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EXTENT OF CAPILLARY RISE IN SANDS AND SILTS

by

Rachel Salim

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
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EXTENT OF CAPILLARY RISE IN SANDS AND SILTS

Rachel Salim, M.S.

Western Michigan University, 2016

The values reported in literature for the height of capillary rise in fine sands, silts, and clays are contradictory. Most of the values were based on mathematical models, which used estimated rather than measured input data. This work measured capillary rise values in laboratory experiments in fine-grained sands and silts.

Two uniform sands with grains 0.35--0.7 mm in diameter and 0.3-0.6 mm in diameter, silt with an average grain size below 40 microns, and 0.35--0.7 mm sand coated with a water-repellant spray were carefully packed into two-inch diameter glass columns. These columns were placed into clear plastic tanks with water levels held constant. The average height of capillary rise was 13.5 cm for the 0.35--0.7 mm sand, 14.85 cm for the 0.3-0.6 mm sand, at least 310 cm for the silt (the capillary rise was limited by the height of the column, 310 cm), and -5.75 cm for the 0.35--0.7 mm water-repellant sand.

All of the tests above were repeated using kerosene instead of water; in two silt columns, the capillary rise of kerosene was 210 cm. This value for kerosene gives a scaled value for water capillary rise of 360 cm. The silt tests took years to reach equilibrium; some columns failed.

Two equations were analyzed to determine if either one may be useful in predicting capillary rise. When analyzed, constants for the surface tension were replaced with actual values, and grain sizes were actually measured. The Polubarinova-Kochina (1952) equation, $h_c = 0.45 ((1 - n) / n) / d_{10}$, where n is the porosity, h_c is the capillary rise and d_{10} is the effective grain diameter (h_c and d_{10} in cm). A better-known equation is $h_c = (2\sigma \cos\lambda) / (\rho_w g R)$, where h_c is the height of

the capillary rise and σ is the surface tension of the fluid. Fetter (1994) uses $R = 0.2 d_{10}$. Both equations predicted capillary rise heights that were smaller than values measured in the laboratory; Fetter's values were larger. Fetter's equation matched the measured values better when his $R = 0.2 d_{10}$ was replaced with $0.1 d_{10}$.

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CHAPTER 1

INTRODUCTION

Literature Review and Background Information

The capillary fringe is the height water rises above the water table in porous media. The water will rise, displacing air until the pressure under the meniscus, which is under tension, is at equilibrium with the gravitational forces pulling the water downward. Knowing the capillary rise in different soils for different fluids is important for many reasons that are discussed toward the end of Chapter 1. Unfortunately, the data on capillary rise and the literature reviewed for this paper show a wide range of estimates for capillary rise, especially capillary rise in fine-grained sediments. This thesis begins by discussing the following topics pertaining to capillary rise: the flaws of the capillary rise testing from the literature, why capillary rise testing is important, the parameters needed to determine capillary rise, previous results using different testing methods, and how soil texture affects the capillary fringe height. Once those topics are discussed, the results from the laboratory tests will be presented with sections focusing on: research goals, materials, methods (packing and wetting the columns), measured data, scaled data, problems, and conclusions.

Importance of Knowing the Capillary Rise

The importance of knowing the capillary rise of a material varies depending on the application and the industry. This manuscript focuses on the importance of capillary rise in soils.

Understanding the capillary rise value for different soils affects various industries such as environmental remediation, construction, and farming.

The capillary fringe zone is an important area of study for biodegradation processes and chemical reactions due to the presence of water, air, and soil (Affek et al., 1998; Sinke et al., 1998). Biodegradation processes and chemical reactions are especially important to the environmental remediation industry. When a site has experienced pollution, clean-up procedures in the saturated zone (below the top of the tension-saturated capillary fringe) and the unsaturated zone (above the capillary fringe) are investigated. Methods appropriate to the type and location of the pollution are then selected and applied. Due to the differences in biological processes and chemical reactions, the capillary fringe should be looked at as its own zone. To do this, the capillary fringe must be defined for the area. In order to define the capillary fringe area the capillary rise must be known for the soil and for any of the fluids involved that have a table (e.g., water table or oil table).

Capillary rise is important in the construction industry. It is necessary to know the rising moisture in building materials (Lockington and Parlange, 2004). A building's foundation may be above the water table but may be within the capillary fringe. Building within the capillary fringe can increase the moisture in a building's foundation, which can lead to mold problems, weakening of the building's structure, and weakening of the building's foundation.

Knowing the capillary rise of the materials used within a building is equally as important as knowing the capillary zone around the building. Every material has a unique capillary rise. For example, fluids will rise in wood creating mold and causing the wood to swell and warp. In areas where water use is common, such as kitchens and bathrooms, materials with a low capillary rise should be selected to prevent damage within those rooms.

Another industry that relies heavily on knowledge of the capillary rise is farming. Knowing the capillary rise for different soils is essential for water irrigation management (Lockington and

Parlange, 2004). Capillary rise can also affect the salinity of soil used for farmland. If the water at the water table is brackish, capillary rise may bring the capillary fringe close enough to the surface to evaporate, leaving salt deposits. This has been a major problem in many parts of the world including the Middle East, Australia and Colorado (Hillel, 2004),

Factors Needed to Determine Capillary Rise

The data on the extent of capillary rise in fine-grained soils is inconsistent throughout the literature. By examining the factors that are used to determine capillary rise, inconsistencies in the data can be minimized. For this study, the factors used to determine capillary rise are the diameter of the capillary tube (representing the diameter of the pores in a soil), the contact angle between the liquid and the surface to which it adheres, the density of the liquid, the viscosity of the liquid, surface tension, and whether or not the capillary surface is hydrophobic, or water repellant. The diameter of the capillary is inversely related to the capillary rise; as one increases, the other decreases. For this reason, the tube diameter has the largest effect on capillary rise. Single tubes were not used in our research; the pore space is used as the tube diameter. The pore space diameter is discussed later as pore size in soils. Pore size is controlled by grain-size distribution of the porous medium, as well as packing. A sand, silt, or clay can be packed to different bulk densities, which along with the grain-size distribution controls the pore-size distribution.

The angle between a liquid and the surface with which it contacts is very important, because this shows how wettable a surface is. The contact angle is the angle at which the liquid contacts a smooth, homogeneous, solid surface (Schwartz, 1980). If the angle is 0 degrees, then the liquid perfectly wets the surface. An angle of 180 degrees would show that no wetting occurred, and the liquid drop remained in a spherical shape resting upon the surface. Wetting must occur for capillary rise to take place. There should be no capillary rise when the wetting

angle is 180 degrees, and in general as the wetting angle approaches zero, the capillary rise height increases. In hydrophobic porous media, with high wetting angles, the capillary rise actually becomes negative. Put in a different way, in hydrophobic media, air is attracted downward by capillary forces, displacing water.

Different surfaces may produce different contact angles for the same liquid. Wolkowa (1934) found that as the moisture content of the surface increases, wetting of the surface also increases. Wladitchensky (1966) proved Wolkowa (1934) by treating the same type of glass plate different ways so there was a different level of moisture on each plate. He also found the surface with the most moisture to have the most wetting, thus a smaller angle of wetting, and the glass that was oven dried (least moisture) to have the least wetting, thus the largest angle of wetting or contact angle. See Table 1.

Table 1.

The Angle of Wetting (degrees, average of 10 replications) (Wladitchensky, 1966)

Glass Plate Ignited	5.3
Glass Plate Oven Dried	37.6
Glass Plate Air Dried	22.4
Glass Plate Saturated Over K ₂ SO ₄	6.9
Glass Plate Wetted In Water	6

To see the importance of the contact angle, see Table 2 in the following section. Even though the contact angle is important to understanding capillary rise, the contact angle is usually assumed to be zero degrees (Hillel, 2004)

How Soil Texture Affects the Capillary Fringe

Capillary rise of water in soils depends primarily upon the soil's particle-size distribution. The main factor that affects capillary rise is the pore size of the soil, which is directly related to

the grain-size distribution of the soil. The larger and more uniform the grain size, the larger the pore size, which is inversely proportional to the capillary rise. The data in the literature review appeared to be more consistent for the larger-grained soils such as coarse- to medium- grained sand. This may be related to data pointing to the widely used Washburn equation (Washburn, 1921) only being accurate for short time periods (which is discussed later). Capillary rise in coarse-grained soils will reach equilibrium in a much shorter time than in fine-grained soils. The finest soils, such as fine-grained silts and clays, take a long time to reach equilibrium and have varying reported values.

Different soils can affect the contact angles of specific liquids. Coarse-grained soils such as sandy soils have a slightly higher contact angle (less wettable) than finer texture soils (Pal and Varade, 1971). Soils treated with a hydrophobic coating have a higher contact angle than untreated soils when water is the liquid wetting them (Pal and Varade, 1971). Table 2 from Pal and Varade (1971) shows the relationship between contact angles and capillary rise for treated and untreated soils. It also shows the relationship for soils with different grain sizes.

Table 2.

Capillary Rise Untreated Soils versus Soils Treated with Hydrophobic Coating

Untreated Soil				Treated Soil With Hydrophobic Coating		
Mesh Size	Capillary rise (cm)	Cos θ	Angle θ (degree)	Capillary rise (cm)	Cos θ	Angle θ (degree)
0-30	11.6	0.466	62.2	10	0.388	67.2
30-50	23.2	0.48	61.3	18.8	0.39	67
50-60	23.2	0.485	61	19.1	0.396	66.7
60-80	26	0.503	59.8	29.3	0.505	66.1
80-100	38.8	0.535	57.6	29.8	0.411	65.7
unsieved	22.7	0.471	59.9	19.2	0.397	66.6

Table 2 also shows the relationship of hydrophobic capillaries or soil pores. If the soil is hydrophobic or treated with a water-repellant substance, the water does not rise as high as in the same soil not treated with the hydrophobic substance. The contact angle is also larger (less wetting) for the hydrophobic soil.

How Capillary Rise Has Been Tested and the Results

According to Lago and Arujo (2001), capillary rise in porous media has been studied extensively since the work of Washburn in 1921. Throughout time, capillary fringe has been defined in many different ways. This may be part of the reason capillary rise data has varied. Some methods were surveyed that were used to quantify capillary rise in soils, including mathematical calculations, laboratory experiments, and field observations.

Equations for Capillary Rise

The Washburn equation and variations of the Washburn equation are the widely used equations to describe and predict capillary rise. The Washburn equation states, “The rate of penetration into a small capillary of radius r is:

$$dl/dt = P (r^2 + 4\epsilon r) / 8\eta l$$

where P is the driving pressure

ϵ the coefficient of slip

and η the fluid's viscosity”

The Washburn equation appears to be a good starting point when predicting the rate of capillary rise, and throughout the literature reviewed appears to be accurate for use in soils in which capillary rise occurs quickly (soil with larger pores like coarse-grained sands).

Even though the equation has been found to be helpful when looking at capillary rise in tubes, applying this equation to soils brings up some problems.

One problem is the equation predicts capillary rise in a single capillary tube, instead of a series of capillary tubes, which is a more accurate model of soil pores. Agapoff (1937) suggested that ordinary capillary laws cannot be applied to soil since it is a system of different capillary and non-capillary pores (Wladitchensky, 1966). Wladitchensky (1966) also found that when watching the soil on a macroscopic level the water does not rise continuously, but has a series of irregular movements as pores suddenly fill with water.

Another problem with the Washburn equation is that it does not appear to be accurate for longer time periods (Lockington and Parlange, 2004; Lago and Araujo, 2001). This is most noticeable when looking at capillary rise predicted by the Washburn equation for fine-grained sediments. Figure 1 from Lu and Lukos (2004) compares two of the main methods

(Terzaghi's vs. Lane and Washburn) for calculating the rate of capillary rise.

The graphs in Figure 1 show the difference in two methods used for calculating capillary rise.

One can see there is considerable difference in the equations by Terzaghi (1943) along with Lane and Washburn (1946). It should be noted that Terzaghi's equation, which is based on Darcy's law and saturated hydraulic conductivity, overestimates the rate of capillary rise rate by around 2 orders of magnitude (Lu and Likos, 2004) This is a noticeable difference.

One of the widely used sources for hydrogeology students and professionals is the late C. W. Fetter's Applied Hydrogeology textbook. Table 3 came from his 3rd edition.

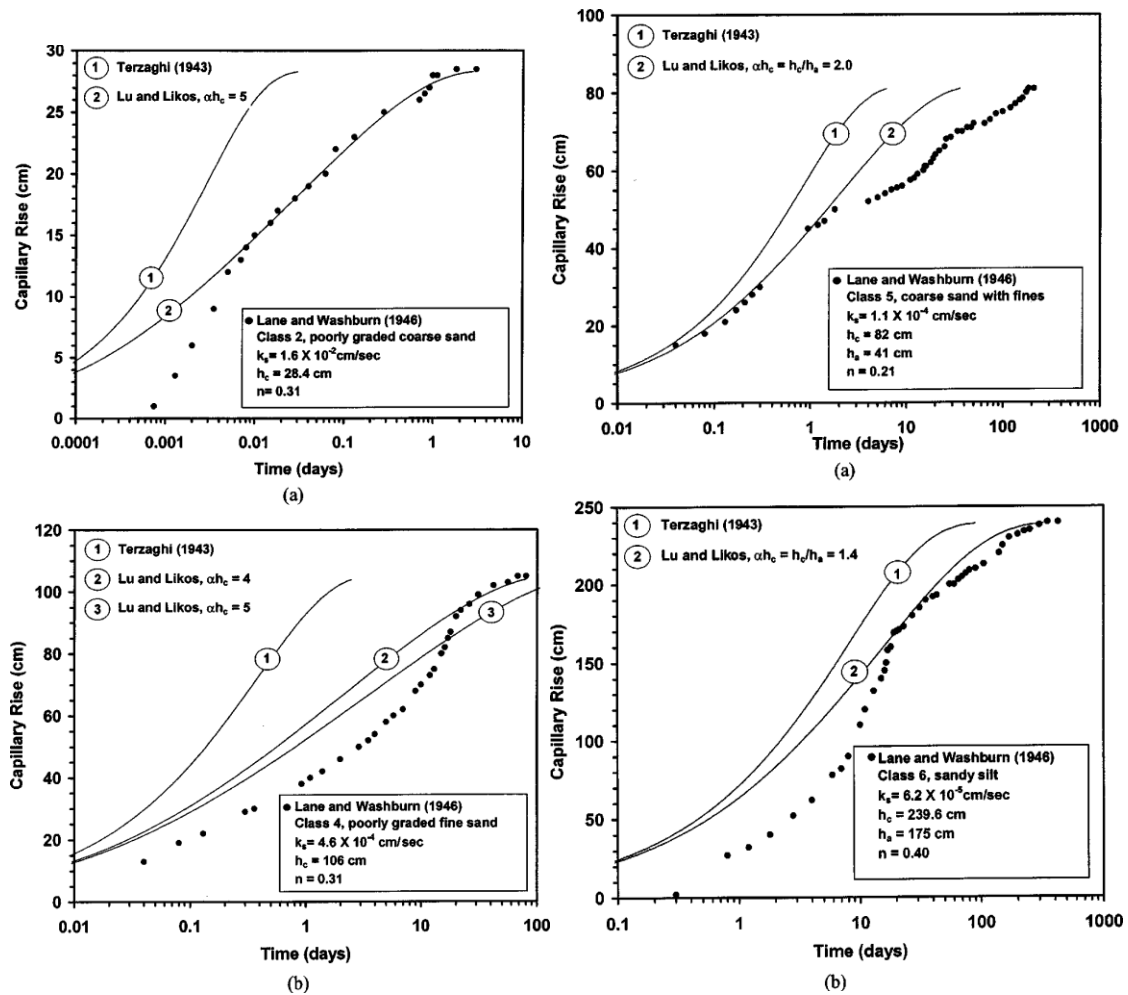


Figure 1. Comparison of Terzaghi's solution, experimental data from Lane and Washburn (1946) on (a, left) well-sorted coarse sand, (a, right) coarse sand with fines, and (b, left) well-sorted fine sand, (b, right) sandy silt data and the Lu and Lukos (2004) analytical solution.

Table 3.

Height of Capillary Rise in Sediments, Fetter (1994)

Sediment	Uniform Grain Diameter (cm)	Pore Radius (cm)	Capillary Rise (cm)
Fine silt	0.0008	0.0002	750
Coarse silt	0.0025	0.0005	300
Very fine sand	0.0075	0.0015	100
Fine sand	0.0150	0.003	50
Medium sand	0.03	0.006	25
Coarse sand	0.05	0.010	15
Very coarse sand	0.20	0.040	4
Fine gravel	0.50	0.100	1.5

Table 3 was developed using a mathematical model. The values for the coarse grains appear to be reasonable, according to Dr. Duane Hampton who observed similar values in laboratory sand tank studies, and to take the least amount of time for the capillary rise to reach equilibrium (which should occur within hours). The values for fine silt appear to be unbelievably large, 7.5 meters, according to Dr. Hampton. The fine silt takes the longest time for capillary rise to reach equilibrium (which which may take years).

The capillary rise equation in Fetter 3rd edition pg. 181, 1994, is:

$$h_c = (2\sigma \cos\lambda)/(\rho_w g R)$$

h_c is the height of the capillary rise (L; cm or mm)

σ is the surface tension of the fluid (M/T² ; g/s² or kg/s²)

λ is the contact angle of the fluid meniscus with the capillary tube wall (degrees)

ρ_w is the density of the fluid (M/L³ ; g/cm³ or kg/m³)

g is the acceleration of gravity (L/T² ; cm/s² or m/s²), a known constant

R is the radius of the capillary tube (L; cm or m)

Fetter (1994) suggests that “with cubic packing of spherical grains of equal diameter, it can be shown that the radius of the pore throats is equal to 0.2 times the grain diameter”. That is the basis for the values in Table 3. Since silt-sized particles are often not spherical, perhaps that is why the numbers for capillary rise appeared to be too large.

When Dr. Hampton contacted C. W. Fetter about the high values of capillary rise for fine-grained sands and silts in Table 3 (“Table 6.1 in his 3rd edition), Fetter accepted that the numbers did seem high. He left the entire section out of his 4th and final edition. The fourth edition now has less information on capillary rise, and if a person needs this information s/he must look elsewhere, or uses the questionable third edition data.

Adamski et al. (2005, pg 103) used the above equation with a different assumption for the value of R , “using the soil particle size analysis data to approximate the size of an average pore

radius of the soil matrix (d_{10} and $1/5 d_{10}$)". It is unclear what they mean by this. They cited Bear (1972) as the source of this assumption, but a close examination of Bear (1972) does not support this as being the source. Their assumption of $R = 0.2 d_{10}$ leads to even higher values of capillary rise as shown in Table 4, if one also assumes that $d_{10} = d_{50}/4$. That assumption for d_{10} is not true for many soils, but is a better assumption than $d_{10} = d_{50}$.

Table 4.

Capillary Rise Partially Based on Adamski et al.'s (2005) Calculations

Sediment	Average Grain Diameter (cm)	Representative d_{10} (cm)	Pore Radius $=d_{10}/5$ (cm)	Capillary Rise (cm)
Fine silt	0.0008	0.0002	0.00004	3750
Coarse silt	0.0025	0.00063	0.00013	1154
Very fine sand	0.0075	0.0019	0.00037	405
Fine sand	0.0150	0.00375	0.00075	200
Medium sand	0.03	0.0075	0.0015	100
Coarse sand	0.05	0.0125	0.0025	60
Very coarse sand	0.20	0.050	0.010	15
Fine gravel	0.50	0.125	0.025	6

According to Hillel (2004), the equation relating the equilibrium height of capillary rise to the radii of the pores is:

$$h_c = (2\gamma \cos \alpha) / g(\rho_l - \rho_g) r$$

For water and air, this equation can be simplified to:

$$h_c = (2\gamma \cos \alpha) / r\rho_w g$$

ρ_g is the density of gas

ρ_l is the density of the liquid

g is the acceleration of gravity

r is the capillary radius, α is the contact angle

γ is the surface tension This equation is used for rise of water in a glass capillary tube. However, its application to capillary rise in soils is not so clear-cut. One reason is the pores in soil are not

perfectly uniform. Also, as described earlier, each pore represents a different capillary tube, meaning the rise will be different in a lab compared to in the field. It is difficult if not impossible to get the pores to be uniform even in controlled laboratory experiments. Due to the soil being complex with different pores, and not being packed evenly, it is very hard to predict capillary rise in soils. It should be expected that a mathematical model will fail to make accurate predictions for longer periods. It is very hard to make predictions using this method and to take into account all the variables that may occur over time, so the longer the time, the less accurate the prediction. Figure 2 is a graph comparing some of the major mathematical models to show the differences in predictions.

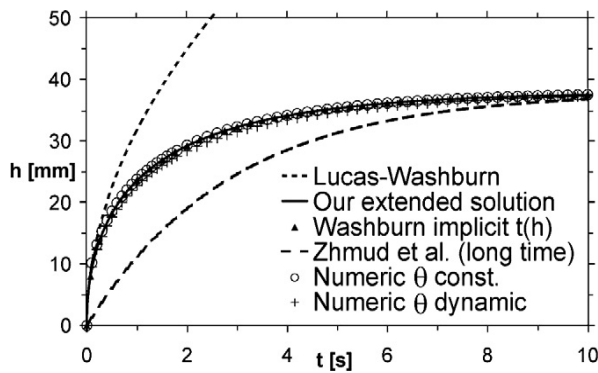


Figure 2. Diagram showing the different solutions for rise of silicon fluid 0.93 in. a 0.1-mm radius borosilicate glass capillary. Height h is plotted versus time t . (Fries and Dreyer, 2008)

Laboratory Measurements of Capillary Rise

Laboratory experiments simulating processes that occur in the field are one way to test capillary rise. The lab experiments appear to be more accurate than mathematical models. One reason for this is they do not make as many assumptions as some of the mathematical equations. Laboratory experiments appear to give more accurate data for longer time periods, unlike mathematical models.

Many of the papers reviewed above conducted laboratory experiments to test capillary rise in a variety of different soils and liquids. Each paper has its own approach to how the experiments are set up, but there are some common techniques.

For many experiments a specific grain size for a specific material such as glass beads is packed in a certain way that limits the angles in the pore space. A water table is created in the system and capillary rise is watched throughout the system. This is then repeated different ways such as adjusting the grain size, material of the grain, liquids used, or packing of the grains. These are changed depending on what the researcher is looking for. The setup usually looks similar to the following (Figure 3).

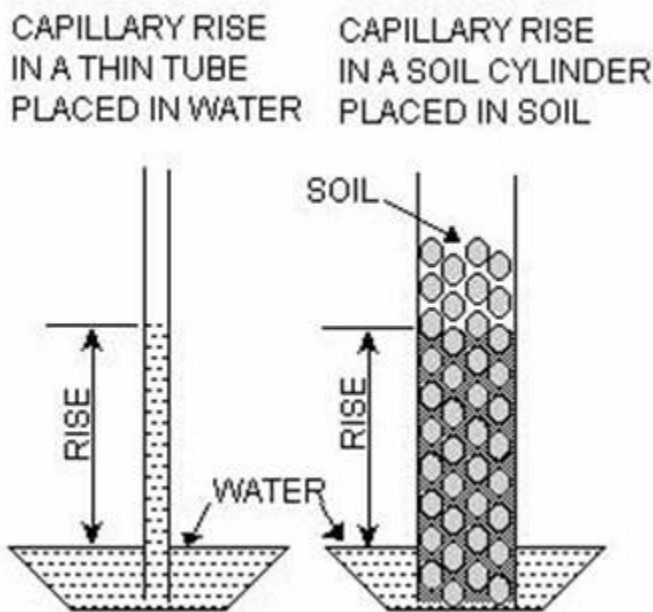


Figure 3. Basic diagram of capillary rise.

Many different laboratory methods were used in the papers reviewed. Their methods are not detailed here, but the papers are cited for those interested in the ways the researchers conducted their laboratory experiments.

Even though the laboratory experiments give good data on how capillary rise can be affected by adjusting the parameters of the experiment, it is rare in the field setting to find the perfect conditions that are used in a laboratory setting. In the field, there are many interactions that affect capillary rise in soils. Some of these include variations in soil grain size and packing, presence of organic matter, coatings on soil particles, and history of past water level fluctuations.

Field Measurements of Capillary Rise

Another way to find capillary rise is to take samples in the field. This is one of the most difficult ways to determine capillary rise, but only by studying capillary rise in the field will one be able to see if the other methods described above can be applicable to the field. It is very difficult if not impossible to get an undisturbed sample from a field soil. Ronen et al. (2000) showed this by using a Geoprobe and carefully extracting samples. Table 5 shows some of the published values for capillary rise in different soils.

Table 5.

Range of Values Found for Capillary Rise in Different Soils

Soil texture	Capillary rise (in cm)
coarse (sand)	20 to 50 cm
medium	50 to 80 cm
fine (clay)	more than 80 cm up to several meters

(Food and Agriculture Organization of the United Nations) Natural Resources Management and Environment Department, 1985)

Conclusions

The capillary fringe is a very important zone that everything must travel through before reaching the water table. Even though it is very important to know the capillary rise and capillary

fringe height in soils, it tends either to be completely ignored or to be given an inaccurate value. Almost 100 years after Washburn's breakthrough capillary-rise testing, there is still much improvement needed in predicting and calculating capillary rise. The equations many people use do not take into account all of the important parameters and use assumptions that may not be accurate.

This review has shown some of the important parameters that need to be taken into account when studying capillary rise in soils, how capillary rise has been tested, and the results from the methods used, and how different soils with a strong emphasis on fine-grained sediments affect the capillary fringe. Many articles were used to point out problems with some of the methods reviewed, and to be a starting point for setting up more laboratory and field testing.

CHAPTER 2

LABORATORY TESTING OF CAPILLARY RISE IN SANDS AND SILTS

Research Goals

The first goal is to measure capillary rise of water and kerosene in medium sand, fine sand, and silt, as well as the capillary depression of water in hydrophobic sand. The principal goal is to identify equations for calculating capillary rise that come close to measured values. The primary focus is on the equation Fetter used, as well as the Polubarinova-Kochina (1952) (P-K) equation which is:

$$h_c = 0.45 ((1 - n) / n) / d_{10}$$

n = porosity

h_c = capillary rise in cm

d_{10} = effective grain diameter in cm

Materials

Materials List: 4 Plexiglas boxes, 4 glass columns with stop cocks and bases, 3 glass column extensions, 3 connectors, purified water, tap water, silica flour, sands, funnel and tube, color changing candy, camera w/ video recording, water repellent spray, denatured ethanol, bungee cords, particulate filtering face masks, Mettler scale, measuring sticks, nitrile gloves, kerosene, air vents, foil lids, threaded Teflon stopper, and sieves.

Four Plexiglas boxes were made to hold water and glass columns for laboratory tests (see Materials Figures 1 & 2 in Appendix A). Three boxes were made by the same craftsman; the

measurements of the boxes are 20 x 33 x 33 cm. The other box was made previously, but appears to be made with the same materials. This box is slightly smaller at 17 x 32 x 32 cm.

Four glass columns were made by Frank Meints (Materials Figures 3 & 4) of Meints Glass Blowing at 436 N Park St #119, Kalamazoo, MI, 49007. He currently makes glassware for Pfizer, Western Michigan University Chemistry Department, Physics Department, and Geology Department, as well as the public.

The glass columns were originally made to 121.9 cm (4ft) in height, 5 cm in diameter; their weights are listed in Table 6.

Table 6.

Original Glass Tube Weights

	kg	Lbs.
1	3.02	6.659
2	3.01	6.640
3	2.90	6.387
4	3.00	6.607

(Weight of glass tubes used for laboratory testing)

The differences in weight may be due to the bases of the columns. The columns appeared to be uniform, but the bases were different in diameter and thickness.

The glass columns were extended, due to some of the laboratory tests extending at least to the top if not past the 121.92 cm tubes. Three columns, 1, 2, and 3, were brought back to Frank Meints to have their tops threaded, so extensions could be screwed on and added to the top to extend the length of the columns. Three extensions were made, two 121.92 cm (4 ft.) and one 60.96 cm (2 ft.), to screw on the glass columns. (Materials Figures 5 & 6) The extended tubes

came with three connectors (Materials Figures 7 & 8 and three lids (Materials Figures 9 & 10). The lids help to keep evaporation down, but had either a small hole or were able to vent out. This was done so pressure wouldn't build up in the columns.

One shorter glass tube was made in January 2014. It was made to use for sand for which extended height was not necessary. It is beneficial to have a smaller tube for space and cost reasons.

City water was used in the first few experiments of capillary rise. The water used in the practice tests was city tap water taken from the sink in the lab. When this water was used in practice tests, one week into the test algae grew in the columns with silt. The algae may affect the capillary rise in the laboratory tests. To solve the algae growth issue, Glacier Water Island (www.glacierwater.com) was then bought from Harding's Grocery Store. According to the website, this water is city water that is filtered with carbon and micron-scale filters, reverse osmosis membrane, and UV treated. (see Materials Figure 11 in Appendix A) The treated water has worked in preventing the growth of algae during testing.

City tap water was used to rinse the tubes after each experiment. Water was flushed through the tubes to get out excess sand and or silt from the tubes.

Five 50 pound bags of 200 mesh silica flour were ordered from Soil Moisture Equipment (materials document 1 for order form and 2 for grain size analysis) (see Materials Figures 12, 13, 14, 15, & 16 in Appendix A). The silica flour is made up of ground silica. It has a texture that looked similar to baking flour.

Four 50 pound bags of 0.45—0.55 mm sand were ordered (see Materials Figures 17, 18, & 19 in Appendix A). The Aqua Quartz pool filter sand bag states that the contents of the bag are thoroughly washed and graded and the particles are closely sized. The sand was all of a similar light color (mostly white) with round grains of similar size. The sand grain-size analysis conducted shows the sand to be between 0.4-0.7 mm. This sand was used for testing capillary

rise, and capillary depression in hydrophobic sand. The hydrophobic sand was treated with a water-repellant spray, Kiwi Camp Dry (see Materials Figures 22 & 23 in Appendix A), to make the sand water repellent. The untreated sand was also used to mix with the silt to help provide more stability and to prevent large cracks leading to the silt collapsing in intervals.

A slightly-finer sand, which analysis showed to be between 0.3-0.7 mm, was also used. This sand, like the sand described previously, came in 50 pound bags. It also had light colored (mostly white), rounded sand grains, which were of similar size.

A funnel with an attached PVC tube was used to attempt to pack the silt and sand evenly. (see Materials Figures 20 & 21 in Appendix A). The funnel helps get the sand and silt into the tubes. The 2 cm diameter tube attached to the bottom of the funnel is steadily moved inside the column in a circular pattern to pack the sand and silt as evenly as possible. It should be noted that while this packing method has worked, there were concerns with packing the silt evenly, and the sand appeared to have layers.

Denatured ethanol was used to clean out the glass tubes and Plexiglas boxes after water repellent spray was used. After each of the first few tests, tap water was used for cleaning when the sand was sprayed with water repellent spray. Bubbles of air were noticeable covering the glass and Plexiglas during the beginning tests. It became apparent that water was not removing all traces of the water-repellant treatment. The columns and boxes were rinsed and scrubbed with denatured ethanol to remove the water repellent spray. When using the denatured ethanol, the columns and boxes were taken outside to ensure proper ventilation. Bungee cords were used to help keep glass tubes from falling.

A color-changing candy powder was mixed into the silt for early tests to help see the capillary rise more clearly. This was very useful for photos and videos, in which the rise and patterns of travel for the water were more evident. The candy is a powder that is made of sugar, corn syrup, buffered lactic acid, natural and artificial flavors, titanium dioxide, blue 1, yellow 5

lake, and blue 1 lake. Since this candy is mostly sugar which dissolves in water, the grain size of this candy should not affect the capillary rise. It should be noted that even though this is true, the rise was slightly higher than that observed in tests without the color-changing candy.

Two different cameras with video capability were used. The two cameras were used together in some instances to capture video from two different angles of capillary rise flow patterns simultaneously. The main camera used was a 12 megapixel Panasonic camera with micro photo capability and HD video recording. This camera suffered some damage due to silt getting into it, and the backup camera was a 5 megapixel iPhone 4 camera with video recording capabilities.

Particulate masks were used when pouring, mixing, or dumping silica flour. These masks were used to prevent the silica flour from being inhaled. When silica flour gets inhaled it can cause trouble breathing or silicosis. (See Materials Figure 24 in Appendix A)

A Mettler scale supplied and calibrated by the State of Michigan Department of Agriculture Weights and Measures section was used to measure mass for density calculations. (See Materials Figure 25 in Appendix A).

Measuring sticks in inches/feet and centimeters/meters were used. All measurements in inches/feet were converted to centimeters for consistency.

When mixing the sand/silt mixture, Nitrile gloves were used so moisture from researchers' hands would not affect the experiments. The gloves were also used to protect skin exposure from kerosene.

Kerosene was purchased from a motor fuel retail outlet for testing capillary rise of kerosene. A dyed kerosene used for off road was the type of kerosene used. However, the kerosene appeared clear, not dyed. A fuel was chosen to measure capillary rise of fuel in fine-grained sand and silt. This study was done because the reported capillary rise numbers for fuels appeared to be considerably higher than expected (Adamski et al., 2005), and there are many

leaking underground storage tanks. Kerosene was chosen for laboratory experiments over gasoline as a safety precaution due to the high flammability of gasoline fumes. Kerosene was also chosen over diesel due to the strong odor of diesel fuel and how hard it can be to clean off equipment.

Foil lids were made to put over the Plexiglas boxes to use when kerosene experiments were underway, so the fumes of the kerosene could be minimized. These lids had a hole in the middle for the glass columns to fit through. Then duct tape was used to cover the small air spaces and to hold the lids in place (see Materials Figure 26 in Appendix A).

A vent pipe was placed next to the kerosene experiments and turned on to help with extra ventilation. This allowed the fumes from the kerosene to escape. .

A sieve shaker machine (Ro-Tap) was used to shake the sieves in the sand analysis for the proper time (5 minutes) at a constant standardized amount. This was used to check the grain size to verify the size printed on the bag.

Methods

The basic set up for measuring capillary rise in the sand and silts of different grain sizes is as follows: 4 ft. tall glass tubes with optional 2 and 4 ft. Extension tubes, all 5 cm in diameter, were weighed empty, then filled with the sediment (sand, silt, or hydrophobic sand) and weighed full before the experiment started. They were then placed standing upright in a Plexiglas bucket filled with liquid (water or kerosene). The liquid was maintained at a fairly constant level (usually 5 inches of liquid, but this varied on certain tests). The test was left for a while and watched to verify that rise was no longer occurring, that the equilibrium value had been attained.

Measurements were taken by visually looking for the line between damp and dry. To verify the final capillary rise measurements, when the tubes are carefully emptied, the dry sediment falls out easily, and one can accurately measure the damp or wet sediment remaining in the column. For

most tests the visual measurement and measurement of remaining sediment were the same (see Materials section for more detailed description of the materials mentioned).

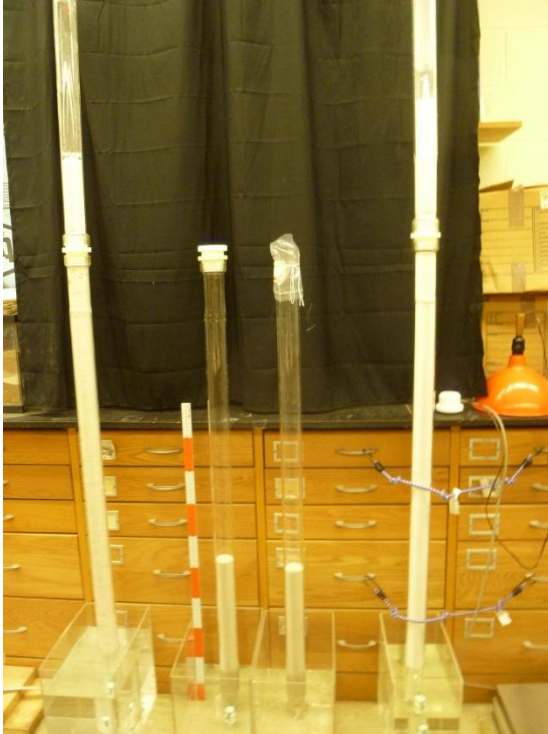


Figure 4. Laboratory setup with all 4 tubes and testing underway.

To pour the sediment we used a funnel with an attached PVC tube. The designated sediment was picked up with a scoop and slowly poured into the funnel. The goal was to pour at a constant rate. The sediment fell through the glass column (column of air). In a few tests, attempts were made to try to pack the columns more tightly by tamping the sediment or agitating it to pack tighter. Density was calculated in each of the experiments to account for the differences in packing. Figure 4 above shows all four tubes with different water tests underway and the laboratory set up.

Figure 5 below shows the set up and packing of the two connected columns for a capillary rise in silt test.



Figure 5. Filling silt column with 2 attached tubes.

CHAPTER 3
LABORATORY RESULTS
Measured Data

Surface Tension

Surface tension values were measured using a surface tensiometer. Table 7 shows the measured values:

Table 7.

Surface Tensions of Wetting Liquids

Date	8/7/2012	8/8/2012	1/28/2014
	G(mN/m)	G(mN/m)	G(mN/m)
Purified Water	72.4	68.8	67.2
Water used in silt testing	54.8	50.6	45.1
Kerosene	25.7	26.1	26.7
Soapy water	24.6		

The values from 8/7/2012 are slightly different from 8/8/2012. The values from 8/7/2012 are being used in our calculations. The reason for these differences might be because the platinum plate used by the tensiometer to measure surface tensions is difficult to clean. The plate appeared to be cleaned more thoroughly on 8/7/2012 than 8/8/2012, when proper cleaning techniques may not have been used.

Kerosene Density

The weights and volumes of kerosene in a graduated cylinder were measured as it was filled with kerosene. The values were entered into the table (see Table 8) and then graphed. Using the inverse of the slope value from the Table 8 we found kerosene density to be 0.8003 g/ml (see figure 6).

Table 8.

Kerosene Density

Volume (ml)	Weight (g)
25	20.41
50	39.91
75	60.33
100	80.29

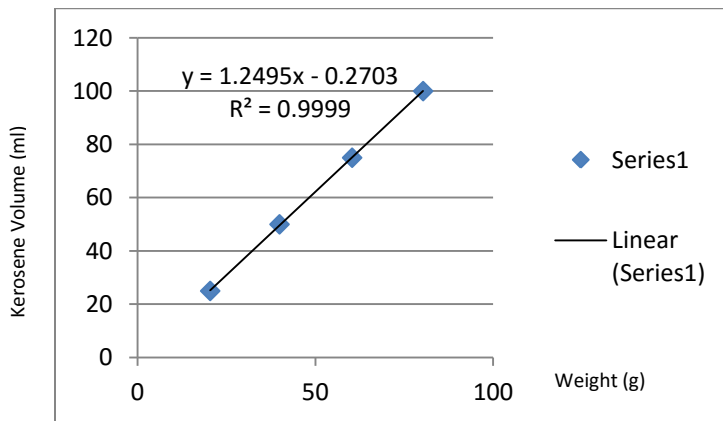


Figure 6. Kerosene density slope.

Sand Analysis

A grain size analysis was conducted to figure out the particle-size distribution for the fine sands being used. The sand bag for Sand #1 (the coarser fine sand) stated the sand grain size was

0.45-0.55 mm. Even though this number may be correct, there are two reasons it was important to still do a sand analysis. One reason is to verify the sand actually was the grain size the bag stated. The other reason was to find the sand grain size that was smaller than 90% of the fine sand to use in the Polubarinova-Kochina (1952) equation.

To conduct the sand grain-size analysis, samples from both types of fine sands were collected on 1/29/2013. The two sand types were poured into separate jars. Jar #1, with the coarser of the two fine sands, and Jar #2, with the finer of the two fine sands. The sands were brought to a soils laboratory in Wood Hall on Western Michigan University's campus. Then the sands were weighed individually and set aside. Different size sieves were chosen to conduct a grain-size analysis. The sieves were cleaned, weighed, and recorded. The sand from Jar #1 was added to its stack of sieves and placed in the sieve shaker for five minutes. The sieves were taken apart one by one and weighed individually. The data was then recorded. The amounts recovered were added up to verify that most of the sand was accounted for. These steps were repeated for Jar #2.

The grain-size analysis was done on 2/1/2013 with sieves 20 to 80 (see Tables 9 & 10 below). All of the steps described above were followed.

Table 9.

Jar #1 Medium Sand 2/1/2013

US Sieve #	mm	A Pan Tare Weight (g)	B Pan with Sand (g)	B – A Sand weight on pan (g)	Percent of total %	Cumulative weight %	Just sand measured (g)
20	0.84	459.66	461.07	1.43	0.24	0.24	1.46
25	0.70 7	453.3	468.22	14.92	2.5	2.74	14.52
30	0.59 5	601.93	769.51	167.58	28.12	30.86	167.18
35	0.50	376.01	668.22	292.21	49.03	79.89	292.22
40	0.42	418.68	420.39	1.71	0.29	80.18	1.72
45	0.35 4	419.54	534.55	115.01	19.29	99.47	115.08
50	0.29 7	405.88	407.89	2.01	0.33	99.8	2.01
60	0.25	347.45	348.21	0.76	0.13	99.93	0.77
70	0.21	396.25	396.37	0.12	0.02	99.95	0.09
80	0.17 7	498.5	498.57	0.07	0.012	99.96	0.02
Pan		360.85	360.96	0.11	0.02	99.98	0.09
Totals				595.93			595.22

The beginning weight of the sand was 596.51 g. 595.93 g was recovered using the previous method with a recovery of 99.90%. The measured sand was the amount of sand poured out of each pan and weighed individually by pan. This amount recovered was 595.22 g, or 99.78% recovery.

For Jar #1 the sand size was found to be between 0.35--0.7 mm. The sand bag states the sand is 0.45--0.55 mm.

Table 10.

Jar #2 Finer Sand 2/1/2013 Chart

US Sieve #	mm	A Pan Tare Weight (g)	B Pan with Sand (g)	B – A Sand weight on pan (g)	Percent of total	Cumulative weight %	Just sand measured (g)
20	0.84	459.76	459.71	-0.05	0	0	0
25	0.707	453.23	453.35	0.12	0.02	0.2	0.06
30	0.595	501.81	613.91	11.21	2.2	2.22	11.92
35	0.50	374.55	526.66	152.11	29.9	32.12	150.44
40	0.42	418.58	444.07	25.49	5.01	37.13	25.39
45	0.354	419.42	690.62	271.2	53.3	90.43	271.09
50	0.297	405.88	430.28	24.4	4.7	95.13	24.4
60	0.25	347.42	364.32	16.9	3.3	98.43	16.9
70	0.21	396.25	400.78	4.53	0.89	99.32	4.52
80	0.177	498.54	499.52	0.98	0.19	99.51	1
Pan		360.85	362.69	1.84	0.36	99.87	1.81
Totals				508.78			507.44

For Jar #2 (Table 10) the sand size was found to be between 0.3-0.6 mm. The beginning weight of the sand was 509.70 g, and 508.78 g was recovered using the pan weight with sand minus pan weight. This created a recovery of 99.81%. The measured sand was the sand poured out of each pan and weighed individually by pan. The amount recovered was 507.44 g with a recovery of 99.55%. The smaller amount recovered by this method may have been due to some of the sand grains sticking in the pans and not being weighed. All further calculations were done using the numbers from the 508.78 column.

The sand analysis done on 2/1/2013 gave enough data that the data could be plotted on a sand analysis graph by Johnson Screens (Johnson Filtration Systems Inc.) (see Sand Analysis figures 7 & 8). The data was plotted on the graphs to find the d_{10} . This is the 10% of the finest sand. According to the Polubarinova-Kochina (1952):

$h_c = 0.45 ((1 - n) / n) / d_{10}$, with h_c and d_{10} in cm (d_{10} is the effective particle diameter).

According to Polubarinova-Kochina the d_{10} will largely determine the capillary rise.

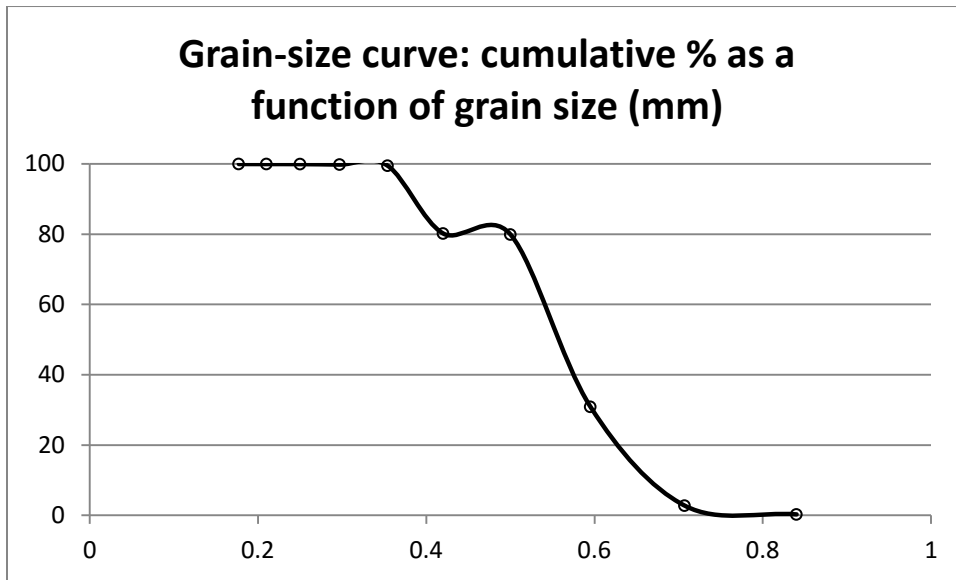


Figure 7. Sand analysis for medium sand from Jar A.

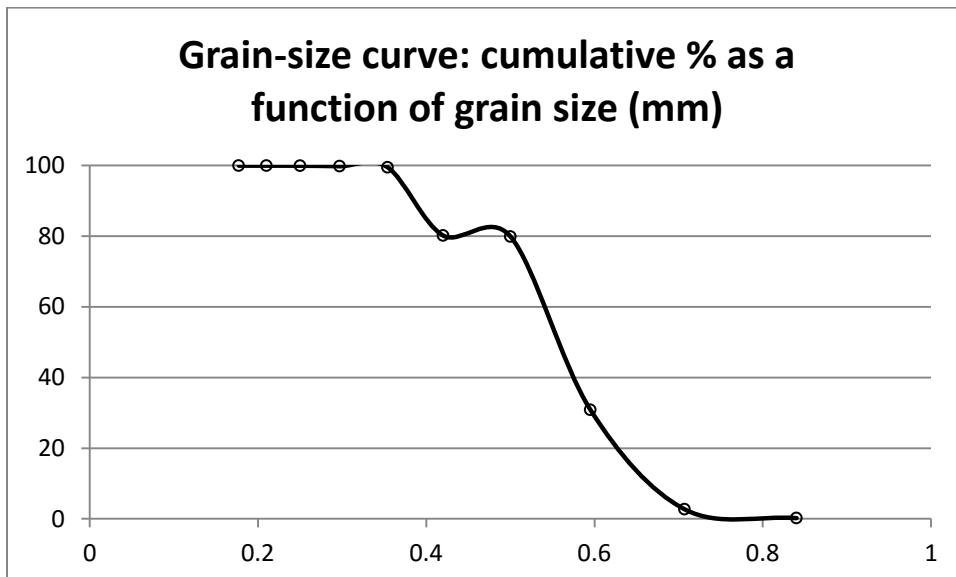


Figure 8. Sand analysis for finer sand from Jar B.

The d_{10} for medium sand was 0.0457cm

The d_{10} for the finer sand was 0.0355cm

Silt analysis

The silt was too fine to determine its grain size by sieving. The vendor of the silt provided a grain-size analysis (see materials documents) which stated that 88% passes through a (45 micron) 325 sieve, so we assumed $d_{10} = 90\%$ retained = 40 microns = 0.004 cm.

The d_{10} for silt is approximately 0.004 cm.

Actual Capillary Rise Values

Table 11 shows the difficulties of testing the silt/sand mixture; these difficulties are discussed in Chapter 4 Discussions. The test ran from 4/10/2013-7/10/2013, and went to the top at 225 cm, which gave 212 cm of rise. Since the test went to the top, changes had to be made to the test. On 11/26/2013 a slightly different method to fill the columns and calculate silt/sand density was used. The rate of rise 1 month after the test started was also looked at.

This test used a 4 ft glass column, a 4 ft extension, and a 2 ft. extension. This is the highest column that can be built in this laboratory. This column had to be filled in place and could not be moved due to its height. See figure 9 for images of the set up. The 4ft column was filled and used for density calculations; then the 4ft and 2ft extensions were filled in place and not weighed for their density calculations. Density is assumed to be the same as the previous section due to the same mixture of sand/silt and method of filling the tubes were used. Density is calculated as follows:

2.848 kg glass column

7.374 kg Glass columns with silt sand mixture

7.374 kg -- 2.848 kg = 4.526 kg silt/sand

142 cm height of silt/sand

5 cm inside diameter of glass tube

Density = Mass/Volume

Volume = πr^2 height

Volume of silt/sand = $3.1415 \times 2.5 \text{ cm} \times 2.5 \text{ cm} \times 142 \text{ cm} = 2,788 \text{ cm}^3$

Density of silt/sand = $4526 \text{ g} / 2788 \text{ cm}^3 = 1.62 \text{ g/cm}^3$

Table 11.

Capillary Rise of Water in Silt Columns

Density	Date started	Date ended	Material used Silt/Sand	Total rise (cm)
1.59			50/50	unknown
1.54	2/5/12	3/1/12	50/50	132.08
	2/16/12	3/3/12	50/50	129.54
1.56	3/5/12	3/22/12	50/50	unknown
	3/15/12	4/8/12	50/50	unknown
1.6	4/2/12	4/20/12	50/50	129.8
	4/27/12	5/16/12	50/50	unknown
	5/8/12	5/16/12	50/50	unknown
1.75	7/3/12	7/31/12	50/50 tamped	
1.76	3/5/13	4/2/13	25/75	100
	4/10/13	7/10/13	33/66	225 top
	9/3/13	9/17/13	33/66	failed
1.62	11/26/13	09/02/15	33/66	310 top



Figure 9. Filling in place the 10 ft column with 1/3 silt, 2/3 sand to be used with water.

Table 12.

Capillary Rise of Kerosene in Silt Columns (1/3 silt, 2/3 Sand)

Density	Date began	Date ended	Capillary rise
	6/21/12	7/24/12	132.08
1.63	8/21/12	9/25/12	135
	8/27/13	03/15/2016	213

The silt in kerosene test from 8/27/2013 to 03/15/2016 from table 12 was also used to study the rate of capillary rise in our tests. As mentioned above, our goal was to measure the extent of capillary rise, not the rate of rise. The rate of rise may be useful to determine where the capillary rise may be at a given time when the line may be hard to see. It also may be useful in planning how much time a test may take from start to finish for future tests. Figure 10 shows the measurements taken for the silt kerosene test that began on 8/27/2013 (these measurements are the total rise – the level of kerosene in clear box = capillary rise).

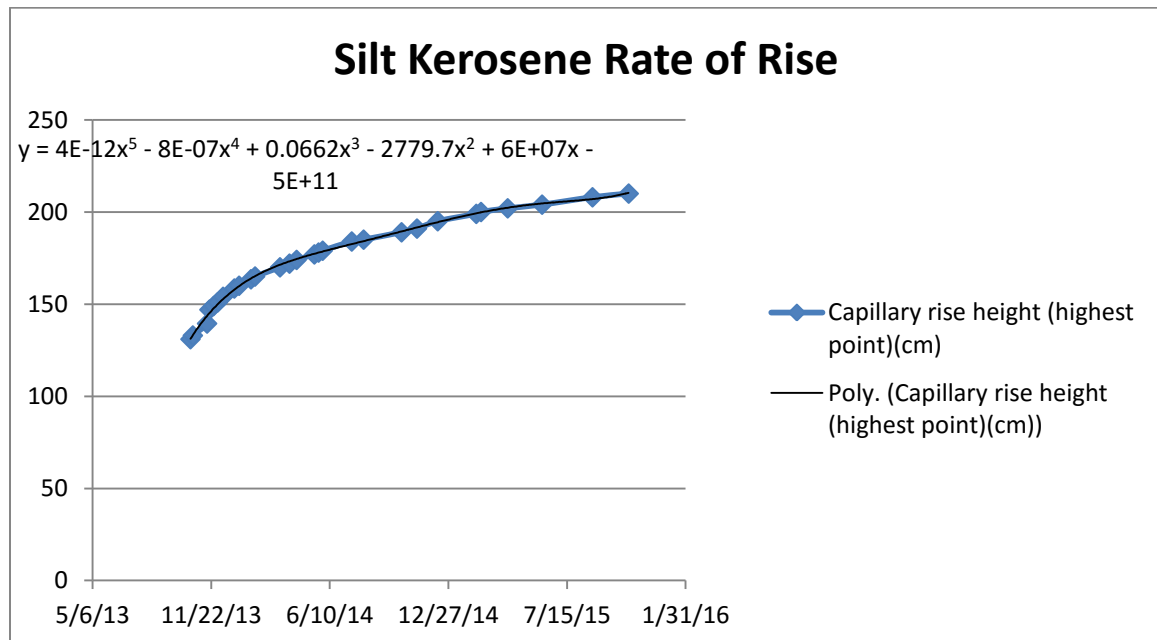


Figure 10. Capillary rise (cm) of kerosene in 1/3 silt 2/3 sand column began 8/27/2013.

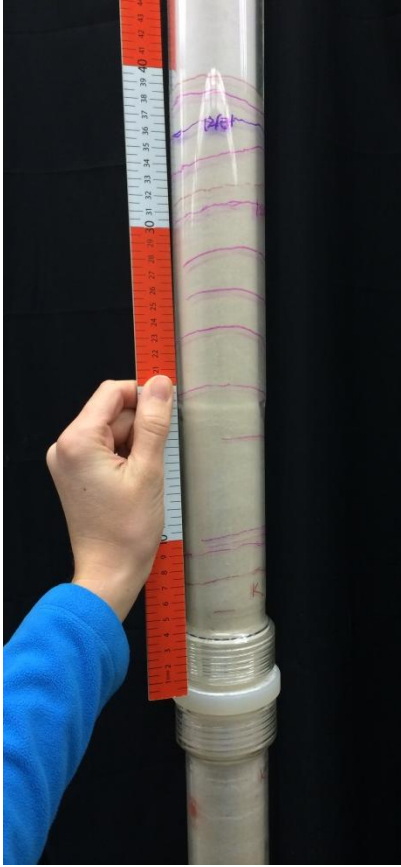


Figure 11. Silt column showing tops of kerosene capillary rise over time.

The silt water test began on 11/26/2013. This test was used to look at the rates of capillary rise to compare to the rates in the silt kerosene. Figure 11 shows some of the markings and measurements taken off the glass tubes on recorded dates to look at the rates of rise. Figure 12 is the data taken from figure 11 and plotted in a graph.

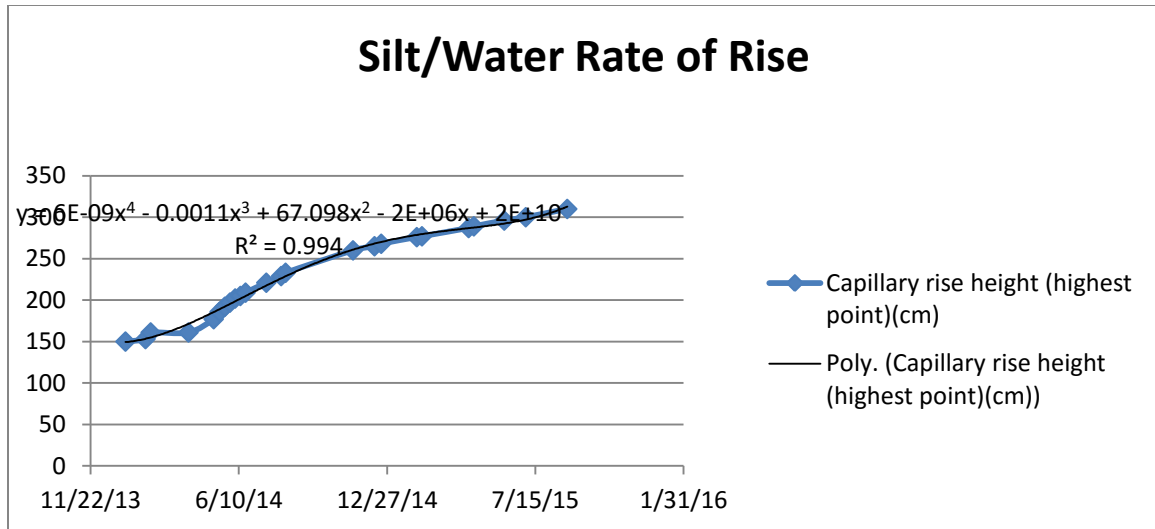


Figure 12. Water capillary rise in column of 1/3 silt 2/3 sand began 11/26/2013.

Table 13.

Water Capillary Rise in Column of Medium Sand

Density	Tension Saturated Capillary Fringe Height after 1 hour cm	Tension Saturated Capillary Fringe Height after 1 week cm	Height of Damp 1 week cm	Total Tension Saturated Rise cm	Total Rise (Damp) cm	Material Sand	Date Began	Date Ended
	22.86	21.59	33.02	8.89	20.32		11/1/2011	11/7/2011
1.62	20.32	20.32	32.004	7.62	19.304	w/color	11/7/2011	11/15/2012
1.66	20.32	20.32	33.02	7.62	20.32	w/color	11/15/2011	11/28/2011
1.57	20.32	20.32	29.845	7.62	20.32	w/color	11/28/2011	12/6/2011
1.59	20.32	20.32	27.94	7.62	17.145	No color	2/5/2012	2/13/2012
1.62	Unk	22.86	25.4	10.16	12.7	No color	3/22/2012	3/30/2012
1.56	Ukn	26.67	27.94	7.62	8.89	No color	3/25/2012	3/30/2012
1.54	20.32	17.78	22.86	5.08	10.16	No color	4/2/2012	4/8/2012
1.56	20.32	19.05	25.4	7.62	12.7	No color	4/2/2012	4/8/2012
	10	18	25	8	15	No color	4/27/2012	5/6/2012
			22		12	No color	10/25/2013	11/5/2013
			19		7	No color	11/12/2014	11/19/2014
			23		14	No color	4/3/2014	4/15/2014
			24		13	No color	4/3/2014	4/15/2014

Table 14.

Water Capillary Rise in Column of 0.3-0.6 mm Fine Sand

Density	Total Rise	Date	Date
	(Damp)	Began	Ended
	cm		
1.657	21	11/13/2012	11/21/2012
1.57	failed	11/21/2012	11/30/2012
1.61	failed	3/5/2013	3/11/2013
	10	11/19/2014	11/26/2014
1.63	16.5	4/30/2014	5/15/2014
	14	4/30/2014	5/15/2014
1.79	14	5/22/2014	6/5/2014
1.65	15	5/22/2014	6/5/2014

Table 15.

Capillary Depression Values for Water in Hydrophobic 0.4-0.7 mm Sand

Density	Total	Date	Date
	Depression	Began	Ended
	cm		
1.66	-5.5	2/27/2012	3/11/2012
	-5	2/27/2012	3/11/2012
	-6.5	2/5/2012	2/25/2012
1.60	-6	3/22/2012	3/25/2012

Tables 11-15 are data tables that show the capillary rise and depression values for each test. More detailed versions are located in Appendix C.

Average capillary depression was 5.75 cm for the hydrophobic sands.

Calculation of Polubarinova-Kochina (1952) Equation using Measured Values

Polubarinova-Kochina (1952) equation is:

$h_c = 0.45 ((1 - n) / n) / d_{10}$, with n = porosity, h_c = capillary rise and d_{10} = effective grain diameter (h_c and d_{10} in cm).

$$1-n = \rho_b/\rho_s$$

$$N = \theta = 1 - \rho_b / \rho_s$$

$$\rho_b = \text{Bulk density} = 1.59 \text{ g/cm}^3$$

$$\rho_s = \text{particle density} = 2.65 \text{ g/cm}^3 \text{ for silica sand}$$

$$1.59 \text{ g/cm}^3 / 2.65 \text{ g/cm}^3 = 0.6$$

$$n = 1 - 0.6 = 0.4$$

$$n = 0.4$$

Medium sand in water ($d_{10} = 0.457 \text{ mm}$):

$$h_c = 0.45((0.6)/0.4/0.0457 \text{ cm} = 14.77 \text{ cm}$$

Finer sand in water ($d_{10} = 0.355 \text{ mm}$):

$$h_c = 0.45((0.6)/0.4/0.0355 \text{ cm} = 19 \text{ cm}$$

Silt in water:

$$\text{Density average of silt} = 1.6 \text{ g/cm}^3 = \rho_b$$

$$\text{Assume } d_{10} = 0.0038 \text{ cm}$$

$$n = \theta = 1 - (1.6 / 2.65) = 1 - 0.604 = 0.396 = n$$

$$h_c = (0.45 (0.604) / (0.396)) / 0.0038 = 180.55 \text{ cm} = 181 \text{ cm rise for water in silt.}$$

Kerosene in silt and sand :

No calculations using the Polubarinova-Kochina (1952) equation can be done using kerosene. The Polubarinova-Kochina (1952) was intended to be used only for water. However, the calculated values could be scaled using the different surface tensions and densities of water and kerosene.

Calculation of Fetter 3rd Edition (1994) Equation using Measured Values

Fetter 3rd edition (1994) equation:

$$h_c = (2\sigma \cos\lambda) / (\rho_w g R)$$

h_c is the height of the capillary rise

σ is the surface tension of the fluid (measured water with silt =54.8, and kerosene = 25.7

G(mN/m)

λ is the angle of the meniscus with the capillary tube (assuming contact angle is 0)

ρ_w is the density of the fluid (assuming water = 1, and measured Kerosene = 0.8003 g/ml³)

g is the acceleration of gravity (980 cm/s²)

R is the radius of the capillary tube (d_{10} silt = 0.004 cm, d_{10} for medium sand = 0.0457 cm and d_{10}

finer sand =0.0355 cm) According to Fetter R of capillary = 0.2d, therefore

R for silt = 0.2 (0.004cm) = 0.0008 cm

R for medium sand = 0.2 (0.0457cm) = 0.00914 cm

R for finer sand = 0.2 (0.0355cm) = 0.0071cm Using Fetter's equation with the above values we

can predict the capillary rise of water in silt

$$h_c = (2\sigma \cos\lambda)/(\rho_w g R)$$

Water in medium sand:

$$(2 (54.8) (1)g/s^2) / (1g/cm^3 980 cm/s^2 (0.00914 cm)) = 12.24 cm$$

Water in finer sand:

$$(2 (54.8) (1)g/s^2) / (1g/cm^3 980c m/s^2 (0.0071 cm))= 15.75 cm$$

Water in silt:

$$(2 (54.8) (1)g/s^2) / (1g/cm^3 980 cm/s^2 (0.0008 cm)) = 140 cm$$

Kerosene in medium sand:

$$(2 (25.7) (1)g/s^2) / (0.80003g/cm^3 980 cm/s^2 (0.00914 cm)) = 7.17 cm$$

Kerosene in silt:

$$(2 (25.7) (1)g/s^2) / (0.80003g/cm^3 980cm/s^2 (0.0008 cm))= 81.98 cm$$

CHAPTER 4

DISCUSSION (PROBLEMS AND CORRECTIONS)

Most of the problems encountered dealt with silt. With silt, the researchers ran into difficulties, especially testing with water as the liquid. The main problem with the silt was it would crack, creating a horizontal air gap. This problem allowed no rise to occur in the air gap. To try to solve this difficulty, a 50/50 mixture of sand and silt was used. The sand would provide some stability to the internal structure and should have no effect on the rise. The smaller silt particles will control the rise as long as they are evenly mixed, which means there are no intervals of pure sand. This 50/50 sand and silt mixture worked better than the pure silt. However, none of the 50/50 sand and silt mixture experiments had capillary rise occur above the joint connecting the 4-foot tube to the extension tube. The reason likely is because there was still cracking, even though there was less cracking shown in the tubes (see photos with and without sand cracking in Figure 13). Since the 50/50 mixture worked better than the pure silt, a 2:1 ratio of sand and silt was made using two parts sand to every part silt by volume. One out of the two tests which was run with this method failed at the joint connector, but this 2:1 ratio of sand to silt is the only mixing method that produced a successful test without failing.

Mixing was also difficult. Since the sand-silt mixture falls through a column of air while packing the column, there is time for the different size grains to separate themselves creating thin layers (see Figure 14).

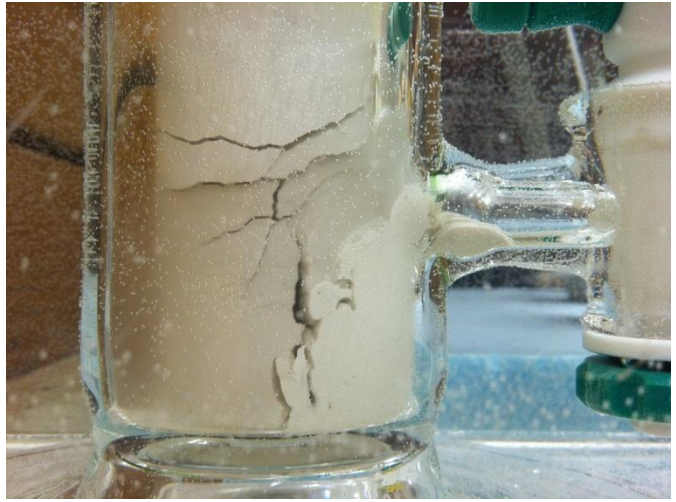


Figure13. Visible cracking in the silt/sand mixture and pure silt tests.

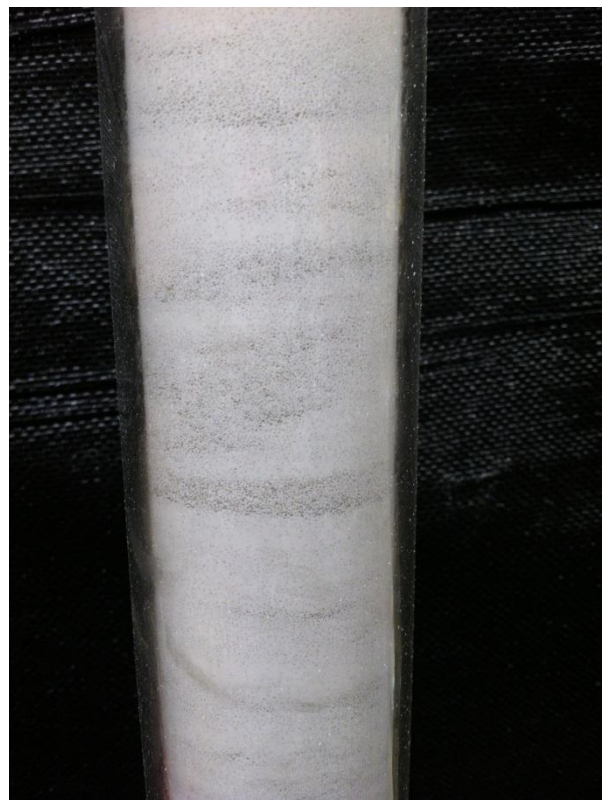


Figure 14. Some visible layers in the 50/50 silt sand mixture.

It was difficult to see the line between damp and dry sand. To solve this problem, a water-detecting powdered candy was added to the sand by mixing it in. The sand would turn bright blue when it was exposed to water (see Figures 15 & 16). This allowed the highest point of capillary rise to be easily seen (see Figure 16). By doing this method, the capillary rise values with the color-changing candy appeared slightly higher than without the candy. So the results with the color-changing candy were not used in calculating equations. The results can be found in the medium sand testing in table 13. An explanation for the capillary rise being higher than normal was that the candy may have affected the surface tension of the water, thus affecting the rise. However, most compounds added to water will reduce surface tension and capillary rise. Another problem with the candy is some areas in the tubes would turn bright blue very far up the column well into the dry area (see Figure 15). This may have been due to water vapor or humidity in the air. Even though the results from these color changing experiments were not used to quantitatively characterize capillary rise, the color changing did show very clear patterns and pathways of rise. This allowed enhanced photographs to be taken (see Figure 15). The photograph on the right in Figure 15 showed water color change and most likely had a lower surface tension.

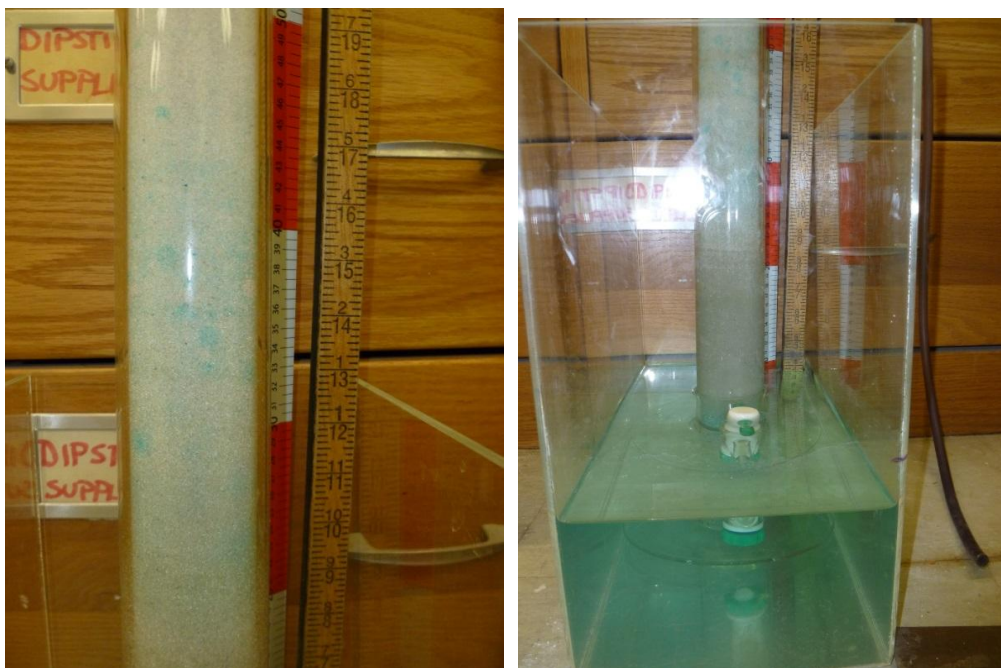


Figure 15. Visible blue dots scattered throughout the column.



Figure 16. Color changing candy showing line of capillary rise.

The color changing candy was difficult and messy to use. The candy also appeared in the experiments to increase capillary rise and surface tension by some unknown mechanism. Therefore, color-changing candy was not used in further tests. The kerosene tests were easy to see. However, in the water tests it remained difficult to see where the capillary rise ended. To solve this problem, the lights in the room were turned off and bright cell phone lights were shone through the column. This made the capillary rise lines very noticeable in both types of sediments with water. At the end of the experiment to see the extent of capillary rise in sand in water tests, the dry sand was poured out. It would leave a cylinder of wet sand that was held together by capillarity. The damp sand left in the columns was measured to get a more accurate measurement of the extent of capillary rise.

After completing the hydrophobic tests, we noticed some of the sand test (without the hydrophobic coating) capillary rise measurements were much lower than previous results. Upon careful investigation of the box and glass tube, it was discovered that there were little dots (air pockets see figure 17) covering the Plexiglas and glass. These air pockets were found to only go to the height of water used during the hydrophobic sand tests. This suggested that during the previous experiments with the hydrophobic tests, some of the hydrophobic coating on the sand may have adhered to the glass column and Plexiglas box. This would have made the capillary rise lower than it would have been without this hydrophobic coating. Denatured ethanol was used to clean the glass tubes and Plexiglas boxes. The tubes were air dried, rinsed with water, and air dried again. Results after the ethanol cleaning confirmed that the hydrophobic treatment lowered the extent of capillary rise.

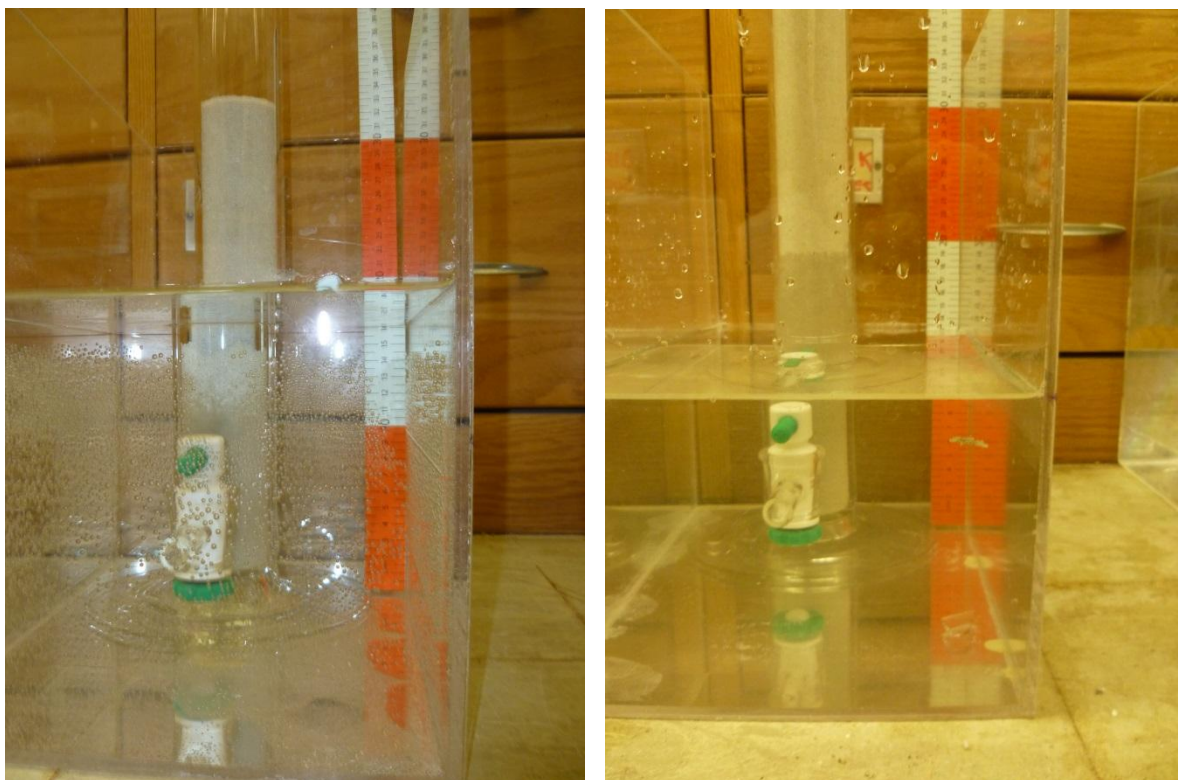


Figure 17. Left: Air pockets were left from the hydrophobic coating. Right: A normal test after cleaning with ethanol.

After cleaning out the tubes and Plexiglas boxes, in more recent tests in medium sand the capillary rise measurements were significantly lower than the first five capillary rise tests. During testing the sand ran out and more was ordered. New sand bags were ordered from the company that previously provided the sand. The grain size of the new sand appeared to be different than the sand used at the beginning of the tests. The company from which the bags of sand were ordered stated the sand's grain size was exactly the same. This led to a hypothesis that these new bags of sand were different in grain size, which could have caused the sudden drop in capillary rise during more recent testing. A grain-size analysis of the new medium sand was conducted. The results showed the grain size to be nearly the same as the previous sand, confirming the new sand ordered was the same grain size as the previous order and invalidating the hypothesis.

To verify the tubes were cleaned out properly and the hydrophobic sand or the kerosene tests were not having a lingering effect on capillary rise, a new tube was ordered. The new tube is the shorter tube listed in the materials section. Two sand tests were run side by side, one with a cleaned tube and one with a new tube. Both tubes had the same sand, same water, and same Plexiglas boxes. Water was filled to the same levels in those boxes. This was done on two separate occasions, one with the medium sand and one with the finer sand. Each time both tubes gave similar results, thus showing the tube that had been used for hydrophobic sand and kerosene had been cleaned properly and no lingering effects were lowering the capillary rise. Thus, the reason for the change in measured capillary rise is not known.

Time was another problem that occurred during testing. The amount of time for the tests in silt to reach equilibrium equaled years. The kerosene in silt test began in August of 2013, and has still not stopped as of March 2016 (Figure 10 and Table 12). Figure 11 shows the test column markings as where the capillary rise in silt and kerosene has progressed.

This research was done in part due to the high capillary rise values in Table 16, which came from Fetter's Applied Hydrogeology, 3rd edition.

Table 16.

Height of Capillary Rise in Sediments (Fetter, 1994)

Sediment	Grain Diameter (cm)	Pore Radius (cm)	Capillary Rise (cm)
Fine silt	0.0008	0.0002	750
Coarse silt	0.0025	0.0005	300
Very fine sand	0.0075	0.0015	100
Fine sand	0.015	0.003	50
Medium sand	0.03	0.006	25
Coarse sand	0.05	0.01	15
Very coarse sand	0.2	0.04	4
Fine gravel	0.5	0.1	1.5

After running several capillary rise experiments, the table was looked at again to compare the data from those experiments with Fetter's chart. The silt purchased for the experiments was ground silica flour 200 mesh silica flour (see materials for description). This consisted of a 200-mesh silica with a grain diameter of 0.0074 cm or less to pass through the 200 mesh sieve. According to Fetter's chart (Table 16), 0.0074 cm is just slightly smaller than very fine sand at 0.0075 cm. The sand was then analyzed (see sand analysis) and was found to be 0.03-0.06 cm with a d_{10} of 0.0355 cm, and 0.04-0.07 cm and a d_{10} of 0.0457 cm, which according to Fetter's table, puts the sand used at medium sand and coarse sand. If Fetter's classifications of silt and sand are correct, our experimental values are not far off what Fetter predicted. Other soil classification systems were then looked at, and we found that there are many different soil classification methods and descriptions. Table 17 combines some widely used soil classifications for comparison.

Table 17 shows some of the differences in soil classification systems. One can see the soil textural descriptions should be used more carefully, and actual grain size diameters would be a more uniform and useful way to describe the grain size for comparison of capillary rise data.

Table 17.

Comparison of Widely Used Soil Descriptions with Grain Sizes

Sediment size description	Fetter (1994) grain diameter (cm)	USDA Classification (cm)	ISSS Classification (cm)	Fetter (1994) capillary rise (cm)
Fine silt	0.0008	Silt range 0.0002--0.004	Silt range 0.0002--0.002	750
Coarse silt	0.0025			300
Very fine sand	0.0075	0.007	NA	100
Fine sand	0.015	0.02	Range 0.002-0.02	50
Medium sand	0.03	0.04	NA	25
Coarse sand	0.05	0.07	Range 0.02-0.2	15
Very coarse sand	0.2	0.2	NA	4
Fine gravel	0.5	0.4	0.03	1.5

Conclusions

The initial reason for this project was to check values for capillary rise using a table in the 3rd edition of Fetter's Applied Hydrogeology. Fetter calculates the capillary rise values using the Young-Laplace equation for a simple cylindrical pore. The table appeared to make sense for sand, but as the texture fined, the capillary rise numbers appeared to be way too high. Based on the laboratory data from this study, Fetter's numbers appear to be reasonable for the grain sizes in his table. In some instances, his names of sediment texture were inconsistent with the grain sizes they purportedly described.

Two equations for capillary rise compared favorably with the measured values.

Polubarinova-Kochina presents an empirical equation. Both her equation and Fetter's correlate well with the measured capillary rise values in sands. Both equations under predict the capillary rise in silt. See Table 18.

Table 18.

Comparison of Measured Values Compared to the Equations Analyzed

Sediment type	Liquid used	Average total height of damp sediment (cm)	Scaled total height of damp sediment (cm)	Predicted height of damp sediment (cm) by Polubarinova Kochina (1952)	Predicted height of damp sediment (cm) by Fetter (1994)
Medium sand	water	19.5	19.6	14.8	12.2
Finer sand	water	21		19	15.8
Silt	water	At least 310	360	181	140
Medium sand	kerosene	11.5	11.4	NA	7.2
Silt	kerosene	210		NA	82
Hydrophobic Sand	water	-5.75 (depression)	NA	NA	NA

Table 18 above has no values for scaled and predicted depressions for the hydrophobic sands, as the equations can't take into account the depression. The table also has no values for the Polubarinova equation predictive values for kerosene as there is no way in the equation to adjust for anything but water in the equation except by scaling, which was not done here.

Table 18 shows the measured capillary rise values for silt in water are greater than 2 times the predicted values from the Fetter calculations and just at 2 times the predicted value from the Polubarinova equation.

It was thought that the values for the calculations were high, but the measured values show the opposite. The values in the calculations are much too low compared to the measured values as shown in Table 18.

Fetter's equation uses $0.2 d_{10}$. The reasoning for this was not located during the literature analysis. If the equation takes into account all the measured data as done in table 18 and not

constants as Fettters original table and $0.2 d_{10}$ is replaced with $0.1 d_{10}$, the equation may be very close to actual values that were measured.

The following will show Fettters equation replaced with $0.1 d_{10}$.

R is the radius of the capillary tube (d_{10} silt = 0.004 cm, d_{10} for medium sand = 0.0457 cm and d_{10} finer sand = 0.0355 cm) According to Fetter R of capillary = $0.2 d$, but this is being replaced with $0.1 d$

R for silt = $0.1 (0.004 \text{ cm}) = 0.0004 \text{ cm}$

R for medium sand = $0.1 (0.0457 \text{ cm}) = 0.00457 \text{ cm}$

R for finer sand = $0.1 (0.0355 \text{ cm}) = 0.00355 \text{ cm}$

By using Fetter's equation with the above values we can predict the capillary rise of water in silt

$$h_c = (2\sigma \cos\lambda) / (\rho_w g R)$$

Water in medium sand:

$$(2 (54.8) (1) \text{g/s}^2) / (1 \text{g/cm}^3 980 \text{ cm/s}^2 (0.00457 \text{ cm})) = 24.47 \text{ cm}$$

Water in finer sand:

$$(2 (54.8) (1) \text{g/s}^2) / (1 \text{g/cm}^3 980 \text{ cm/s}^2 (0.00355 \text{ cm})) = 31.50 \text{ cm}$$

Water in silt:

$$(2 (54.8) (1) \text{g/s}^2) / (1 \text{g/cm}^3 980 \text{ cm/s}^2 (0.0004 \text{ cm})) = 279.59 \text{ cm}$$

Kerosene in medium sand:

$$(2 (25.7) (1) \text{g/s}^2) / (0.80003 \text{g/cm}^3 980 \text{ cm/s}^2 (0.00457 \text{ cm})) = 14.35 \text{ cm}$$

Kerosene in silt:

$$(2 (25.7) (1) \text{g/s}^2) / (0.80003 \text{g/cm}^3 980 \text{ cm/s}^2 (0.0004 \text{ cm})) = 163.90 \text{ cm}$$

Further work would need to be done, but changing from $0.2 d_{10}$ to $0.1 d_{10}$, along with replacing constants for surface tension with measured values, may be helpful corrections to more closely calculate capillary rise in fine-grained materials.

While our focus was on height of capillary rise rather than the rate of capillary rise, it took over two years for fluids to rise by capillarity in silt and equilibrate in the lab experiments. The rates of rise as seen in Table 10 actually proved to be valuable as the kerosene never stopped rising and the tests took around three years and counting. The rates were graphed and used to predict when and where the rise will eventually stop. Problems with cracks in the silt columns, algae growth and evaporation increased over time. To minimize silt cracking, the experiments were performed using sand/ silt mixtures. A mixture of 2/3 sand, 1/3 silt was most effective. The laboratory measurements of capillary rise in a sand/ silt mixture reasonably represent silt behavior. According to the equations cited above, the small pores in the finest materials control the height of capillary rise; the lab experiments show that is correct.

addition to measuring capillary rise with water, kerosene was used in some columns with sand and with the sand/ silt mixture. There were fewer problems with the silt mixture cracking when kerosene was the fluid. The capillary rise measured with kerosene was then scaled to compare with measurements using water. In most instances, the capillary rises were consistent with expectations. In the last silt experiment, kerosene has risen over 2 years. During the first 3 to 6 months, capillary rise was faster; since then the rise has slowed down. Sands treated with hydrophobic chemicals have a negative capillary rise, a capillary depression. Further work should be done to design and carry out measurements of capillary rise in clays. The experimental methods used in this study for sands and silts would not be suitable for clay.

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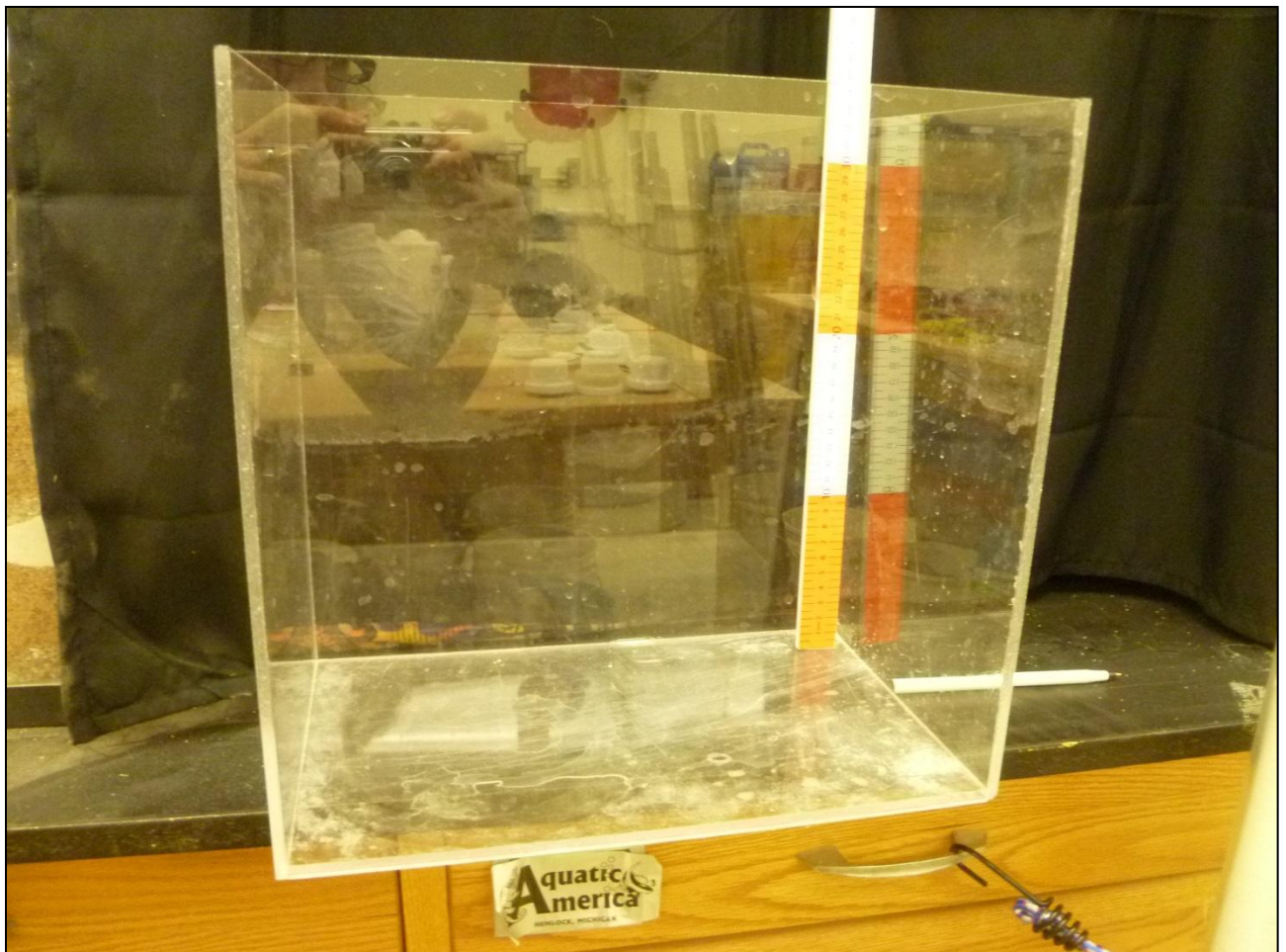
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Appendix A
Materials Figures

Plexiglas Boxes Materials Figure 1



Plexiglas Boxes Materials Figure 2



Glass Columns Materials Figure 3



Materials Figure 4 Glass Columns



Glass Column Extensions Materials Figure 5



Glass Column Extensions Materials Figure 6



Connectors Materials Figure 7



Connectors Materials Figure 8



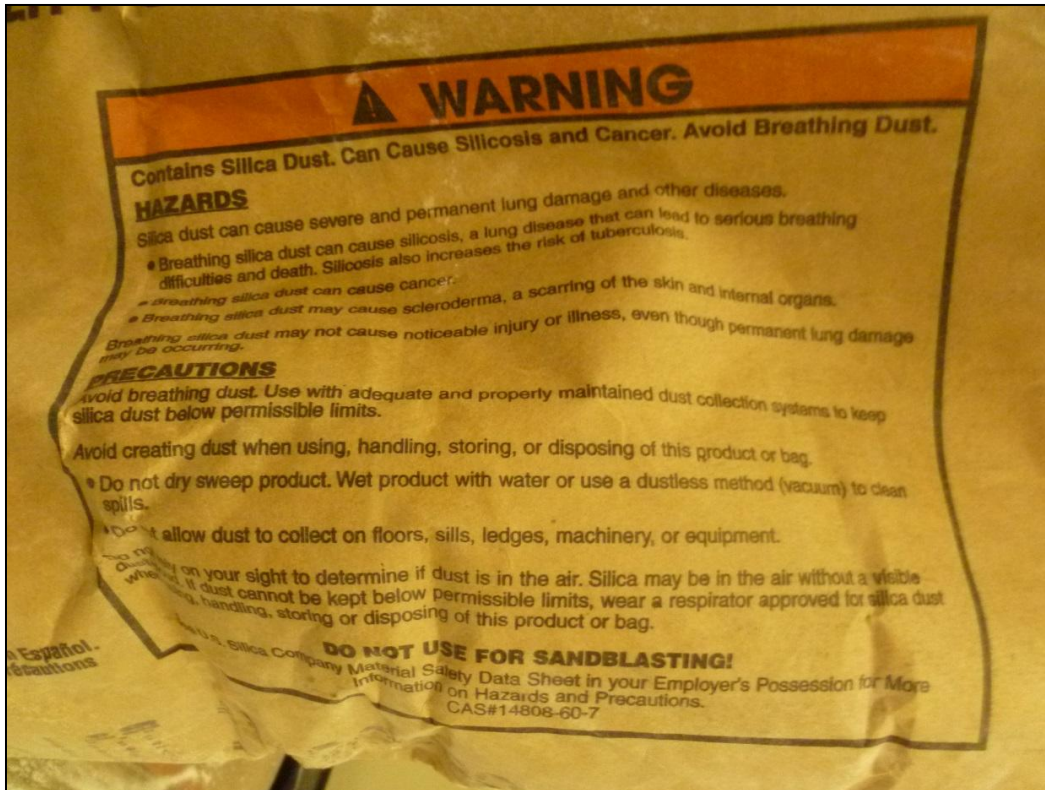
Lids Materials Figure 9



Lids Materials Figure 10



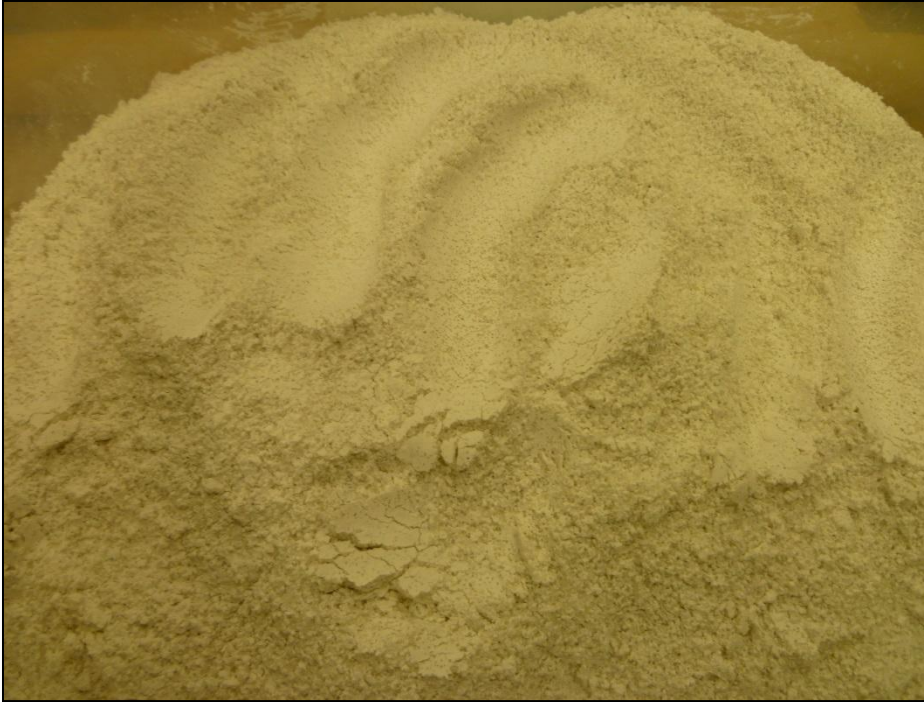
Silica Flour Materials Figure 13



Silica Flour Materials Figure 14



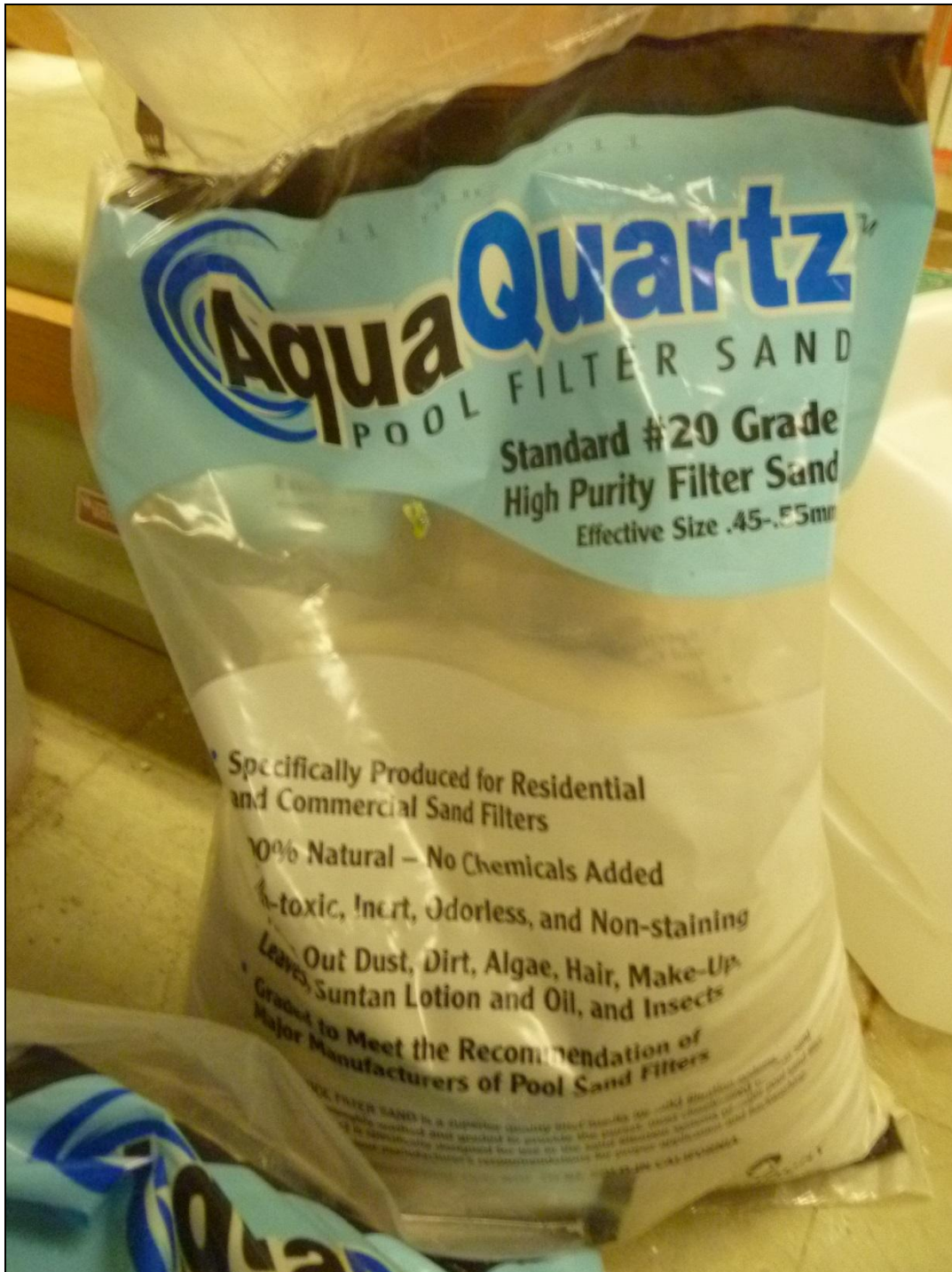
50/50 Sand Silt Mixture before Testing Materials Figure 15



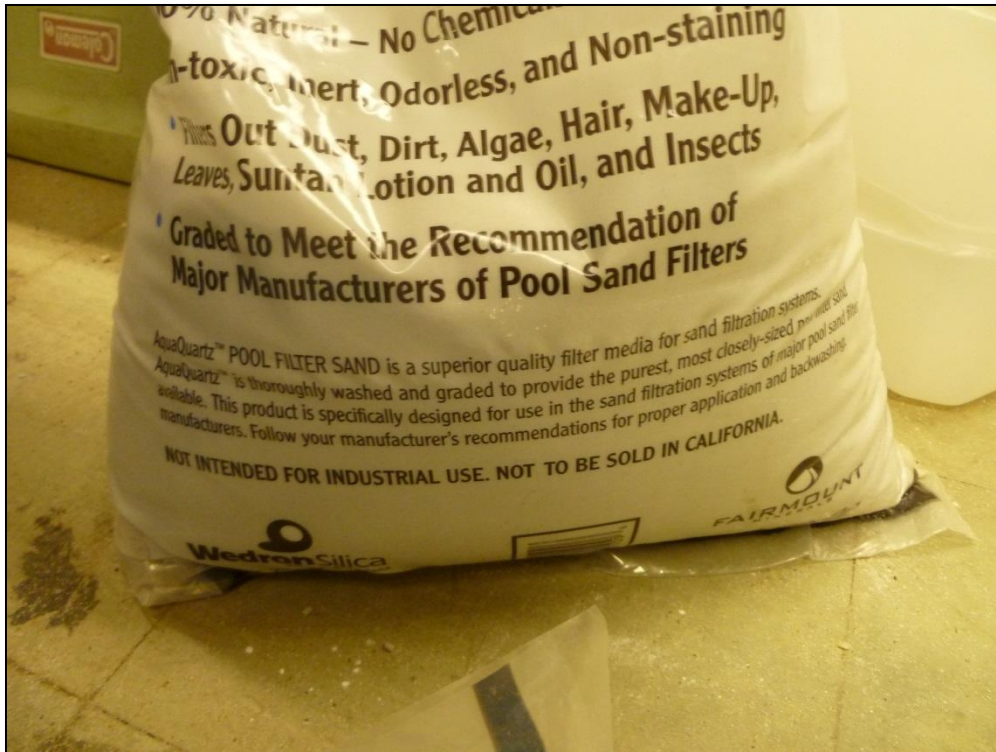
50/50 Sand Silt Mixture after Testing Materials Figure 16



Sand Figure 17



Sand Materials Figure 18



Sand Materials Figure 19



Funnel and Tube Materials Figure 20



Funnel and Tube Materials Figure 21



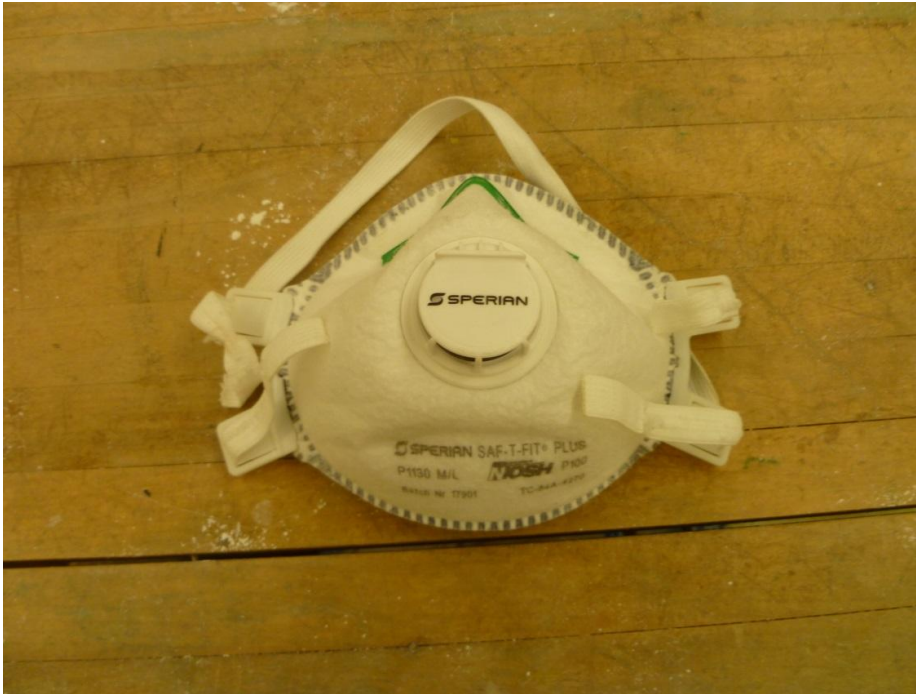
Water Repellant Spray Materials Figure 22



Water Repellant Spray Materials Figure 23



Particulate Mask Materials Figure 24



Mettler Scale Materials Figure 25



Kerosene Testing Set Up, Vent Pipe, and Foil Lid Materials Figure 26



Sieve Shaker Machine Materials Figure 27



Appendix B
Materials Documents

1



SALES QUOTATION

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 FREIGHT CHARGES ARE ON THE CUSTOMERS'S ACCOUNT.

THIS QUOTATION IS VALID FOR 30 DAYS.

SHIPMENT: 10-15 DAYS AFTER RECEIPT OF ORDER.

SHIPMENT CONSISTS OF:
 5 CARTONS, 24X15X7, 50 LBS EACH
 GROSS WT. 240 LBS.

IF YOU WISH TO PLACE AN ORDER FOR THESE ITEMS, YOU MUST REFERENCE THIS
 QUOTATION NUMBER ON YOUR ORDER.

Ln	Item Number	UM	Quantity	Tax	Unit Price	Net Price
1	0930W050	EA	5.00	no	\$78.00	\$390.00
SILICA FLOUR, 200 MESH, 50 LB. BAG						

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Line Total:	\$390.00
UPS GROUND/INSURANCE:	\$345.00
MIN. PACKING/HANDLING:	\$30.00
SPECIAL:	\$0.00
Total Tax:	\$0.00
Total (USD):	\$765.00

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By:  Authorized Signature

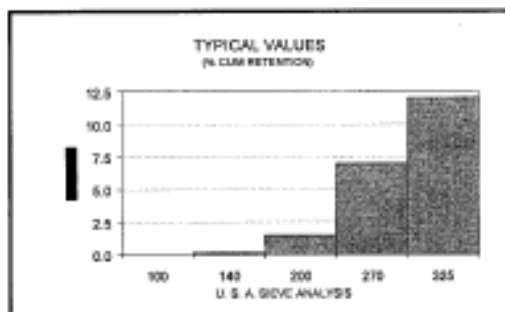


SIL-CO-SIL® 75

GROUND SILICA

PLANT: BERKELEY SPRINGS, WEST VIRGINIA

PRODUCT DATA



USA STD SIEVE SIZE		TYPICAL VALUES		
MESH	MICRONS	% RETAINED		% PASSING
		INDIVIDUAL	CUMULATIVE	CUMULATIVE
100	150	0.0	0.0	100.0
140	106	0.2	0.2	99.9
200	75	1.3	1.5	98.5
270	53	5.5	7.0	93.0
325	45	5.0	12.0	88.0

TYPICAL PHYSICAL PROPERTIES

HARDNESS (Mohs)	7	REFLECTANCE (%)	88
MINERAL	QUARTZ	YELLOWNESS INDEX	4.3
pH	7.0	SPECIFIC GRAVITY	2.65

TYPICAL CHEMICAL ANALYSIS, %

SiO ₂ (SILICON DIOXIDE)	99.5	MgO (MAGNESIUM OXIDE)	0.01
Fe ₂ O ₃ (IRON OXIDE)	0.022	Na ₂ O (SODIUM OXIDE)	0.01
Al ₂ O ₃ (ALUMINUM OXIDE)	0.30	K ₂ O (POTASSIUM OXIDE)	0.01
TiO ₂ (TITANIUM DIOXIDE)	0.01	LOI (LOSS ON IGNITION)	0.2
CaO (CALCIUM OXIDE)	0.02		

January 7, 1999

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Appendix C
Original Data Tables

Sand Height (cm)	Tube Diameter (cm)	Density (g/ML)	Capillary Fringe Height after 1 hour (cm)	Capillary Fringe Height after 1 week (cm)	Height of Damp after 1 week (cm)	Height damp after 2 weeks (cm)	Water Height (cm)	Total Tension Saturated Rise (cm)	Total Rise Damp (cm)	Material Sand	Date Began	Date Ended
0	5	#DIV/0!	22.86	21.59	33.02		12.7	8.89	20.32		11/1/2011	11/7/2011
76.2	5	1.62	20.32	20.32	32.004		12.7	7.62	19.304	Sandwcol or	11/7/2011	11/15/2012
73.66	5	1.66	20.32	20.32	33.02		12.7	7.62	20.32	Sandwcol or	11/15/2011	11/28/2011
78.74	5	1.57	20.32	20.32	29.845		12.7	7.62	20.32	Sandwcol or	11/28/2011	12/6/2011
73.66	5	1.59	20.32	20.32	27.94		12.7	7.62	17.145	sandnocol or	2/5/2012	2/13/2012
58.42	5	1.62	unk	22.86	25.4		12.7	10.16	12.7	sandnocol or	3/22/2012	3/30/2012
48.26	5	1.56	ukn	26.67	27.94		19.05	7.62	8.89	sandnocol or	3/25/2012	3/30/2012
53.34	5	1.54	20.32	17.78	22.86		12.7	5.08	10.16	sandnocol or	4/2/2012	4/8/2012
55.88	5	1.56	20.32	19.05	25.4		12.7	7.62	12.7	sandnocol or	4/2/2012	4/8/2012
49	5		10	18	25		10	8	15	sandnocol or	4/27/2012	5/6/2012
61	5				22		10		12	sandnocol or	10/25/2013	11/5/2013
55.5	5				19		12		7	sandnocol or	11/12/2014	11/19/2014
65	5				23	25	11		14	sandnocol or	4/3/2014	4/15/2014
55	5.35				24	24.5	11.5		13	sandnocol or	4/3/2014	4/15/2014

Table 19_ medium sand in water tests

Tube weight (kg)	Tube Weight w/sand (kg)	Sand Height (cm)	Tube Diameter (cm)	Density (g/mL)	Height of Damp after 1 week (cm)	Height damp after 2 weeks (cm)	Water Height (cm)	Total Rise Damp (cm) (Damp)	Date Began	Date Ended
2.833	5.696	88	5	1.657	33		12	21	11/13/2012	11/21/2012
2.803	5.849	99	5	1.57				failed	11/21/2012	11/30/2012
2.881	5.318	77	5	1.61			13	failed	3/5/2013	3/11/2013
2.762	4.547	58	5		20.5		10.5	10	11/19/2014	11/26/2014
2.881	4.558	52	5	1.63	21	23	6.5	16.5	4/30/2014	5/15/2014
0.852		50	5.35		18	20	6	14	4/30/2014	5/15/2014

Table 20 fine sand in water

Tube #	Tube Weight in (Kg)	Tube Weight w/sand (Kg)	Sand Height (cm)	Tube Diameter (cm)	Density	Kerosene height in cm	Total Tension Saturated Rise (cm)	Total Rise Damp (cm)	Capillary Rise (Total damp-Kerosene height) (cm)	Date Began	Date Ended
2	2.94	5.05	70	5	1.53	12	15.5	21	9	6/19/2012	6/21/2012
4	2.88	4.59	53.34	5	1.63	9.5	13.5	24	14.5	8/28/2012	9/11/2012
	2.934	4.75	57	5	1.62	12	17	26	14	2/5/2013	3/5/2013

Table 21 Medium sand in Kerosene

Tube #	Tube Weight (Kg)	Tube Weight w/sand (Kg)	Sand Height (cm)	Tube Diameter (cm)	Density	Water Level (cm)	Depression (cm)	Total Depression (cm)	Material	Date Began	Date Ended
4	3.00	3.97	30	5	1.66	25	19.5	5.5	hydrophobic sand	2/27/2012	3/11/2012
1	2.91		32	5		24.5	19	5	hydrophobic sand	2/27/2012	3/11/2012
4	3.01		33	5		26.5	20	6.5	hydrophobic sand	2/5/2012	2/25/2012
1	2.90	4.03	36	5	1.60	25	19	6	hydrophobic sand	3/22/2012	3/25/2012

Table 22 Medium hydrophobic sand in water

Tube #	Tube Weight (kg)	Tube weight w/ sand and candy	Height of sand (cm)	Inside tube diameter (cm)	Density (g/mL)	Height of damp after 1 week (cm)	Date started	date ended	Material used	Capillary rise final reading (cm)	water height (cm)	total rise (cm)
4	3	7.30	137.2	5	1.59	132.08			Silt/sand 50/50	failed	12.7	ukn
1 & 5	5.46	13.74	274.3	5	1.54	104.14	2/5/2012	3/1/2012	Silt/sand 50/50	144.78	12.7	132.08
2 & 7	4.22	10.84		5		0	2/16/2012	3/3/2012	Silt/sand 50/50	142.24	12.7	129.54
3 & 5	5.02	10.16	167.6	5	1.56	101.6	3/5/2012	3/22/2012	silt/sand 50/50	149.86 (failed crack)	12.7	ukn
2 & 7	3.89			5		109.22	3/15/2012	4/8/2012	Silt/sand 50/50	152.4 (failed crack)	25.4	ukn
1 & 5	5.1	10.70	177.8	5	1.61	0	4/2/2012	4/20/2012	Silt/sand 50/50	153.8	24	129.8
2 & 6	0	9.00	171.5	5		0	4/27/2012	5/16/2012	Silt/sand 50/50	at least 114 cm (crack)	10.16	ukn
3 & 7	5.23	10.43				104.14	5/8/2012	5/16/2012	Silt/sand 50/50	failed crack		ukn
	5.09	11.88	198.1	5	1.75		7/3/2012	7/31/2012	Silt/sand 50/50 tamped	121.92 failed	12.7	
	6.3	15.12	255.3	5	1.76		3/5/2013	4/2/2013	Silt/sand 25/75	119 failed	19	100
	5.02	12.73	224.8			5/14=188, 5/2=198, 7/5=225	4/10/2013	7/10/2013	silt/sand 33/66	225 all way to top	13	212
	5.13	13.54	254	5			9/3/2013	9/17/2013	silt/sand 33/66	failed glass tube broke		
					1.62		11/26/2013	10/30/2015	Silt/sand 33/66	To top 320	10	320 at least

Table 23 Silt in water

Tube Weight (kg)	Tube Weight w/sand (kg)	Sand Height (cm)	Tube Diameter (cm)	Density (g/mL)	Height of Damp final reading (cm)	Kerosene height (cm)	Total Rise (Height damp-Kerosene) (cm)	Date Began	Date Ended
3.76	9.09		5		144.78	12.7	132.08	6/21/2012	7/24/2012
3.89	9.64	180	5	1.63	148	12.5	135	8/21/2012	9/25/2012
			5		234	21	213	8/27/2013	3/10/2016

Table 24 Silt in Kerosene