples with the highest remaining residual organic matter showed the closest correspondence, while those with the lowest residual organic matter showed the greatest deviations between the two methods. The reasons for this trend are unclear.

4.4 Particle Size Distributions

Particle size distributions for each of the 9 soils were measured, after the removal of organic matter and physical and chemical dispersion, in an attempt to further distinguish between the different geometrical models presented for this study. If a particle size distribution is non-uniform then four of the six models would still be valid; the Euclidean Solid, Surface Fractal, Pore Fractal, and the Pore-Solid Fractal models. If

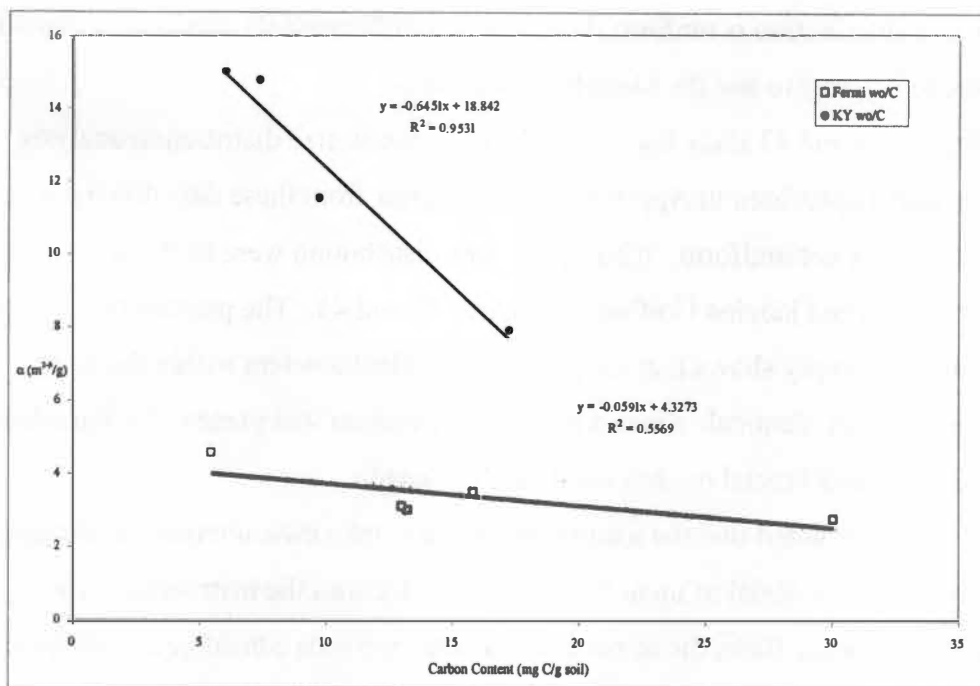


Figure 41: The α parameter in the relationship of $\text{SSA} = \alpha \cdot L^\beta$ vs. the amount of residual carbon remaining.

Table 11: SSA measurements of the largest sized aggregates using particle size distributions and gas adsorption.

Soil Treatment	Particle Size Distribution SSA (m^2/g)	N_2 Gas SSA (m^2/g)	OM Remaining (mg c/g soil)
RRD	2.91	2.19	30.06
5D	3.14	2.88	15.84
11D	2.74	2.62	13.22
N3D	1.69	3.10	12.99
AgD	2.77	4.77	5.47
NT300	5.79	7.28	17.22
NT0N	5.05	9.13	9.71
CT300	3.83	13.75	7.35
CT0N	3.22	13.71	6.02

a particle size distribution is uniform then only two of the models would be acceptable; the Euclidean Aggregate and the Mass Fractal models.

Figures 42 and 43 show the results for the particle size distribution analysis (numerical data is provided in Appendix C). It is clear from these data that the particle size distribution is non-uniform. If a particle size distribution were uniform the graph would show the trend labeled Uniform in Figures 42 and 43. The presence of a particle size distribution simply shows that the primary particle diameters within the soil aggregates were not identical. Since a particle distribution was present the Euclidean Aggregate and Mass Fractal models must be eliminated.

It should be noted that the instrument began to take measurements at roughly 10 μ m even though material of up to 53 μ m was injected into the instrument. The instrument considered 10 μ m the upper limit of sizes and thus considered it the largest size possible and equilibrated it to 100%. This is not ideal since there are surely particles greater than 10 μ m in size, but the instrument does not sense them possibly because they are too large and settle out of suspension before they can be analyzed. For comparison with the pore size distributions (Section 4.5.2) the same scale was used in all figures. Table 12 shows the upper and lower limits plotted in Figures 42 and 43. The percentages in this table were normalized to the largest particle size analyzed by the instrument.

4.5 Water Retention Curves and Pore Size Distributions

4.5.1 Water Retention Curves

Water retention data was collected on the drying curve for each of the 9 soil treatments. Due to the accuracy of the WP4 Dew Point PotentialMeter only water potentials between -1 to -40 MPa were analyzed. The water content was measured at various potentials. Figures 44 and 45 show the water retention curves for each of the 9 soil treatments (numerical data is provided in Appendix D). The dots represent measured data points while the lines represent a best-fit approximation using non-linear regression techniques. Based upon these measurements pore size distributions were determined.

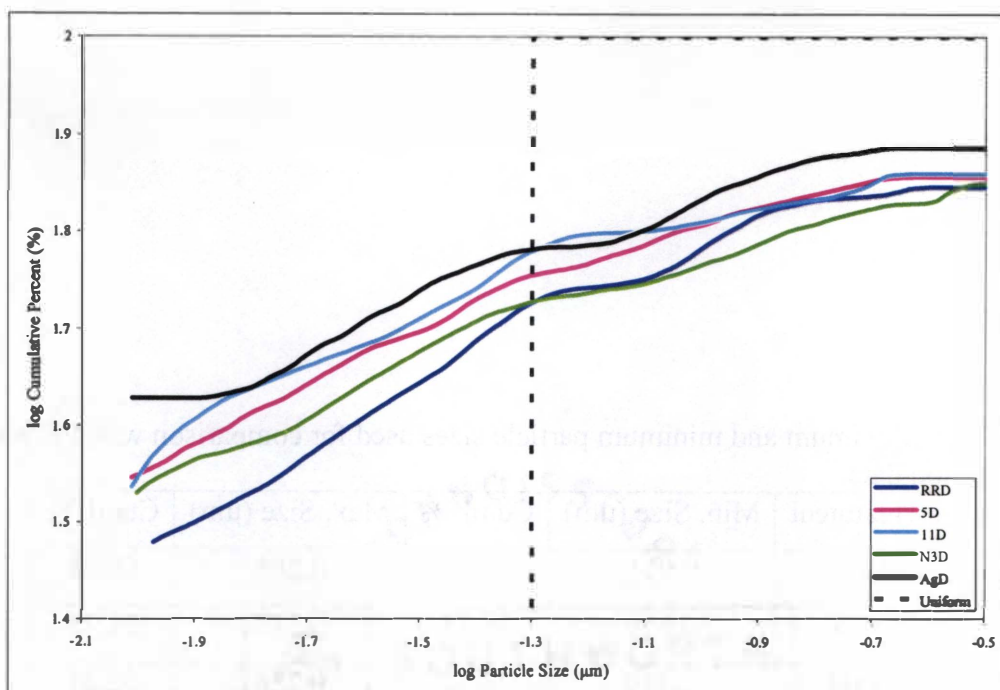


Figure 42: Particle size distribution for the Fermilab soils. These curves only show the range of particle sizes that fall within the upper and lower limits of the water retention measurements for purposes of comparison.

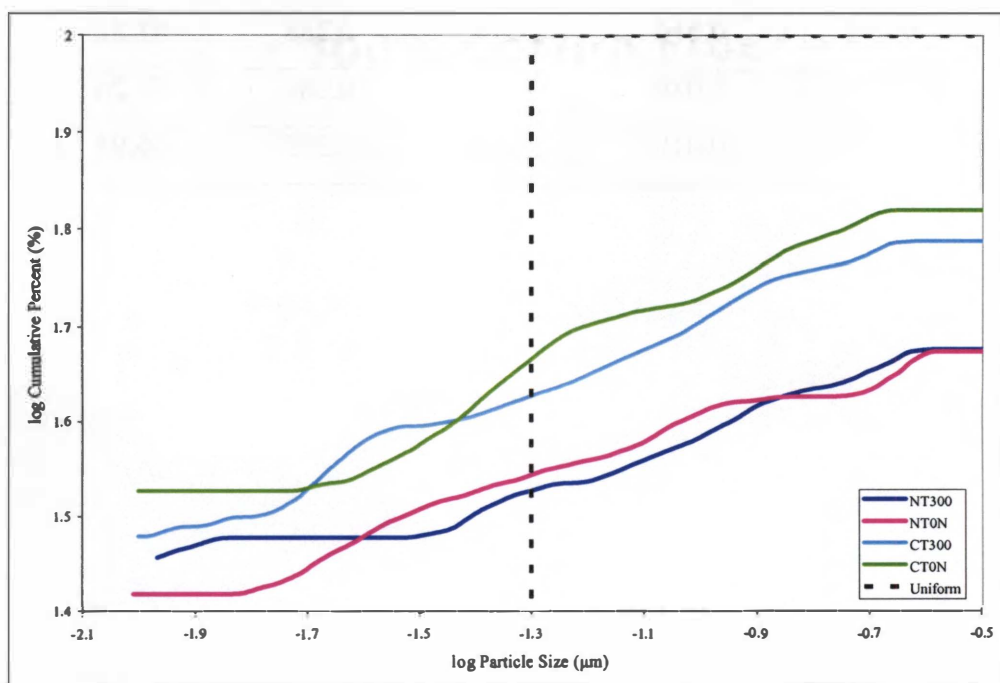


Figure 43: Particle size distribution for the Kentucky soils. These curves only show the range of particle sizes that fall within the upper and lower limits of the water retention measurements for purposes of comparison.

Table 12: Maximum and minimum particle sizes used for comparison with the pore size distribution data.

Treatment	Min. Size (μm)	Cuml. %	Max. Size (μm)	Cuml. %
RRD	0.011	30.14	0.285	69.98
5D	0.010	35.15	0.289	71.75
11D	0.010	34.34	0.286	72.21
N3D	0.010	33.85	0.284	69.84
AgD	0.010	42.49	0.289	77.09
NT300	0.011	28.64	0.287	47.44
NT0N	0.010	26.23	0.288	47.22
CT300	0.010	30.13	0.286	61.26
CT0N	0.010	33.64	0.285	65.95

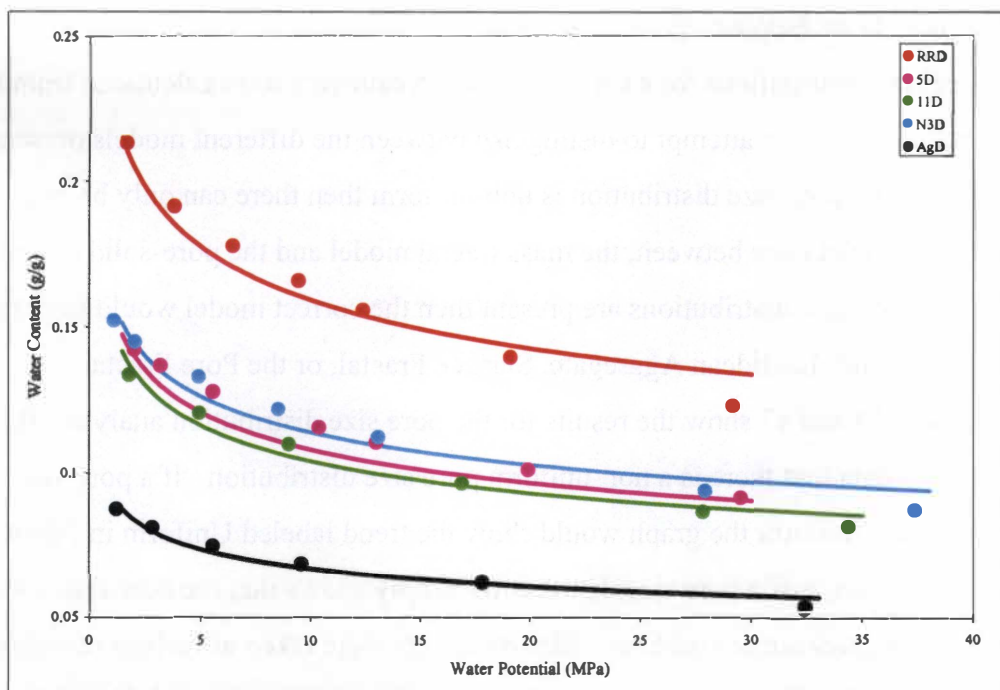


Figure 44: Water retention of the Fermilab soils.

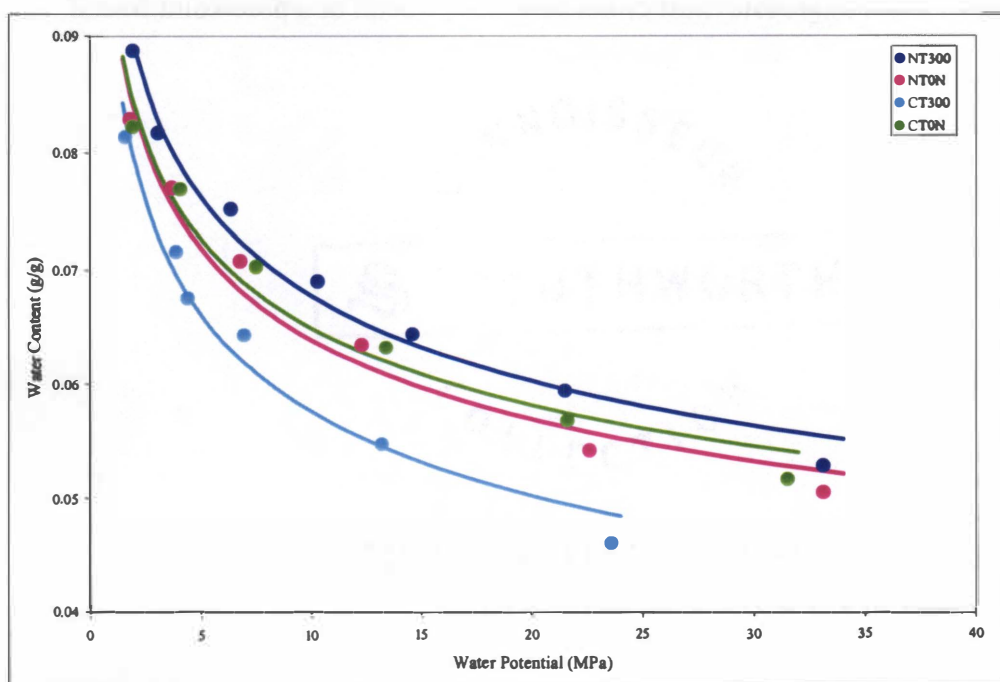


Figure 45: Water retention of the Kentucky soils.

4.5.2 Pore Size Distributions

Pore size distributions for each of the 9 soil treatments were calculated from the water retention data in an attempt to distinguish between the different models presented for this study. If a pore size distribution is non-uniform then there can only be two possible models to choose between, the mass fractal model and the pore-solid fractal model. If no pore size distributions are present then the correct model would have to be the Euclidean Solid, Euclidean Aggregate, Surface Fractal, or the Pore Fractal.

Figures 46 and 47 show the results for the pore size distribution analysis. It is clear from this data that there is a non-uniform pore size distribution. If a pore size distribution were uniform the graph would show the trend labeled Uniform in Figures 46 and 47. The presence of a pore size distribution simply shows that the pore diameters within the aggregates are not uniform. Measurements were taken at various tensions in order to construct the figures. At very low tensions large pores drain quickly while more tension is needed to drain smaller pores. If all pores were uniform in size then at one tension all of the pores would drain simultaneously as shown by the Uniform trends. The results of this analysis show that the correct model to determine the internal structure of a soil aggregate must either be a mass fractal or a pore-solid fractal.

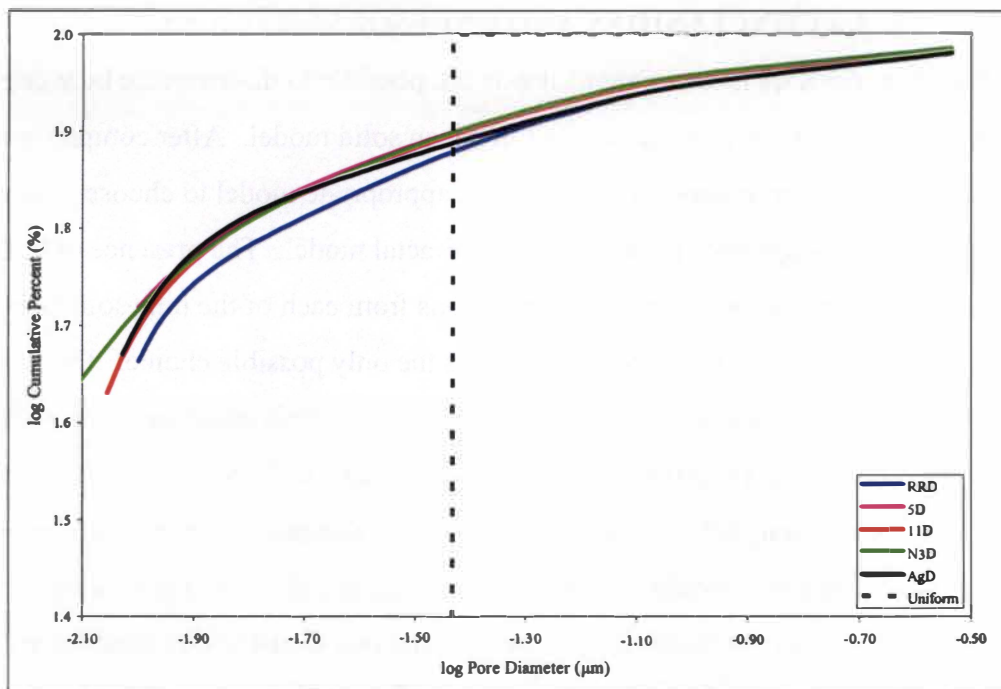


Figure 46: Pore size distribution for the Fermilab soils.

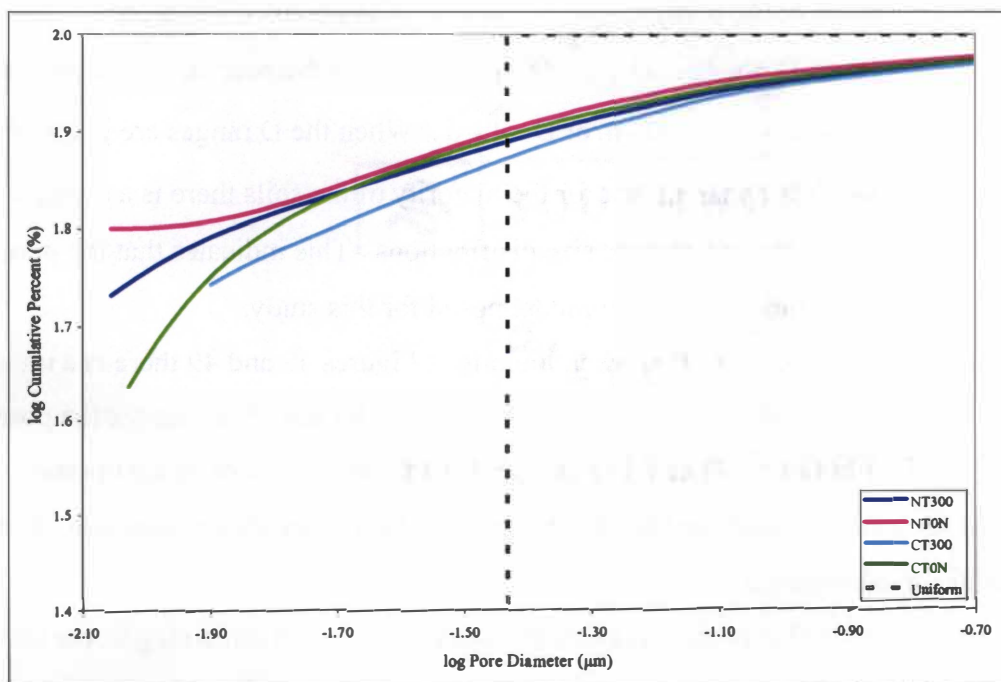


Figure 47: Pore size distribution for the Kentucky soils.

5.0 CONCLUSIONS AND UNRESOLVED ISSUES

Based on the SSA measurements it was not possible to discriminate between the various models, other than eliminating the Euclidean solid model. After completion of all the analyses however, it appears that the most appropriate model to choose regarding the structure of soil aggregates is the Pore-Solid Fractal model. The presence of both particle size distributions and pore size distributions from each of the nine soils indicates according to Figure 28 that a Pore-Solid Fractal is the only possible choice. The combination of each of these factors lends strong support to this conclusion. However, according to Perrier et al. (1999) a true Pore-Solid Fractal would not just have a particle and pore size distribution, but these distributions would themselves be fractal. Perrier et al. (1999) also claim that it would not be enough for a material to have both a fractal particle and a fractal pore size distribution but that the two distributions must have the same fractal dimension. Tables 13 and 14 show the fractal dimensions of each soil treatment as determined by nonlinear regression using SAS following the equation $X = \alpha \cdot L^\beta$, where α was a constant, β was the scaling factor, and L was a length. The fractal dimensions were obtained using the procedures shown in Bird et al. (2000) where the fractal dimension of the particle size distribution was obtained using the equation $\beta = d - D$ or $D = d - \beta$. The fractal dimension for the pore size distribution was obtained using the equation $\beta = D - d$ or $D = \beta - d$. When the D ranges are graphed (Figures 48 and 49) it is apparent that for the majority of the soils there is a definite overlap between the pore and particle size distributions. This indicates that the pore-solid fractal model is the most correct model posed for this study.

It should also be noted that when looking at Figures 48 and 49 there is a much larger distribution of estimates of the fractal dimension for the SSA than for the pore and particle size distributions. Since there are roughly the same number of data points measured for water retention as for SSA this may indicate that SSA measurements are less useful for estimating D .

From Figure 41 it is apparent that the amount of carbon remaining in the soil after removal with NaOCl influences the SSA behavior of the soils. The amount of carbon left within the Kentucky soils appears to have a dramatic effect on the SSA

Table 13: Fractal dimension determination using particle size distribution data. The D range are the bounds of the 95% confidence interval for the fractal dimension, and R^2 was a measure of the goodness of fit which was determined by taking the observed data vs. the predicted data. [] numbers represent the approximate standard error for each parameter. D was calculated following Bird et al. 2002.

Soil Treatment	α	β	D Range	R^2
RRD	150.0 [2.49]	0.25 [0.006]	$2.73 \leq D \leq 2.76$	0.96
5D	138.0 [1.64]	0.20 [0.004]	$2.79 \leq D \leq 2.81$	0.97
11D	134.3 [1.93]	0.19 [0.005]	$2.80 \leq D \leq 2.82$	0.95
N3D	132.2 [1.30]	0.20 [0.004]	$2.79 \leq D \leq 2.81$	0.98
AgD	135.9 [1.40]	0.20 [0.004]	$2.80 \leq D \leq 2.81$	0.97
NT300	123.7 [1.51]	0.18 [0.005]	$2.81 \leq D \leq 2.83$	0.95
NT0N	128.1 [0.96]	0.19 [0.003]	$2.81 \leq D \leq 2.82$	0.98
CT300	140.2 [1.00]	0.23 [0.003]	$2.76 \leq D \leq 2.77$	0.99
CT0N	144.5 [1.70]	0.25 [0.005]	$2.74 \leq D \leq 2.76$	0.98

Table 14: Fractal dimension determination using water retention data. The D range are the bounds of the 95% confidence interval for the fractal dimension, and R^2 was a measure of the goodness of fit which was determined by taking the observed data vs. the predicted data. [] numbers represent the approximate standard error for each parameter. D was calculated following Bird et al. 2002.

Soil Treatment	α	β	D Range	R^2
RRD	0.23 [0.006]	-0.16 [0.014]	$2.81 \leq D \leq 2.88$	0.95
5D	0.16 [0.004]	-0.16 [0.012]	$2.81 \leq D \leq 2.87$	0.92
11D	0.15 [0.005]	-0.16 [0.015]	$2.80 \leq D \leq 2.88$	0.94
N3D	0.16 [0.005]	-0.15 [0.015]	$2.81 \leq D \leq 2.89$	0.93
AgD	0.09 [0.002]	-0.14 [0.013]	$2.82 \leq D \leq 2.89$	0.92
NT300	0.10 [0.002]	-0.17 [0.010]	$2.80 \leq D \leq 2.86$	0.92
NT0N	0.09 [0.003]	-0.17 [0.015]	$2.79 \leq D \leq 2.87$	0.93
CT300	0.09 [0.003]	-0.20 [0.017]	$2.75 \leq D \leq 2.85$	0.96
CT0N	0.09 [0.003]	-0.16 [0.015]	$2.80 \leq D \leq 2.88$	0.93

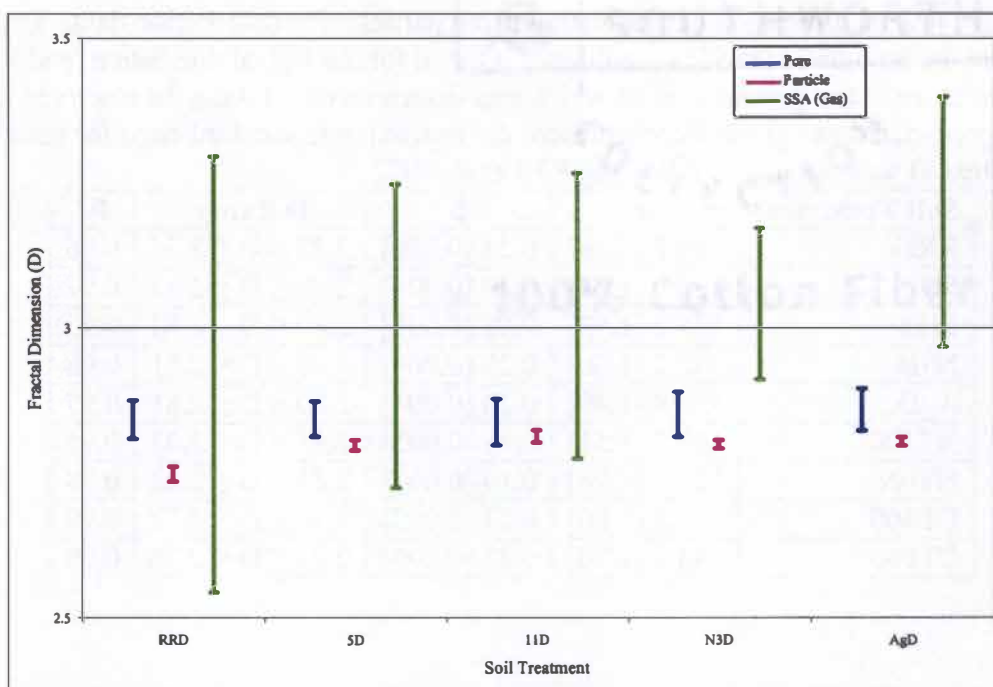


Figure 48: Fractal dimension ranges for the pore and particle size distribution data conducted on the Fermilab soils compared with their SSA (gas) D values.

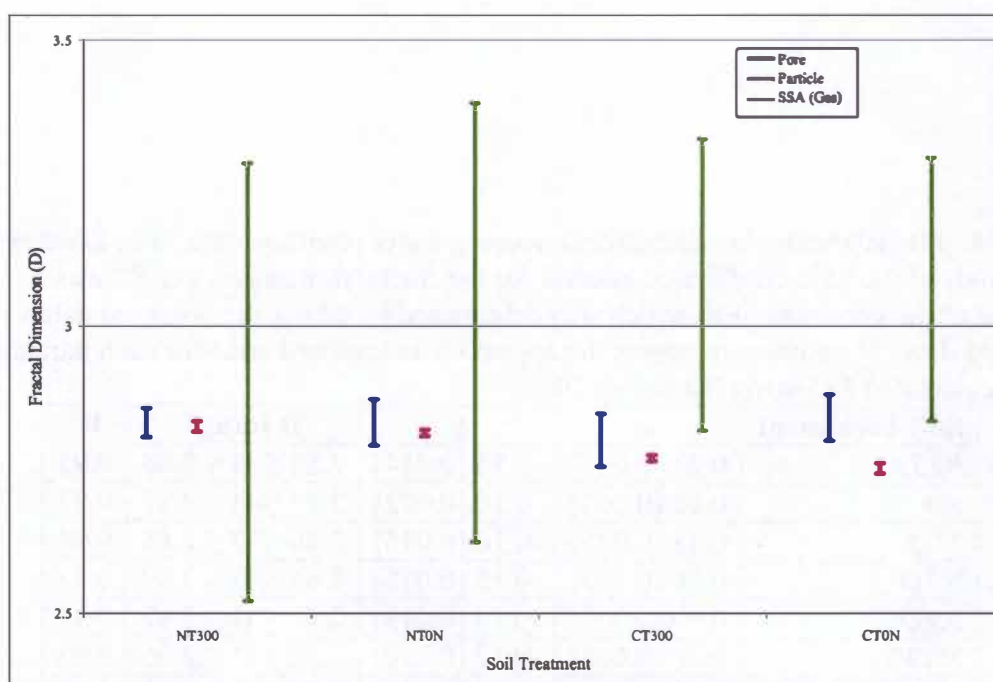


Figure 49: Fractal dimension ranges for the pore and particle size distribution data conducted on the Kentucky soils compared with their SSA (gas) D values.

values obtained. This effect is not as great for the Fermilab soils but a trend still exists that shows as the amount of residual carbon increases, the SSA decreases. This is an important factor that needs to be looked at in greater detail. Since the amount of residual carbon left within the soil after removal appears to have a direct influence on SSA, improved methods need to be developed that either remove all residual carbon, without destroying the integrity of the soil's minerals, or leave a universal amount of residual carbon so that its effects would be consistent. The efficiency of carbon removal on SSA measurements needs to be investigated further.

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APPENDICES

APPENDIX A: TOTAL CARBON STANDARDIZATION

Table A-1: TC standardization using a fructose sugar solution

Amount Injected (µm)	mg C	Area	Average
50	12	6426	6459.5
50	12	6493	
25	6	2904	2947
25	6	2990	
12.5	3	1509	1507
12.5	3	1505	

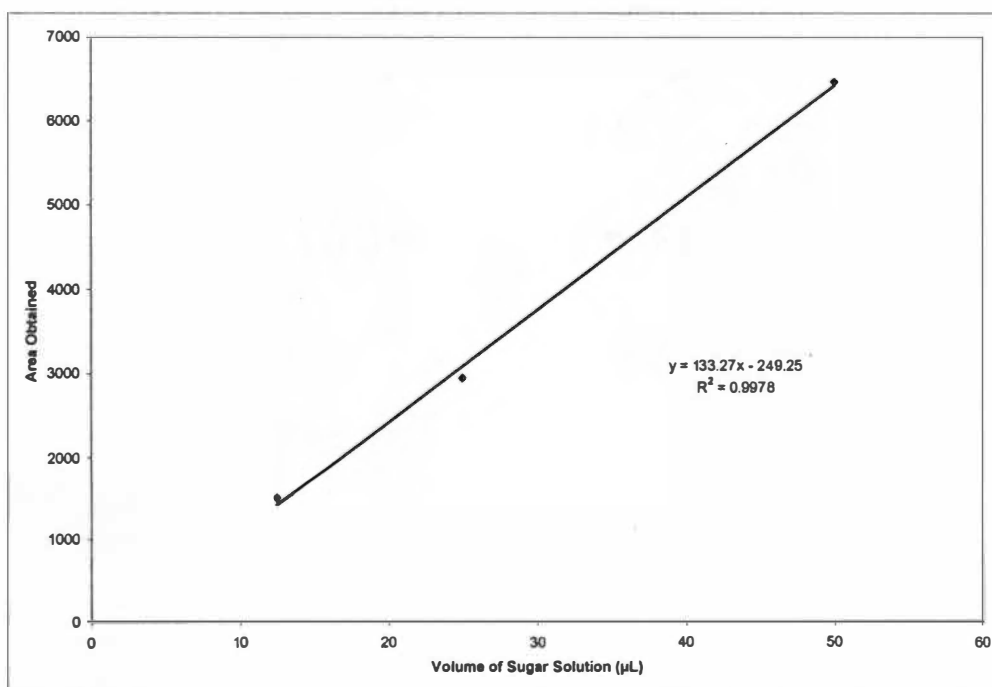


Figure A-1: Standardization curve for TC determination.

APPENDIX B: TC MEASUREMENTS FOR MICROAGGREGATES

Soil Treatment	TC Before (mg C/g soil)	TC After (mg C/g soil)
RRD	85.8	11.3
5D	43.4	6.0
11D	44.1	5.2
N3D	49.0	6.0
AgD	24.1	3.5
NT300	32.8	4.2
NT0N	23.1	2.3
CT300	16.1	2.2
CT0N	14.6	2.2

Organic matter was removed using thermal oxidation at 350⁰C.

APPENDIX C: TOTAL PARTICLE SIZE DISTRIBUTION DATA

(Fermilab Soils p. 81-85, Kentucky Soils p. 86-89)

[illegible]

[illegible]

11D (values in <i>italics</i> are sizes within the water retention range, size is in μm)							
Size	%	Size	%	Size	%	Size	%
<i>0.010</i>	34.34	<i>0.061</i>	62.30	0.335	72.21	1.255	72.21
<i>0.010</i>	35.63	<i>0.063</i>	62.53	0.347	72.21	1.301	72.21
<i>0.011</i>	36.80	<i>0.066</i>	62.65	0.356	72.21	1.341	72.21
<i>0.011</i>	37.85	<i>0.069</i>	62.69	0.369	72.21	1.385	72.21
<i>0.012</i>	38.82	<i>0.072</i>	62.75	0.380	72.21	1.420	72.21
<i>0.012</i>	39.66	<i>0.075</i>	62.84	0.392	72.21	1.470	72.21
<i>0.013</i>	40.37	<i>0.079</i>	62.93	0.405	72.21	1.524	72.22
<i>0.013</i>	41.04	<i>0.082</i>	63.06	0.418	72.21	1.564	72.30
<i>0.014</i>	41.71	<i>0.086</i>	63.27	0.432	72.21	1.623	72.56
<i>0.014</i>	42.34	<i>0.090</i>	63.55	0.445	72.21	1.672	73.03
<i>0.015</i>	42.84	<i>0.093</i>	63.84	0.459	72.21	1.725	73.61
<i>0.016</i>	43.26	<i>0.098</i>	64.16	0.473	72.21	1.785	74.21
<i>0.016</i>	43.71	<i>0.102</i>	64.47	0.488	72.21	1.828	74.77
<i>0.017</i>	44.17	<i>0.107</i>	64.83	0.505	72.21	1.898	75.21
<i>0.018</i>	44.58	<i>0.111</i>	65.29	0.520	72.21	1.950	75.56
<i>0.019</i>	45.04	<i>0.116</i>	65.77	0.538	72.21	2.007	75.93
<i>0.020</i>	45.49	<i>0.122</i>	66.15	0.554	72.21	2.069	76.31
<i>0.020</i>	45.91	<i>0.127</i>	66.46	0.573	72.21	2.137	76.61
<i>0.021</i>	46.36	<i>0.133</i>	66.78	0.590	72.21	2.212	76.82
<i>0.022</i>	46.82	<i>0.138</i>	67.10	0.610	72.21	2.295	76.96
<i>0.023</i>	47.24	<i>0.144</i>	67.41	0.629	72.21	2.341	77.09
<i>0.024</i>	47.69	<i>0.151</i>	67.69	0.648	72.21	2.440	77.23
<i>0.025</i>	48.15	<i>0.158</i>	67.88	0.671	72.21	2.495	77.35
<i>0.027</i>	48.56	<i>0.164</i>	68.10	0.692	72.21	2.617	77.48
<i>0.028</i>	49.06	<i>0.172</i>	68.50	0.714	72.21	2.685	77.67
<i>0.029</i>	49.70	<i>0.179</i>	68.96	0.735	72.21	2.758	77.95
<i>0.030</i>	50.39	<i>0.187</i>	69.45	0.759	72.21	2.838	78.37
<i>0.032</i>	51.09	<i>0.196</i>	70.19	0.785	72.21	2.926	78.92
<i>0.033</i>	51.78	<i>0.205</i>	71.15	0.809	72.21	3.022	79.55
<i>0.034</i>	52.48	<i>0.213</i>	71.87	0.834	72.21	3.128	80.35
<i>0.036</i>	53.17	<i>0.229</i>	72.16	0.861	72.21	3.246	81.34
<i>0.038</i>	53.86	<i>0.236</i>	72.21	0.889	72.21	3.378	82.36
<i>0.039</i>	54.60	<i>0.245</i>	72.21	0.919	72.21	3.528	83.35
<i>0.041</i>	55.49	<i>0.253</i>	72.21	0.947	72.21	3.701	84.53
<i>0.043</i>	56.53	<i>0.260</i>	72.21	0.976	72.21	3.901	85.93
<i>0.045</i>	57.62	<i>0.268</i>	72.21	1.007	72.21	4.137	87.41
<i>0.047</i>	58.64	<i>0.278</i>	72.21	1.041	72.21	4.423	89.01
<i>0.049</i>	59.51	<i>0.286</i>	72.21	1.071	72.21	4.778	90.83
<i>0.051</i>	60.22	<i>0.296</i>	72.21	1.109	72.21	5.233	92.90
<i>0.053</i>	60.88	<i>0.305</i>	72.21	1.143	72.21	5.851	95.17
<i>0.056</i>	61.49	<i>0.315</i>	72.21	1.180	72.21	6.756	97.57
<i>0.058</i>	61.98	<i>0.324</i>	72.21	1.220	72.21	8.275	100.00

N3D (values in italics are sizes within the water retention range, size is in μm)							
Size	%	Size	%	Size	%	Size	%
<i>0.010</i>	33.85	<i>0.062</i>	54.32	0.343	70.70	1.283	82.11
<i>0.010</i>	34.49	<i>0.065</i>	54.58	0.354	70.82	1.330	82.37
<i>0.011</i>	35.09	<i>0.068</i>	54.82	0.364	71.00	1.371	82.55
<i>0.011</i>	35.57	<i>0.071</i>	55.00	0.377	71.12	1.416	82.73
<i>0.012</i>	35.97	<i>0.074</i>	55.15	0.389	71.16	1.452	82.93
<i>0.012</i>	36.41	<i>0.077</i>	55.38	0.400	71.16	1.503	83.06
<i>0.013</i>	36.81	<i>0.080</i>	55.70	0.414	71.18	1.558	83.12
<i>0.014</i>	37.05	<i>0.084</i>	56.14	0.427	71.30	1.599	83.22
<i>0.014</i>	37.25	<i>0.088</i>	56.60	0.441	71.51	1.659	83.37
<i>0.015</i>	37.52	<i>0.092</i>	57.01	0.455	71.77	1.709	83.50
<i>0.015</i>	37.83	<i>0.096</i>	57.50	0.470	72.07	1.764	83.66
<i>0.016</i>	38.15	<i>0.100</i>	58.10	0.484	72.41	1.825	83.90
<i>0.017</i>	38.46	<i>0.104</i>	58.62	0.499	72.84	1.869	84.24
<i>0.018</i>	38.78	<i>0.109</i>	59.03	0.516	73.27	1.941	84.69
<i>0.018</i>	39.14	<i>0.114</i>	59.51	0.532	73.62	1.994	85.16
<i>0.019</i>	39.63	<i>0.119</i>	60.14	0.550	73.93	2.052	85.58
<i>0.020</i>	40.25	<i>0.124</i>	60.83	0.566	74.23	2.115	86.04
<i>0.021</i>	40.91	<i>0.130</i>	61.52	0.585	74.49	2.185	86.50
<i>0.022</i>	41.59	<i>0.136</i>	62.21	0.603	74.68	2.261	86.90
<i>0.023</i>	42.26	<i>0.141</i>	62.86	0.624	74.85	2.347	87.35
<i>0.024</i>	42.93	<i>0.148</i>	63.36	0.643	75.06	2.393	87.81
<i>0.025</i>	43.60	<i>0.154</i>	63.75	0.663	75.23	2.495	88.22
<i>0.026</i>	44.27	<i>0.161</i>	64.20	0.686	75.40	2.551	88.64
<i>0.027</i>	44.94	<i>0.168</i>	64.76	0.708	75.64	2.675	89.07
<i>0.028</i>	45.61	<i>0.176</i>	65.26	0.730	75.93	2.745	89.47
<i>0.030</i>	46.28	<i>0.183</i>	65.65	0.751	76.23	2.820	89.92
<i>0.031</i>	46.95	<i>0.191</i>	66.06	0.776	76.58	2.902	90.37
<i>0.032</i>	47.61	<i>0.200</i>	66.49	0.803	77.02	2.991	90.73
<i>0.034</i>	48.28	<i>0.209</i>	66.83	0.827	77.47	3.089	91.03
<i>0.035</i>	48.94	<i>0.217</i>	67.09	0.853	77.83	3.198	91.31
<i>0.037</i>	49.61	<i>0.235</i>	67.23	0.880	78.13	3.319	91.58
<i>0.038</i>	50.27	<i>0.242</i>	67.28	0.909	78.48	3.454	91.89
<i>0.040</i>	50.93	<i>0.250</i>	67.40	0.940	78.91	3.608	92.28
<i>0.042</i>	51.55	<i>0.259</i>	67.75	0.968	79.36	3.784	92.69
<i>0.044</i>	52.04	<i>0.266</i>	68.41	0.998	79.72	3.988	93.03
<i>0.046</i>	52.42	<i>0.274</i>	69.21	1.030	80.02	4.230	93.47
<i>0.048</i>	52.82	<i>0.284</i>	69.84	1.064	80.32	4.522	94.24
<i>0.050</i>	53.24	0.292	70.22	1.095	80.63	4.885	95.34
<i>0.052</i>	53.57	0.302	70.48	1.134	80.92	5.351	96.60
<i>0.054</i>	53.82	0.312	70.63	1.169	81.22	5.982	97.82
<i>0.057</i>	53.98	0.322	70.67	1.207	81.52	6.908	98.94
<i>0.059</i>	54.12	0.332	70.67	1.248	81.81	8.461	100.00

AgD (values in italics are sizes within the water retention range, size is in μm)							
Size	%		Size	%		Size	%
0.010	42.49		0.061	61.03		0.339	77.09
0.010	42.49		0.064	61.21		0.350	77.09
0.011	42.49		0.067	61.38		0.359	77.09
0.011	42.49		0.070	61.66		0.372	77.09
0.012	42.49		0.073	62.20		0.384	77.09
0.012	42.49		0.076	62.82		0.395	77.09
0.013	42.49		0.079	63.40		0.409	77.09
0.013	42.54		0.083	64.09		0.422	77.09
0.014	42.73		0.086	64.98		0.436	77.09
0.015	43.01		0.090	65.94		0.449	77.09
0.015	43.25		0.094	66.90		0.464	77.09
0.016	43.56		0.099	67.85		0.478	77.09
0.017	44.11		0.103	68.80		0.493	77.09
0.017	44.71		0.108	69.68		0.509	77.09
0.018	45.27		0.112	70.37		0.525	77.09
0.019	45.94		0.117	70.90		0.543	77.09
0.020	46.79		0.123	71.52		0.559	77.09
0.021	47.64		0.128	72.29		0.578	77.09
0.022	48.33		0.134	72.96		0.595	77.09
0.023	48.89		0.139	73.49		0.616	77.09
0.024	49.56		0.146	74.06		0.635	77.09
0.025	50.40		0.152	74.64		0.654	77.09
0.026	51.26		0.159	75.11		0.677	77.09
0.027	51.95		0.166	75.45		0.699	77.09
0.028	52.51		0.174	75.67		0.721	77.09
0.029	53.17		0.181	75.87		0.742	77.09
0.031	54.01		0.189	76.15		0.766	77.09
0.032	54.93		0.198	76.51		0.792	77.09
0.033	55.80		0.206	76.84		0.816	77.09
0.035	56.48		0.215	77.04		0.842	77.09
0.036	57.02		0.232	77.09		0.869	77.09
0.038	57.61		0.239	77.09		0.897	77.09
0.040	58.21		0.247	77.09		0.928	77.09
0.041	58.74		0.256	77.09		0.956	77.09
0.043	59.33		0.262	77.09		0.985	77.09
0.045	59.88		0.271	77.09		1.017	77.09
0.047	60.20		0.280	77.09		1.051	77.09
0.049	60.42		0.289	77.09		1.081	77.09
0.051	60.67		0.298	77.09		1.120	77.09
0.054	60.83		0.308	77.09		1.154	77.09
0.056	60.87		0.318	77.09		1.192	77.09
0.059	60.90		0.327	77.09		1.232	77.09
						1.267	77.09
						1.313	77.09
						1.354	77.09
						1.398	77.09
						1.433	77.09
						1.484	77.09
						1.538	77.09
						1.579	77.09
						1.638	77.09
						1.688	77.09
						1.742	77.09
						1.801	77.09
						1.845	77.09
						1.916	77.09
						1.969	77.09
						2.026	77.09
						2.088	77.09
						2.157	77.09
						2.232	77.09
						2.317	77.09
						2.363	77.09
						2.463	77.09
						2.519	77.09
						2.641	77.09
						2.710	77.09
						2.784	77.09
						2.865	77.09
						2.953	77.10
						3.050	77.15
						3.157	77.37
						3.276	77.83
						3.410	78.48
						3.562	79.36
						3.736	80.58
						3.938	82.16
						4.176	84.05
						4.465	86.18
						4.823	88.62
						5.283	91.38
						5.906	94.27
						6.820	97.14
						8.353	100.00

NT300 (values in italic are sizes within the water retention range, size is in μm)							
Size	%		Size	%		Size	%
<i>0.011</i>	<i>28.64</i>		<i>0.067</i>	<i>34.73</i>		0.370	47.44
<i>0.011</i>	<i>28.86</i>		<i>0.070</i>	<i>35.07</i>		0.383	47.44
<i>0.012</i>	<i>29.12</i>		<i>0.073</i>	<i>35.45</i>		0.393	47.44
<i>0.012</i>	<i>29.34</i>		<i>0.076</i>	<i>35.83</i>		0.407	47.44
<i>0.013</i>	<i>29.56</i>		<i>0.080</i>	<i>36.21</i>		0.420	47.44
<i>0.013</i>	<i>29.82</i>		<i>0.083</i>	<i>36.59</i>		0.432	47.44
<i>0.014</i>	<i>30.00</i>		<i>0.087</i>	<i>36.97</i>		0.447	47.44
<i>0.015</i>	<i>30.04</i>		<i>0.091</i>	<i>37.34</i>		0.462	47.44
<i>0.015</i>	<i>30.04</i>		<i>0.095</i>	<i>37.71</i>		0.477	47.44
<i>0.016</i>	<i>30.04</i>		<i>0.099</i>	<i>38.13</i>		0.492	47.44
<i>0.017</i>	<i>30.04</i>		<i>0.103</i>	<i>38.65</i>		0.507	47.44
<i>0.017</i>	<i>30.04</i>		<i>0.108</i>	<i>39.19</i>		0.523	47.44
<i>0.018</i>	<i>30.04</i>		<i>0.113</i>	<i>39.66</i>		0.539	47.44
<i>0.019</i>	<i>30.04</i>		<i>0.118</i>	<i>40.23</i>		0.557	47.44
<i>0.020</i>	<i>30.04</i>		<i>0.123</i>	<i>40.91</i>		0.574	47.44
<i>0.021</i>	<i>30.04</i>		<i>0.128</i>	<i>41.49</i>		0.594	47.44
<i>0.022</i>	<i>30.04</i>		<i>0.134</i>	<i>41.90</i>		0.611	47.44
<i>0.023</i>	<i>30.04</i>		<i>0.140</i>	<i>42.24</i>		0.632	47.44
<i>0.024</i>	<i>30.04</i>		<i>0.146</i>	<i>42.58</i>		0.651	47.44
<i>0.025</i>	<i>30.04</i>		<i>0.153</i>	<i>42.88</i>		0.674	47.44
<i>0.026</i>	<i>30.04</i>		<i>0.159</i>	<i>43.08</i>		0.694	47.44
<i>0.027</i>	<i>30.04</i>		<i>0.167</i>	<i>43.27</i>		0.716	47.44
<i>0.028</i>	<i>30.04</i>		<i>0.174</i>	<i>43.52</i>		0.741	47.44
<i>0.029</i>	<i>30.04</i>		<i>0.182</i>	<i>43.89</i>		0.764	47.44
<i>0.031</i>	<i>30.07</i>		<i>0.190</i>	<i>44.39</i>		0.789	47.44
<i>0.032</i>	<i>30.17</i>		<i>0.198</i>	<i>44.91</i>		0.811	47.44
<i>0.033</i>	<i>30.33</i>		<i>0.206</i>	<i>45.38</i>		0.838	47.44
<i>0.035</i>	<i>30.48</i>		<i>0.216</i>	<i>45.93</i>		0.867	47.44
<i>0.036</i>	<i>30.75</i>		<i>0.226</i>	<i>46.60</i>		0.893	47.44
<i>0.038</i>	<i>31.24</i>		<i>0.235</i>	<i>47.14</i>		0.921	47.44
<i>0.040</i>	<i>31.78</i>		<i>0.253</i>	<i>47.39</i>		0.950	47.44
<i>0.041</i>	<i>32.22</i>		<i>0.261</i>	<i>47.44</i>		0.982	47.44
<i>0.043</i>	<i>32.61</i>		<i>0.270</i>	<i>47.44</i>		1.015	47.44
<i>0.045</i>	<i>32.99</i>		<i>0.280</i>	<i>47.44</i>		1.045	47.44
<i>0.047</i>	<i>33.32</i>		<i>0.287</i>	<i>47.44</i>		1.078	47.44
<i>0.049</i>	<i>33.56</i>		<i>0.296</i>	<i>47.44</i>		1.112	47.44
<i>0.052</i>	<i>33.78</i>		<i>0.307</i>	<i>47.44</i>		1.149	47.46
<i>0.054</i>	<i>34.05</i>		<i>0.316</i>	<i>47.44</i>		1.182	47.56
<i>0.056</i>	<i>34.22</i>		<i>0.326</i>	<i>47.44</i>		1.225	47.81
<i>0.059</i>	<i>34.26</i>		<i>0.337</i>	<i>47.44</i>		1.263	48.09
<i>0.061</i>	<i>34.30</i>		<i>0.348</i>	<i>47.44</i>		1.304	48.28
<i>0.064</i>	<i>34.45</i>		<i>0.358</i>	<i>47.44</i>		1.348	48.43
							9.137
							100.00

NT0N (values in <i>italics</i> are sizes within the water retention range, size is in μm)							
Size	%	Size	%	Size	%	Size	%
<i>0.010</i>	<i>26.23</i>	<i>0.061</i>	<i>36.04</i>	0.337	47.22	1.263	47.22
<i>0.010</i>	<i>26.23</i>	<i>0.064</i>	<i>36.23</i>	0.349	47.22	1.309	47.22
<i>0.011</i>	<i>26.23</i>	<i>0.066</i>	<i>36.43</i>	0.358	47.22	1.350	47.22
<i>0.011</i>	<i>26.23</i>	<i>0.069</i>	<i>36.70</i>	0.371	47.22	1.393	47.22
<i>0.012</i>	<i>26.23</i>	<i>0.073</i>	<i>37.03</i>	0.383	47.22	1.429	47.22
<i>0.012</i>	<i>26.23</i>	<i>0.076</i>	<i>37.38</i>	0.394	47.22	1.479	47.22
<i>0.013</i>	<i>26.23</i>	<i>0.079</i>	<i>37.77</i>	0.407	47.22	1.533	47.25
<i>0.013</i>	<i>26.23</i>	<i>0.083</i>	<i>38.31</i>	0.421	47.22	1.574	47.38
<i>0.014</i>	<i>26.23</i>	<i>0.086</i>	<i>38.96</i>	0.434	47.22	1.633	47.71
<i>0.015</i>	<i>26.23</i>	<i>0.090</i>	<i>39.51</i>	0.448	47.22	1.682	48.20
<i>0.015</i>	<i>26.27</i>	<i>0.094</i>	<i>39.96</i>	0.462	47.22	1.736	48.77
<i>0.016</i>	<i>26.41</i>	<i>0.098</i>	<i>40.43</i>	0.476	47.22	1.796	49.47
<i>0.017</i>	<i>26.62</i>	<i>0.103</i>	<i>40.92</i>	0.491	47.22	1.839	50.28
<i>0.017</i>	<i>26.81</i>	<i>0.107</i>	<i>41.30</i>	0.508	47.22	1.910	51.11
<i>0.018</i>	<i>27.01</i>	<i>0.112</i>	<i>41.59</i>	0.523	47.22	1.963	51.91
<i>0.019</i>	<i>27.31</i>	<i>0.117</i>	<i>41.74</i>	0.541	47.22	2.020	52.57
<i>0.020</i>	<i>27.69</i>	<i>0.122</i>	<i>41.81</i>	0.557	47.22	2.082	53.12
<i>0.021</i>	<i>28.17</i>	<i>0.128</i>	<i>41.92</i>	0.576	47.22	2.150	53.61
<i>0.022</i>	<i>28.66</i>	<i>0.133</i>	<i>42.09</i>	0.594	47.22	2.225	54.07
<i>0.022</i>	<i>29.05</i>	<i>0.139</i>	<i>42.20</i>	0.614	47.22	2.309	54.42
<i>0.023</i>	<i>29.40</i>	<i>0.145</i>	<i>42.23</i>	0.633	47.22	2.355	54.70
<i>0.024</i>	<i>29.79</i>	<i>0.152</i>	<i>42.23</i>	0.652	47.22	2.455	55.00
<i>0.026</i>	<i>30.27</i>	<i>0.159</i>	<i>42.23</i>	0.675	47.22	2.511	55.32
<i>0.027</i>	<i>30.76</i>	<i>0.165</i>	<i>42.23</i>	0.696	47.22	2.633	55.60
<i>0.028</i>	<i>31.15</i>	<i>0.173</i>	<i>42.25</i>	0.719	47.22	2.702	55.92
<i>0.029</i>	<i>31.49</i>	<i>0.180</i>	<i>42.32</i>	0.739	47.22	2.776	56.37
<i>0.030</i>	<i>31.83</i>	<i>0.188</i>	<i>42.48</i>	0.764	47.22	2.856	56.91
<i>0.032</i>	<i>32.17</i>	<i>0.197</i>	<i>42.79</i>	0.790	47.22	2.944	57.57
<i>0.033</i>	<i>32.51</i>	<i>0.206</i>	<i>43.33</i>	0.814	47.22	3.040	58.37
<i>0.035</i>	<i>32.81</i>	<i>0.214</i>	<i>44.06</i>	0.839	47.22	3.147	59.35
<i>0.036</i>	<i>33.02</i>	<i>0.225</i>	<i>44.89</i>	0.866	47.22	3.266	60.55
<i>0.038</i>	<i>33.21</i>	<i>0.234</i>	<i>45.82</i>	0.895	47.22	3.399	61.95
<i>0.039</i>	<i>33.49</i>	<i>0.246</i>	<i>46.67</i>	0.925	47.22	3.551	63.63
<i>0.041</i>	<i>33.81</i>	<i>0.255</i>	<i>47.12</i>	0.953	47.22	3.724	65.69
<i>0.043</i>	<i>34.11</i>	<i>0.261</i>	<i>47.22</i>	0.982	47.22	3.925	68.25
<i>0.045</i>	<i>34.32</i>	<i>0.270</i>	<i>47.22</i>	1.014	47.22	4.163	71.42
<i>0.047</i>	<i>34.51</i>	<i>0.280</i>	<i>47.22</i>	1.047	47.22	4.451	75.23
<i>0.049</i>	<i>34.79</i>	<i>0.288</i>	<i>47.22</i>	1.077	47.22	4.807	79.54
<i>0.051</i>	<i>35.11</i>	<i>0.297</i>	<i>47.22</i>	1.116	47.22	5.266	84.26
<i>0.054</i>	<i>35.41</i>	<i>0.307</i>	<i>47.22</i>	1.151	47.22	5.888	89.32
<i>0.056</i>	<i>35.62</i>	<i>0.317</i>	<i>47.22</i>	1.188	47.22	6.799	94.61
<i>0.058</i>	<i>35.81</i>	<i>0.326</i>	<i>47.22</i>	1.228	47.22	8.327	100.00

CT300 (values in <i>italic</i> are sizes within the water retention range, size is in μm)								
Size	%		Size	%		Size	%	
<i>0.010</i>	<i>30.13</i>		<i>0.062</i>	<i>44.42</i>		0.345	61.26	
<i>0.011</i>	<i>30.18</i>		<i>0.065</i>	<i>44.97</i>		0.357	61.26	
<i>0.011</i>	<i>30.36</i>		<i>0.068</i>	<i>45.46</i>		0.366	61.26	
<i>0.011</i>	<i>30.64</i>		<i>0.071</i>	<i>46.00</i>		0.380	61.26	
<i>0.012</i>	<i>30.82</i>		<i>0.074</i>	<i>46.54</i>		0.391	61.26	
<i>0.013</i>	<i>30.87</i>		<i>0.077</i>	<i>47.03</i>		0.403	61.26	
<i>0.013</i>	<i>30.91</i>		<i>0.081</i>	<i>47.56</i>		0.417	61.26	
<i>0.014</i>	<i>31.09</i>		<i>0.085</i>	<i>48.09</i>		0.430	61.26	
<i>0.014</i>	<i>31.36</i>		<i>0.088</i>	<i>48.57</i>		0.444	61.26	
<i>0.015</i>	<i>31.53</i>		<i>0.092</i>	<i>49.14</i>		0.458	61.26	
<i>0.016</i>	<i>31.58</i>		<i>0.096</i>	<i>49.88</i>		0.473	61.26	
<i>0.016</i>	<i>31.62</i>		<i>0.101</i>	<i>50.70</i>		0.487	61.26	
<i>0.017</i>	<i>31.80</i>		<i>0.105</i>	<i>51.51</i>		0.502	61.26	
<i>0.018</i>	<i>32.11</i>		<i>0.110</i>	<i>52.32</i>		0.519	61.26	
<i>0.018</i>	<i>32.53</i>		<i>0.114</i>	<i>53.12</i>		0.535	61.26	
<i>0.019</i>	<i>33.11</i>		<i>0.120</i>	<i>53.91</i>		0.553	61.26	
<i>0.020</i>	<i>33.85</i>		<i>0.125</i>	<i>54.70</i>		0.570	61.26	
<i>0.021</i>	<i>34.64</i>		<i>0.131</i>	<i>55.43</i>		0.589	61.26	
<i>0.022</i>	<i>35.44</i>		<i>0.136</i>	<i>56.01</i>		0.607	61.26	
<i>0.023</i>	<i>36.24</i>		<i>0.142</i>	<i>56.40</i>		0.628	61.26	
<i>0.024</i>	<i>37.03</i>		<i>0.149</i>	<i>56.72</i>		0.647	61.26	
<i>0.025</i>	<i>37.78</i>		<i>0.155</i>	<i>57.03</i>		0.667	61.26	
<i>0.026</i>	<i>38.37</i>		<i>0.162</i>	<i>57.34</i>		0.690	61.26	
<i>0.027</i>	<i>38.80</i>		<i>0.169</i>	<i>57.65</i>		0.712	61.26	
<i>0.029</i>	<i>39.13</i>		<i>0.177</i>	<i>57.98</i>		0.735	61.26	
<i>0.030</i>	<i>39.31</i>		<i>0.184</i>	<i>58.36</i>		0.756	61.26	
<i>0.031</i>	<i>39.36</i>		<i>0.192</i>	<i>58.90</i>		0.781	61.26	
<i>0.033</i>	<i>39.39</i>		<i>0.202</i>	<i>59.63</i>		0.808	61.26	
<i>0.034</i>	<i>39.53</i>		<i>0.210</i>	<i>60.39</i>		0.832	61.26	
<i>0.035</i>	<i>39.74</i>		<i>0.219</i>	<i>60.95</i>		0.858	61.26	
<i>0.037</i>	<i>39.92</i>		<i>0.236</i>	<i>61.21</i>		0.886	61.26	
<i>0.039</i>	<i>40.12</i>		<i>0.243</i>	<i>61.26</i>		0.915	61.26	
<i>0.040</i>	<i>40.43</i>		<i>0.252</i>	<i>61.26</i>		0.946	61.26	
<i>0.042</i>	<i>40.80</i>		<i>0.261</i>	<i>61.26</i>		0.974	61.26	
<i>0.044</i>	<i>41.18</i>		<i>0.267</i>	<i>61.26</i>		1.005	61.26	
<i>0.046</i>	<i>41.56</i>		<i>0.276</i>	<i>61.26</i>		1.037	61.26	
<i>0.048</i>	<i>41.94</i>		<i>0.286</i>	<i>61.26</i>		1.071	61.26	
<i>0.050</i>	<i>42.32</i>		<i>0.294</i>	<i>61.26</i>		1.102	61.26	
<i>0.052</i>	<i>42.70</i>		<i>0.304</i>	<i>61.26</i>		1.141	61.26	
<i>0.055</i>	<i>43.08</i>		<i>0.314</i>	<i>61.26</i>		1.177	61.26	
<i>0.057</i>	<i>43.45</i>		<i>0.324</i>	<i>61.26</i>		1.215	61.26	
<i>0.060</i>	<i>43.88</i>		<i>0.334</i>	<i>61.26</i>		1.256	61.26	
							1.291	61.26
							1.339	61.26
							1.380	61.26
							1.425	61.26
							1.461	61.26
							1.513	61.26
							1.568	61.26
							1.609	61.26
							1.670	61.26
							1.721	61.26
							1.776	61.26
							1.837	61.29
							1.881	61.40
							1.954	61.60
							2.007	61.87
							2.065	62.26
							2.129	62.77
							2.199	63.32
							2.276	63.88
							2.362	64.43
							2.409	64.99
							2.511	65.55
							2.568	66.09
							2.693	66.62
							2.763	67.17
							2.839	67.73
							2.921	68.32
							3.011	69.04
							3.110	69.87
							3.219	70.80
							3.340	71.98
							3.477	73.38
							3.631	74.91
							3.808	76.70
							4.014	78.87
							4.258	81.34
							4.552	84.07
							4.917	87.01
							5.386	90.14
							6.022	93.40
							6.953	96.71
							8.516	100.00

CT0N (values in <i>italics</i> are sizes within the water retention range, size is in μm)							
Size	%	Size	%	Size	%	Size	%
0.010	33.64	0.062	50.06	0.333	65.95	1.252	65.95
0.010	33.64	0.065	50.44	0.344	65.95	1.287	65.95
0.011	33.64	0.068	50.81	0.355	65.95	1.335	65.95
0.011	33.64	0.071	51.18	0.365	65.95	1.376	65.95
0.012	33.64	0.074	51.55	0.378	65.95	1.420	65.95
0.012	33.64	0.077	51.89	0.390	65.95	1.456	65.95
0.013	33.64	0.081	52.12	0.402	65.95	1.508	65.95
0.014	33.64	0.084	52.32	0.415	65.95	1.563	65.95
0.014	33.64	0.088	52.56	0.429	65.95	1.604	65.95
0.015	33.64	0.092	52.76	0.443	65.95	1.665	65.95
0.015	33.64	0.096	53.03	0.457	65.95	1.715	65.95
0.016	33.64	0.100	53.53	0.471	65.95	1.770	65.95
0.017	33.64	0.105	54.11	0.486	65.95	1.831	65.95
0.018	33.64	0.109	54.66	0.501	65.95	1.875	65.95
0.018	33.64	0.114	55.33	0.518	65.95	1.947	65.95
0.019	33.68	0.119	56.18	0.533	65.95	2.001	65.95
0.020	33.84	0.125	57.11	0.551	65.95	2.059	65.95
0.021	34.09	0.130	58.05	0.568	65.95	2.122	65.95
0.022	34.25	0.136	58.98	0.587	65.95	2.192	65.95
0.023	34.34	0.142	59.85	0.605	65.95	2.269	65.95
0.024	34.56	0.148	60.53	0.626	65.95	2.354	65.95
0.025	34.94	0.155	61.05	0.645	65.95	2.401	65.95
0.026	35.38	0.162	61.61	0.665	65.95	2.559	65.95
0.027	35.83	0.169	62.18	0.688	65.95	2.684	65.95
0.028	36.29	0.177	62.70	0.710	65.95	2.754	65.95
0.030	36.74	0.184	63.32	0.733	65.95	2.829	65.95
0.031	37.26	0.192	64.14	0.754	65.95	2.911	65.95
0.032	37.89	0.201	64.98	0.779	65.95	3.001	65.95
0.034	38.53	0.210	65.61	0.805	65.95	3.099	65.95
0.035	39.11	0.218	65.89	0.830	65.95	3.208	65.98
0.037	39.80	0.228	65.95	0.856	65.95	3.329	66.23
0.039	40.67	0.235	65.95	0.883	65.95	3.465	66.97
0.040	41.61	0.242	65.95	0.912	65.95	3.619	68.37
0.042	42.55	0.251	65.95	0.943	65.95	3.796	70.32
0.044	43.49	0.260	65.95	0.971	65.95	4.001	72.73
0.046	44.42	0.267	65.95	1.001	65.95	4.244	75.63
0.048	45.34	0.275	65.95	1.033	65.95	4.537	79.03
0.050	46.26	0.285	65.95	1.068	65.95	4.901	82.86
0.052	47.17	0.293	65.95	1.098	65.95	5.368	86.98
0.055	48.08	0.303	65.95	1.138	65.95	6.002	91.30
0.057	48.93	0.313	65.95	1.173	65.95	6.930	95.68
0.059	49.60	0.323	65.95	1.211	65.95	8.488	100.00

APPENDIX D: WATER RETENTION MEASUREMENTS FOR PORE SIZE DISTRIBUTION DETERMINATION

(Fermilab Soils p. 90, Kentucky Soils, p. 91)

RRD	
W. Potential (MPa)	W. Content (g/g)
1.71	0.2128
3.85	0.1912
6.49	0.1775
9.47	0.1657
12.40	0.1557
19.10	0.1396
29.20	0.1232

5D	
W. Potential (MPa)	W. Content (g/g)
2.04	0.1422
3.23	0.1368
5.60	0.1279
10.40	0.1158
13.00	0.1105
19.90	0.1011
29.50	0.0915

11D	
W. Potential (MPa)	W. Content (g/g)
1.81	0.1336
4.98	0.1206
9.03	0.1099
16.90	0.0965
27.80	0.0866
34.40	0.0813

N3D	
W. Potential (MPa)	W. Content (g/g)
1.13	0.1521
2.08	0.1449
4.96	0.1330
8.56	0.1220
13.10	0.1124
27.90	0.0939
37.40	0.0870

AgD	
W. Potential (MPa)	W. Content (g/g)
1.23	0.0877
2.85	0.0814
5.58	0.0750
9.59	0.0688
17.80	0.0621
32.40	0.0534

NT300	
W. Potential (MPa)	W. Content (g/g)
1.95	0.0887
3.09	0.0817
6.37	0.0752
10.30	0.0690
14.60	0.0645
21.50	0.0594
33.10	0.0527

NT0N	
W. Potential (MPa)	W. Content (g/g)
1.83	0.0829
3.72	0.0770
6.79	0.0708
12.30	0.0635
22.60	0.0542
33.10	0.0504

CT0N	
W. Potential (MPa)	W. Content (g/g)
1.95	0.0822
4.09	0.0769
7.51	0.0703
13.40	0.0633
21.60	0.0568
31.50	0.0516

CT300	
W. Potential (MPa)	W. Content (g/g)
1.61	0.0813
3.91	0.0715
4.42	0.0676
6.97	0.0644
13.20	0.0547
23.60	0.0460

VITA

Jeremy Edward Lawson was born in Huntington, WV on August 28, 1979. He was raised in Branchland, WV and graduated from Guyan Valley High School in 1997. He then attended Marshall University in Huntington, WV where he graduated in May of 2002 with B.S. degrees in Environmental Science and Geology with a minor in Mathematics. In the Spring of 2005 he obtained an M.S. degree in Geology at the University of Tennessee, Knoxville.