Permeability of layered glass bead samples

‘’Effect of grain size mixing in layer boundaries’’

By

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Abstract

Geotechnical projects are successful when there is a lot of knowledge about the soil implemented in safe sustainable solutions. Existing models of hydraulic flow in soils need to be tested and confirmed again and again to make sure it’s trustworthy. With the use of three-layered samples containing 1mm and 3mm glass bead sizes a simplified model of the fining upward (1mm top layer) and coarsening upward (3mm top layer) stratification was made. The top and bottom layers consist of a uniform glass bead size. The middle layer is a binary mixed one with different volumetric percentages to mimic the gradual increase of grain sizes like fining and coarsening upward sediment deposits. A decrease in the permeability was observed as the volume percentage of the smaller glass beads increased. The influence of a possible transition/mixed zone between layers was not clear because of the small ratios of the used glass beads. This is also the case for the effect of the porosity on the permeability. In addition, test samples were prepared to calculate the theoretical harmonic permeability to be able to compare it with the actual measured permeability. This theoretical harmonic permeability seems in the case of the coarsening upward samples smaller than the actual measured permeability as was expected from findings of another research. This study confirms the influence of the relative positioning of the layers with their specific properties on the overall permeability and the deviation from the theoretical harmonic permeability. Future prediction of the permeability’s in layered deposits is a little bit more educated with the findings of this study.

Content

1. Introduction

One of the most important engineering properties is the permeability of soils, it's required in the design of various soil structures and for the determination of the productivity of reservoirs as an example.

The driving force for flow in porous media is shown by Darcy's law (eq. 1.1); Darcy's law is a physical principle which applies to most groundwater flows. Here one can see the large influence of the permeability on the overall flow.

Darcy's law is stated as follows:

$$Q = -k\frac{A * \Delta P}{L * \mu} \tag{1.1}$$

The volumetric flow rate (Q [m/s^3]) is directly influenced by the permeability (k [m/s] or [Darcy]).

Many experiments have been conducted to measure permeability in the lab. In a previous research **[1]** for instance, samples containing glass beads with a 1mm and 3mm diameter were used in 4 different settings: only 1mm bead size, only 3mm bead size, 1mm on top of 3mm bead size and 3mm on top of 1mm bead size. From this research one could conclude that there is a decrease in porosity at the transition zone between the different bead sizes. In this transition zone, a certain amount of mixture takes place which reduces the porosity. *Vriesde, K. (2015)* **[2]** conducted a further research of the effect on porosity and permeability by this so called mixture zone by taking binary mixed samples from ϕ0.42mm, ϕ1mm, ϕ3mm and ϕ5mm glass bead sizes at different volumetric fractions. The conclusion of this research is that a decrease in porosity in binary mixtures will influence the permeability of the sample.

In addition to the two mentioned researches above, *Opschoor, T.* **[3]** used samples with layered beds with different bead sizes to create more mixed zones to figure out what the impact will be for the total permeability of the sample. One could conclude from this research that at a low ratio of bead size diameter (1.67), little to no mixing takes place between layers. This results in a small influence on permeability of the layered samples. At increasing ratios of glass bead diameter, more mixing between layers takes place with a decreasing permeability as a result. Also, the more layers in a sample, the more transition/mixing zones, the larger the permeability decrease.

This research will combine the researches of ***Vriesde, K. (2015)*** *and* ***Opschoor, T. (2016)*** by measuring the permeability and porosity in three-layered samples, with the top and bottom layer consisting of uniform glass bead size and the middle layer consisting of a binary mixture with different volumetric fractions. The glass bead sizes used for constructing these samples will be 1mm and 3mm. With this delicate difference in comparison to the previous experiments the aim is to simply simulate geological fining upward and coarsening upward sediment deposits and find out how the permeability is manifested in such formations.

2. Method

2.1 Setup

The permeability measurements were conducted using a falling head setup which is shown in figure 2.1. The falling head setup operates on Bernoulli's principle and Darcy's law. This will be explained mathematically in more detail in section 2.3. The sample holder is at the bottom and it can be filled with unconsolidated material like glass beads. With use of a vacuum pump, water is sucked in the column. A differential pressure meter is connected to the bottom of the column, just above the sample holder. This setup was made by J. Etienne and made practical and functional by K. Heller. The column is then exposed to atmospheric pressure and water starts flowing through the sample holder. The differential pressure meter is also connected to a Temp Press USB Box and by using the LabVIEW System Design Software one can measure the pressure per second. This data can be saved and exported to Excel to calculate the height difference and thus the permeability (see section 2.4). A more step by step explanation can be found in Appendix B.

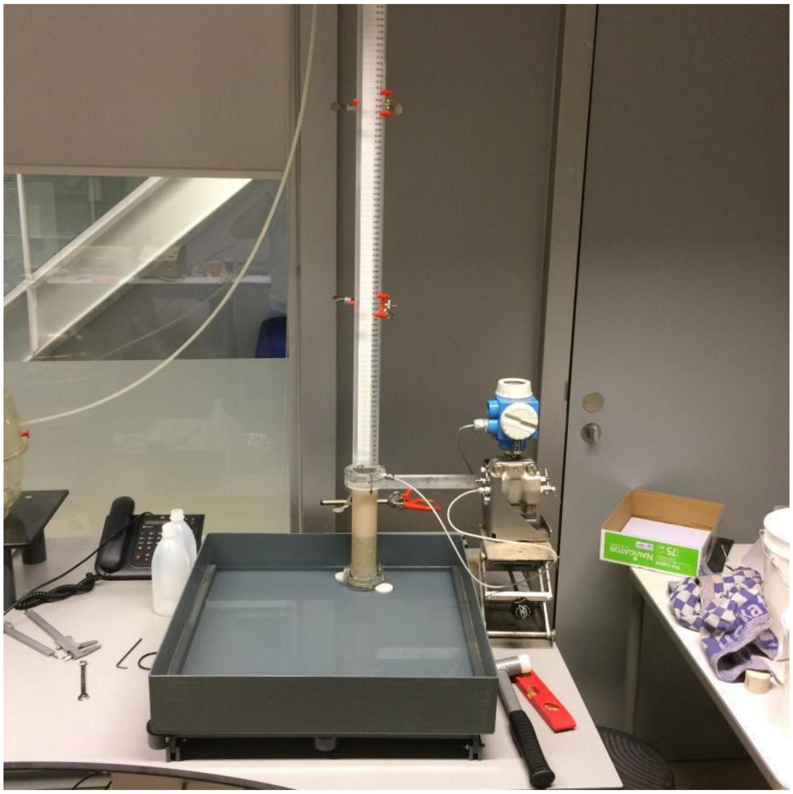


Figure 2.1: Falling head setup

2.2 Samples and Sample Construction

Three kinds of samples are used to determine the permeability. Figure 2.3 is a schematic image of the samples used and can be found on the next page. With the test samples one can measure the permeability's of uniform 1-layered samples, binary mixtures with different volumetric percentages and two-layered samples with different glass bead diameter. These test samples will not only providing comparison results but also provide an experience in construction the actual samples. It's more consistent to use data acquired according the same method instead of using literature values. The 'Coarsening upward' and 'fining upward' samples are the actual samples this research focuses on and try to understand. They are the same except that the bottom and top layer are reversed to initiate transition zones to occur to find out what their impact is on the permeability.

The sample construction is a matter of experience and consistency. The sample holder has a total length of 22cm and its area is perpendicular to the flow direction. The glass beads used must have known densities and known mass, one should be careful when placing the beads in the sample holder and try not to spill any. Unfortunately, when preparing binary mixtures, it's really hard to not spill, so one have to measure always the total mass of the whole sample to be accurate and if needed to start all over again.

Furthermore, one should note the length of the different layers in every sample, because after pouring the glass beads in the sample, settlement will occur. The measured length of the layer will determine the volume of the matrix and if this is not accurate enough, it could lead to big differences in the porosities. Figure 2.2 shows a filled 2-layered sample holder.

Figure 2.2: Filled sample holder

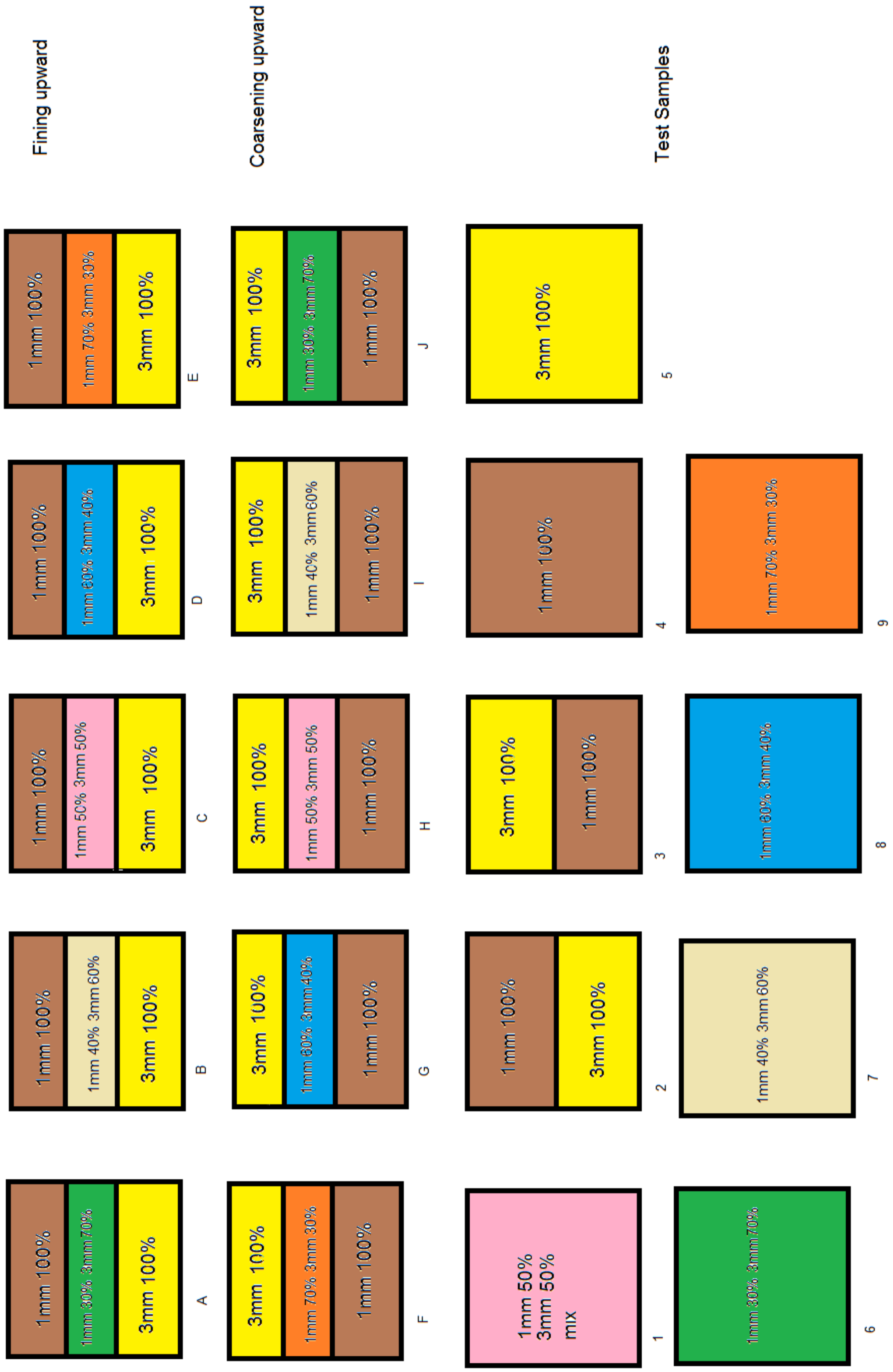


Figure 2.3: Schematic image of the used samples. A-E (fining upward), F-J (coarsening upward) and 1-9 (test samples). In the following sections, to not be ambiguous, samples will be referred by their number or letter.

2.3 Formulae

2.3.1 Permeability of sample

The used formula for the falling head test is derived from Bernoulli's principle and Darcy's law. It must be clear that the total head is a combination of the pressure head as well as the gravitational head. The total pressure is then calculated by multiplying those two heads by the density of water and the gravitational constant. This can be seen in equation 2.1: (the table of symbols is given in Appendix A)

$$P_{total} = (z + h_{column}) * g * \rho_{water} \tag{2.1}$$

The gravitational head 'z' is the same as the length of the sample 'L' which gives eq. 2.2

$$P_{total} = (L + h_{column}) * g * \rho_{water} \tag{2.2}$$

Darcy's law is stated as follows:

$$\mathrm{Q} = -\mathrm{k}\frac{\mathrm{A}* \Delta\mathrm{P}}{\mathrm{L}* \mu} \tag{2.3}$$

The volumetric flow 'Q' can be rewritten as

$$Q = \frac{dV}{dt} = \frac{A*dH}{t} \tag{2.4}$$

Substituting eq. 2.4 into eq. 2.3

$$\frac{dh}{dt} = -k * \frac{\Delta P}{L} * \frac{1}{\mu} \tag{2.5}$$

Eq. 2.2 is substituted in eq. 2.5

$$\frac{dh}{dt} = -k * \frac{(h+L)*\rho_{water}*g}{L} * \frac{1}{\mu} \tag{2.6}$$

Now integrate over height and time

$$\int \frac{1}{(h+L)}\, dh = -\frac{k*\rho_{water}*g}{L*\mu} * \int dt \tag{2.7}$$

$$\ln(h + L) = -\frac{k*\rho_{water}*g}{L*\mu} + C \tag{2.8}$$

With known boundary condition t = 0, then h = h_0,

Constant of integration becomes:

$$C = \ln(h_0 + L) \quad \text{For t = 0} \tag{2.9}$$

Final equation now becomes:

$$k * t = \frac{\mu * L}{\rho_{water} * g} * \ln(\frac{h_0 + L}{h + L}) \tag{2.10}$$

2.3.2 Harmonic permeability

In the field, soils, more often are found to exist as stratified deposits than as homogenous masses. In the used samples A-J (see figure 2.3) there are three layers, each layer with a specific length and specific permeability. When the length and the specific permeability (test samples) are known one can calculate the permeability mathematically of layered systems as a harmonic-average.

The permeability of a stratified soil deposit, when the flow is normal to the orientation of the bedding planes, is obtained by eq. 2.11 **[4]**:

$$k_{average} = \frac{L_{total}}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \dots \frac{L_n}{k_n}} \tag{2.11}$$

2.3.3 Porosity

Porosity is the amount of void space between pores, which is influenced by grain size distribution, cementation, grain shape and grain contact. In this research there are four ways for calculating the porosity depending on which sample is used:

1. Uniform layer
2. Binary mixture
3. Average porosity for multiple layers
4. Transition/mixed zone

1. Uniform layer

For a uniform layer, like in sample 4 and sample 5, it’s easy to calculate the porosity:

$$\varphi = \frac{\mathrm{V_{total}} - \mathrm{V_{matrix}}}{\mathrm{V_{total}}} \tag{2.12}$$

Where V_{matrix} (eq. 2.13) and V_{total} (eq. 2.14) are given by

$$V_{matrix} = \frac{m_{glass\ bead}}{\rho_{glass\ bead}} \tag{2.13}$$

$$V_{total} = \text{Length * Area} \tag{2.14}$$

There are another ways to express V_{total} and V_{matrix}, namely:

$$V_{total} = V_{matrix} + \varphi V_{total} \tag{2.15}$$

$$V_{matrix} = (1 - \varphi) V_{total} \tag{2.16}$$

2. Binary mixture

The porosity of the binary mixtures is more difficult to calculate. First, one should know how to construct binary mixed samples and what assumptions were made.

To calculate the mass needed of the two glass bead sizes that will form a mixture of a certain volume percentage, one must make two assumptions. First, the porosity is set to any realistic arbitrary porosity and secondly a sample length has to be set.

For example, a mixture of glass beads containing sizes of ϕ1mm and ϕ3mm, the V_{matrix} can be expressed as follows:

$$V_{matrix} = V_{1mm} + V_{3mm} \tag{2.17}$$

Equation (2.17) can be rewritten in terms of mass and density:

$$V_{matrix} = \frac{m_{1mm}}{\rho_{1mm}} + \frac{m_{3mm}}{\rho_{3mm}} \tag{2.18}$$

In the case of sample 6, with 30% ϕ1mm and 70% ϕ3mm glass beads the needed mass can be expressed as:

$$m_{1mm} = \frac{3}{10}\left((1-\varphi)V_{total}\right) * \rho_{1mm} \tag{2.19}$$

$$m_{3mm} = \frac{7}{10}\left((1-\varphi)V_{total}\right) * \rho_{3mm} \tag{2.20}$$

In the case of test sample 6, assuming 21 cm length of sample to be filled, the theoretical mass needed to construct this 21cm length is now known. After mixing the glass beads carefully and pouring them into the sample holder, the vacuum pump can turned on water will be sucked into the column. After tapping the sample holder a few times with a hammer, the binary mixture will compact and settle. It's now possible to measure the length of the binary mixed sample, and with this measured length one can calculate the actual porosity.

3. Average Porosity for multiple layers

Samples A-J consists of 3 layers, to calculate the average porosity of the whole sample one should add all the matrix volumes of each sub layer. This is shown in equation 2.21:

$$\varphi = \frac{V_{total} - (V_{matrix,L1} + V_{matrix,L2} + V_{matrix,L3})}{V_{total}} \tag{2.21}$$

4. Transition/mixed zone

This is the hardest porosity to accurately measure. In this research this is only done for test sample 2. This can be found in Appendix E.

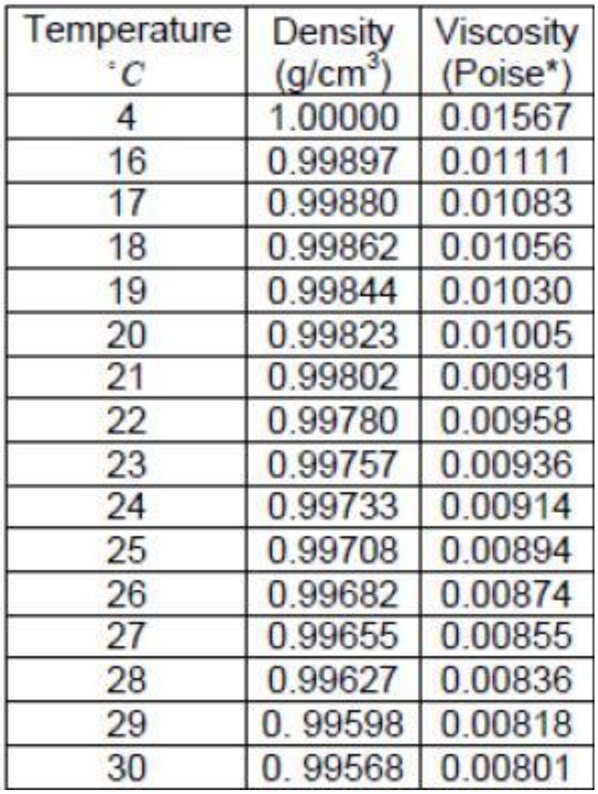
2.4 Pressure to column height

From equation 2.10, it can be concluded that the height of the water column is needed in order to calculate the permeability. The setup measures the pressure difference; a conversion from pressure to height of column is now necessary. The pressure of the column is stated as follows:

$$P_{column} = \rho_{water} * g * h_{column} \qquad (2.22)$$

The pressure meter measures the pressure in mbar. It’s known that 1 bar is equal to 10^5 Pa and this is the same as a column of 10m H_2O.

Table 2.1 shows the properties of demineralized water with temperature:



Temperature °C	Density (g/cm^3)	Viscosity (Poise*)
4	1.00000	0.01567
16	0.99897	0.01111
17	0.99880	0.01083
18	0.99862	0.01056
19	0.99844	0.01030
20	0.99823	0.01005
21	0.99802	0.00981
22	0.99780	0.00958
23	0.99757	0.00936
24	0.99733	0.00914
25	0.99708	0.00894
26	0.99682	0.00874
27	0.99655	0.00855
28	0.99627	0.00836
29	0. 99598	0.00818
30	0. 99568	0.00801

Table 2.1: Properties of demineralized water

Taking the properties at 20 degrees Celsius, equation 2.22 can now be used for the conversion:

$10\ m\ H_2O$ = 998.23 * 9.81 * 10 = 97926 Pa

1 Pa = 1.0212 * 10^{-4} m H_2O (2.23)

3. Results

In the following section the results of the falling head tests will be given. First there will be a brief explanation of the used parameters and software functions for the permeability and porosity calculation. In the second part the results of the test samples will be displayed. Then the results of the fining and coarsening upward will be shown. At last the porosity results will be summarized for all samples. The images of the used samples can be found in Appendix C. There is a variation in the results acquired from the falling head test, so in Appendix D there is an error calculation of the permeability measurements.

3.1 Constants and used software functions

The permeability of each measurement is calculated by using the least square method to draw a straight tangent line through the measured data points. This specific function is called ‘LINEST’. This is done in Microsoft Office Excel as well the rest of the calculations and figures.

The dimensions of the sample holder are as follows:

-Length: 22 cm
-Inner diameter: 4cm

The densities of the ϕ1mm and ϕ3mm glass beads were determined with the use of a Pycno meter; those densities are needed for porosity calculations.

-ϕ1mm: 2946.9 kg/m^3
-ϕ3mm: 2899.8 kg/m^3

Using equation 2.10, there are three constants that need to be specified for the permeability calculations: the water density, the water viscosity and the gravitational constant. Both the water density and the water viscosity are temperature dependent. Because of the air-conditioning in the EMP-laboratory where the permeability machine is located a constant temperature of 20 degrees Celsius is maintained in the demineralized water. So for eq. 2.10 one can use the following constants:

-ρ_{water} = 998.23 kg/m^3
-μ = 0.001005 Pa s
-g = 9.81 m/s^2

3.2 Test samples

There are 9 test samples, 7 of those samples can be displayed as a binary mixture. For example a uniform ϕ3mm glass bead sample, sample 5, is a binary mixture with 0% ϕ1mm glass bead volume percentage. Sample 2 and 3, the two layered test samples will be displayed separately. The purpose of the test samples is to have self measured data that will be used for the harmonic calculations in the next section. Also one is more consistent if the acquired data is done with one and the same permeability testing setup. Trends can now be easily detected.

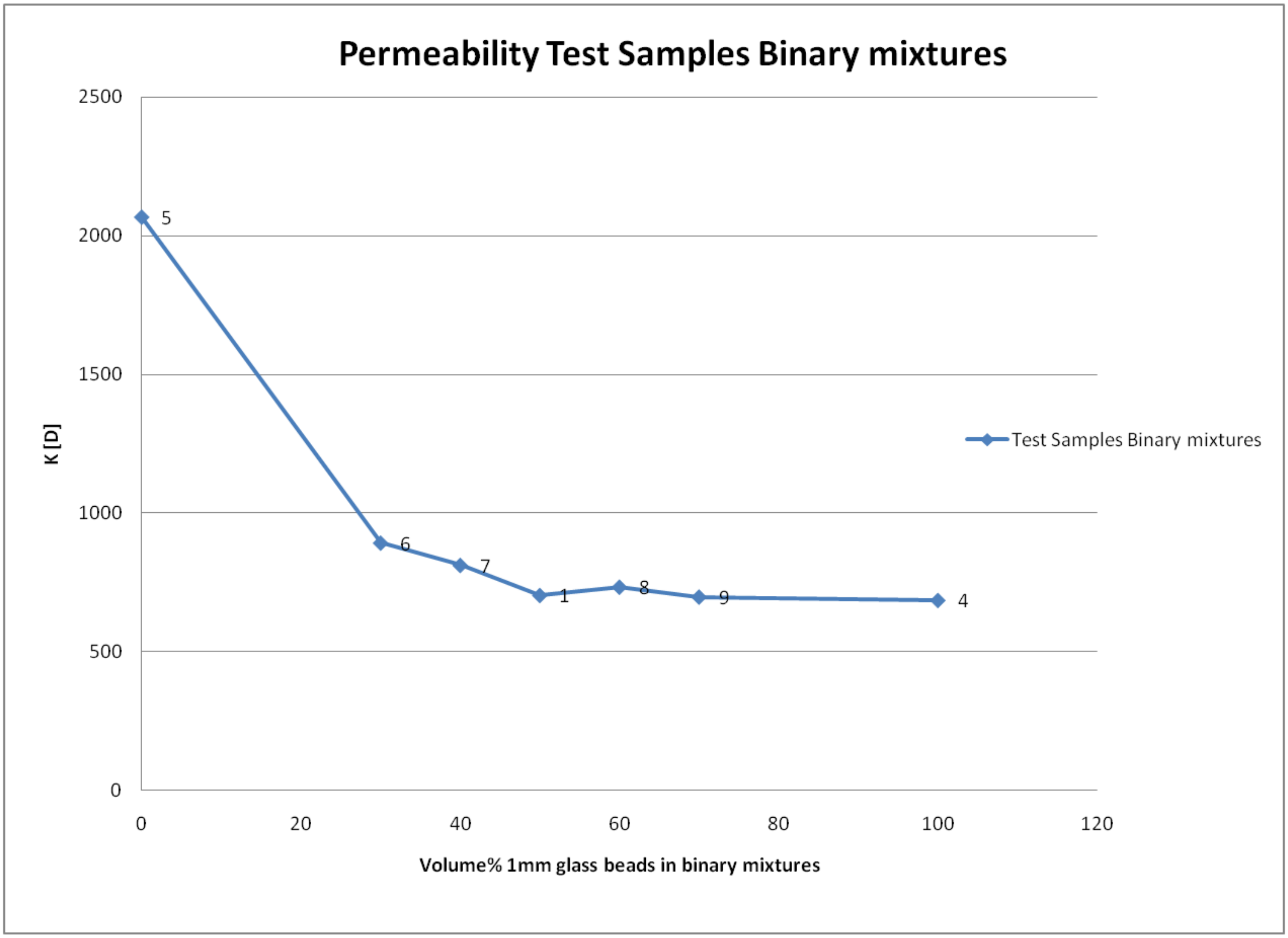


Figure 3.1: The permeability's of the 7 binary mixed test samples

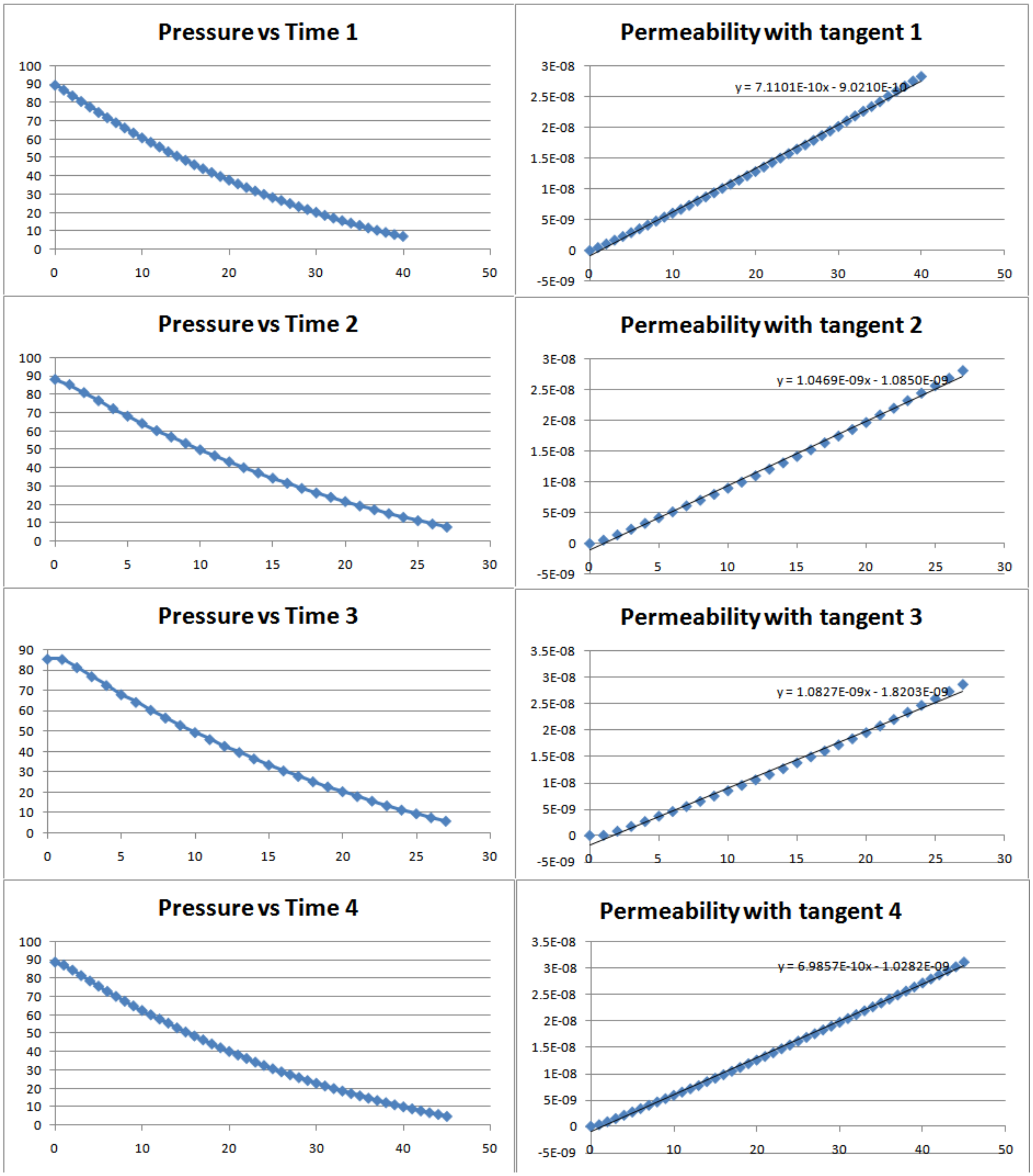
One should notice the visible decrease in permeability as the volume percentage of the ϕ1mm glass beads goes up. With a maximum at 0% ϕ1mm volume percentage (sample 5: 2067.20 D) and at 100% ϕ1mm volume percentage (sample 4: 686.53 D).

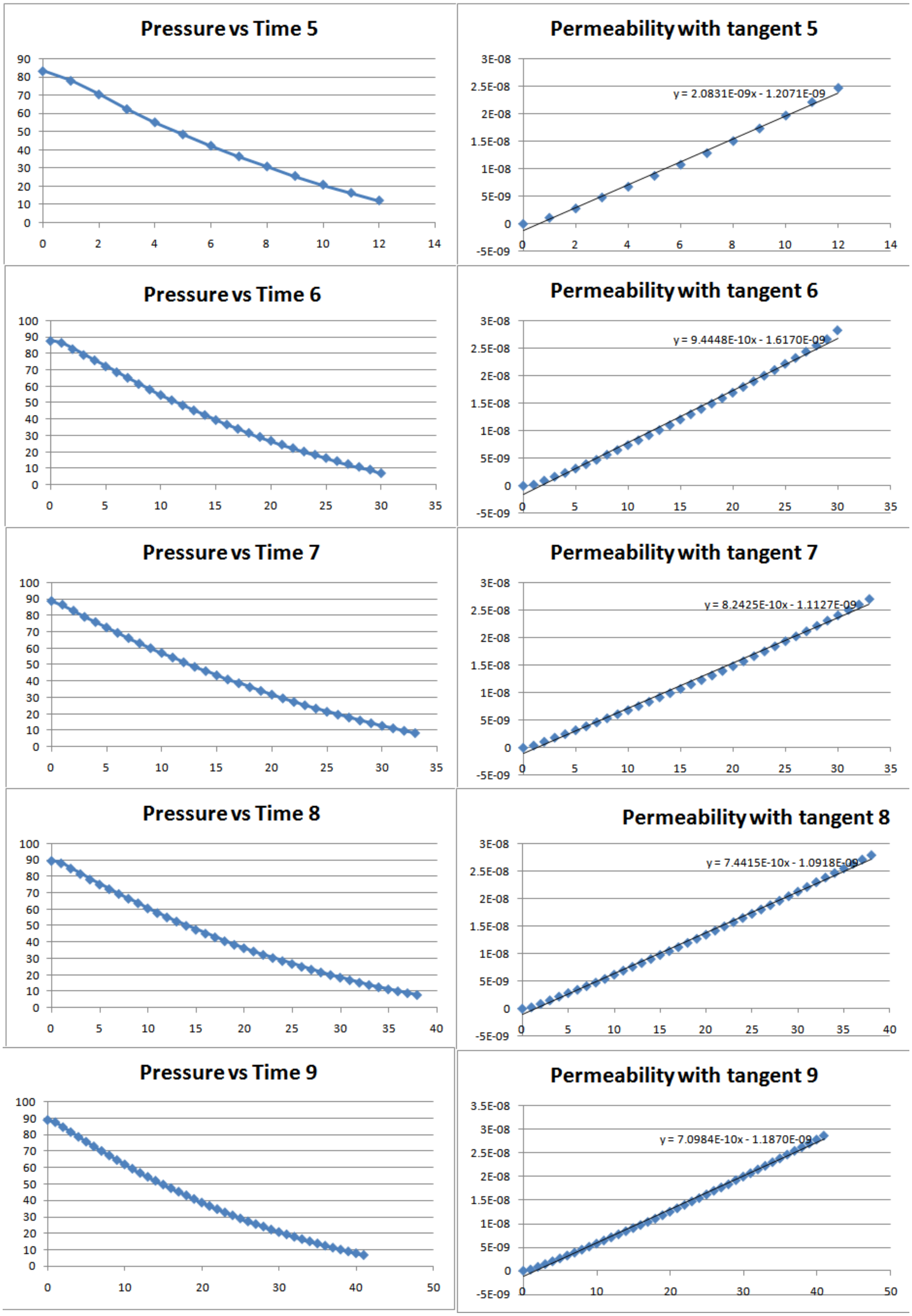
The measured permeability for the two-layered samples 2 and 3 is displayed in table 3.1:

Sample	test 1 [Darcy]	test 2 [Darcy]	test 3 [Darcy]	test 4 [Darcy]	K average [Darcy]
2	1046.870377	1026.98361	1022.746471	1002.157816	**1024.689568**
3	1082.707745	1062.986596	1040.463793	1033.230322	**1054.847114**

Table 3.1: measured permeability of sample 2 and 3

Figure 3.2 shows the pressure vs. time and permeability with tangent for all the test samples for the first test. The trend lines drawn are labeled with their specific equation. The gradients of those trend lines are the permeability in [m^2]. With the conversion of 1 D = 10^{-12} m^2 the permeability in Darcy is now calculated.





Pressure vs Time 5

Permeability with tangent 5

Pressure vs Time 6

Permeability with tangent 6

Pressure vs Time 7

Permeability with tangent 7

Pressure vs Time 8

Permeability with tangent 8

Pressure vs Time 9

Permeability with tangent 9

Figure 3.2: Pressure vs. time and permeability with tangent trend line for all 9 samples for the first test

3.3 Samples A-J and harmonic permeability

Samples A-E resemble a fining upward geologic sequence and samples F-J resemble a coarsening upward geologic sequence. In those 3-layerd samples, one can test if the effect of transitions/mixed zones as earlier described have an influence on the total permeability. It's also possible to compare the measured permeability's with the theoretical harmonic permeability. Finally, it may be interesting to take a look at the effect of the volume percentages of the ϕ1mm glass beads on the total permeability and porosity.

The permeability's of the 10 samples (A-J) are displayed in figure 3.3:

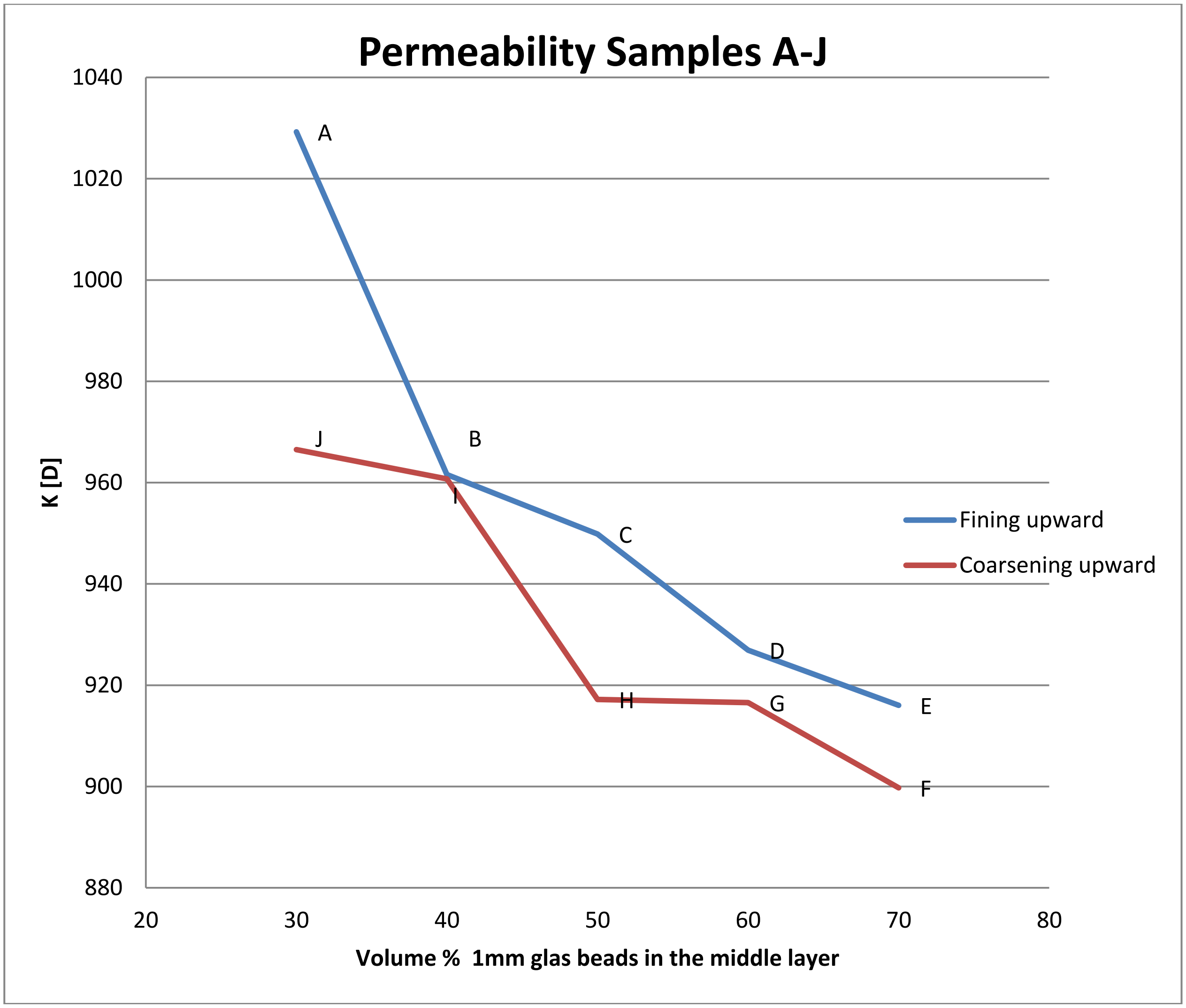


Figure 3.3: Permeability's samples A-J

It's clear from figure 3.3 that as the volume percentage of the 1mm glass beads increase, the permeability drops. This is the same behavior as earlier shown in figure 3.1 for the binary mixtures. It seems that the middle layer, containing the binary mixture in the 3-layered samples is the bottleneck for the flow. One should also notice that there is a less likeable behavior occurring than was expected. The influence of a so called transition/mixed zone in the fining upward samples can't be seen. This will be examined in the discussion section in more detail.

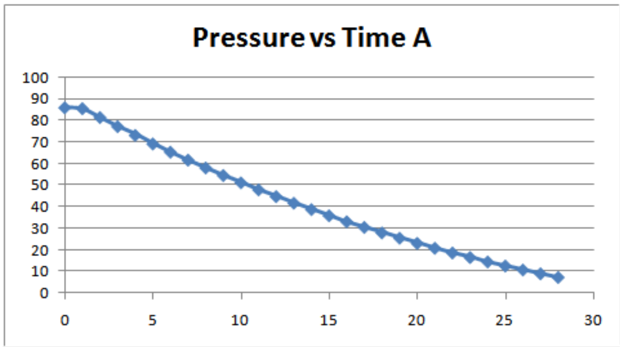
In table 3.2 are the theoretical harmonic permeability's listed as the corresponding measured permeability for samples A-J:

Sample	Measured permeability [D]	Theoretical Harmonic Permeability [D]
A	1029.245592	983.2007786
B	961.5791544	950.7990557
C	949.8288197	900.0074547
D	926.9239439	914.9075378
E	916.0243849	895.8171499
F	899.7324574	895.8171499
G	916.5483286	914.9075378
H	917.1783334	900.0074547
I	960.7354713	950.7990557
J	966.522227	983.2007786

Table 3.2: Measured permeability and theoretical harmonic permeability listed for samples A-J The red value is the only theoretical harmonic value that's higher than the measured permeability.

All the samples have a lower theoretical harmonic permeability than what was actually measured except sample J. This trend will be discussed in the next section in more detail and compared with the findings of other studies.

Finally, the pressure vs. time and permeability with tangent trend lines are displayed in figure 3.4 on the next two pages for samples A-J for the first test.


Pressure vs Time A
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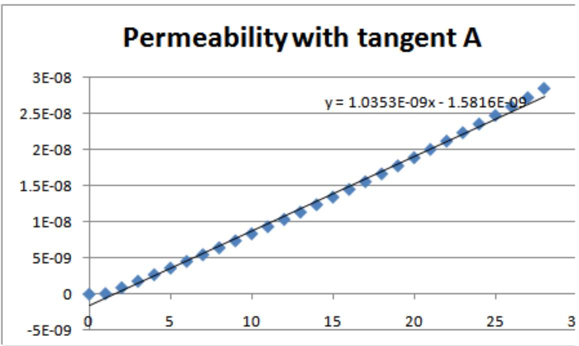
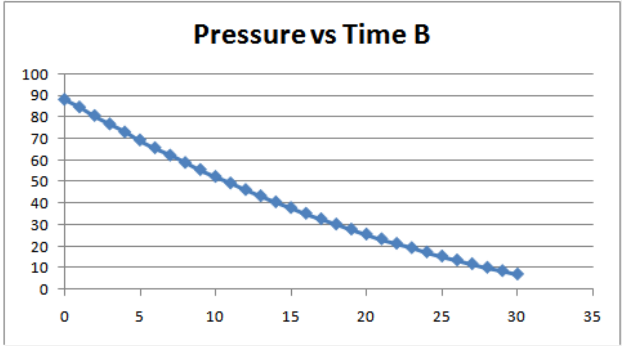
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30


Permeability with tangent A
3E-08
2.5E-08
2E-08
1.5E-08
1E-08
5E-09
0
-5E-09
y = 1.0353E-09x - 1.5816E-09
0
5
10
15
20
25
3


Pressure vs Time B
100
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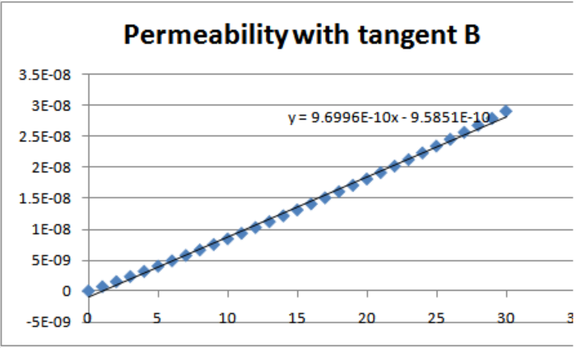
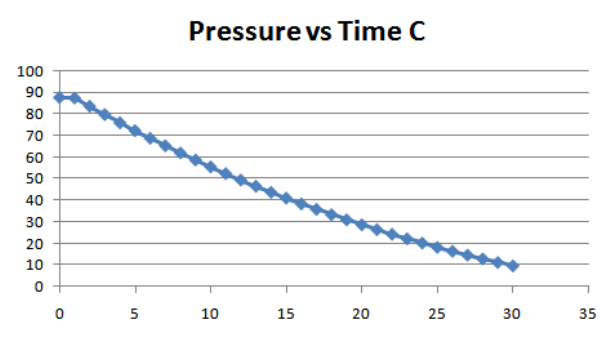
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35


Permeability with tangent B
3.5E-08
3E-08
2.5E-08
2E-08
1.5E-08
1E-08
5E-09
0
-5E-09
y = 9.6996E-10x - 9.5851E-10
0
5
10
15
20
25
30
3


Pressure vs Time C
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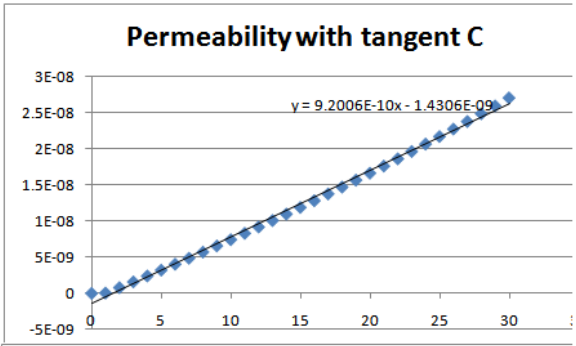
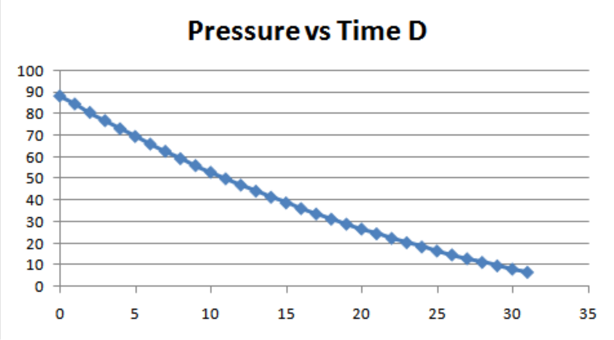

Permeability with tangent C
3E-08
2.5E-08
2E-08
1.5E-08
1E-08
5E-09
0
-5E-09
y = 9.2006E-10x - 1.4306E-09
0
5
10
15
20
25
30


Pressure vs Time D
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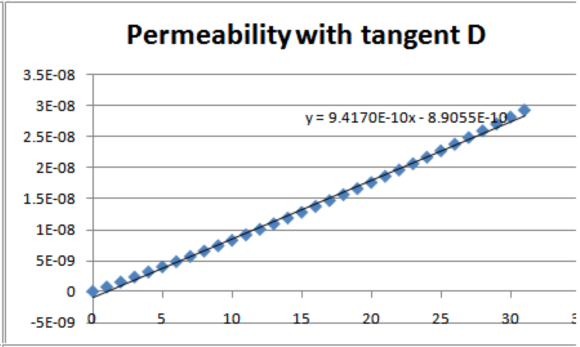
Permeability with tangent D
3.5E-08
3E-08
2.5E-08
2E-08
1.5E-08
1E-08
5E-09
0
-5E-09
y = 9.4170E-10x - 8.9055E-10
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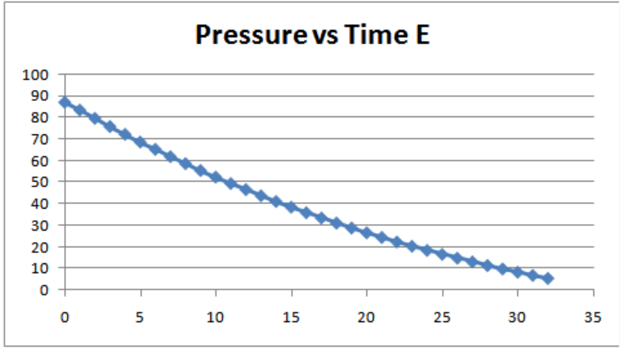
Pressure vs Time E
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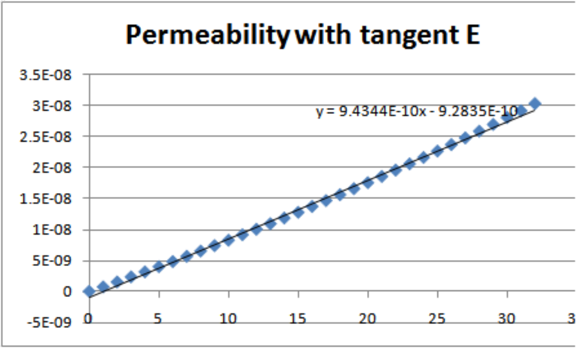
35


Permeability with tangent E
3.5E-08
3E-08
2.5E-08
2E-08
1.5E-08
1E-08
5E-09
0
-5E-09
y = 9.4344E-10x - 9.2835E-10
0
5
10
15
20
25
30
3

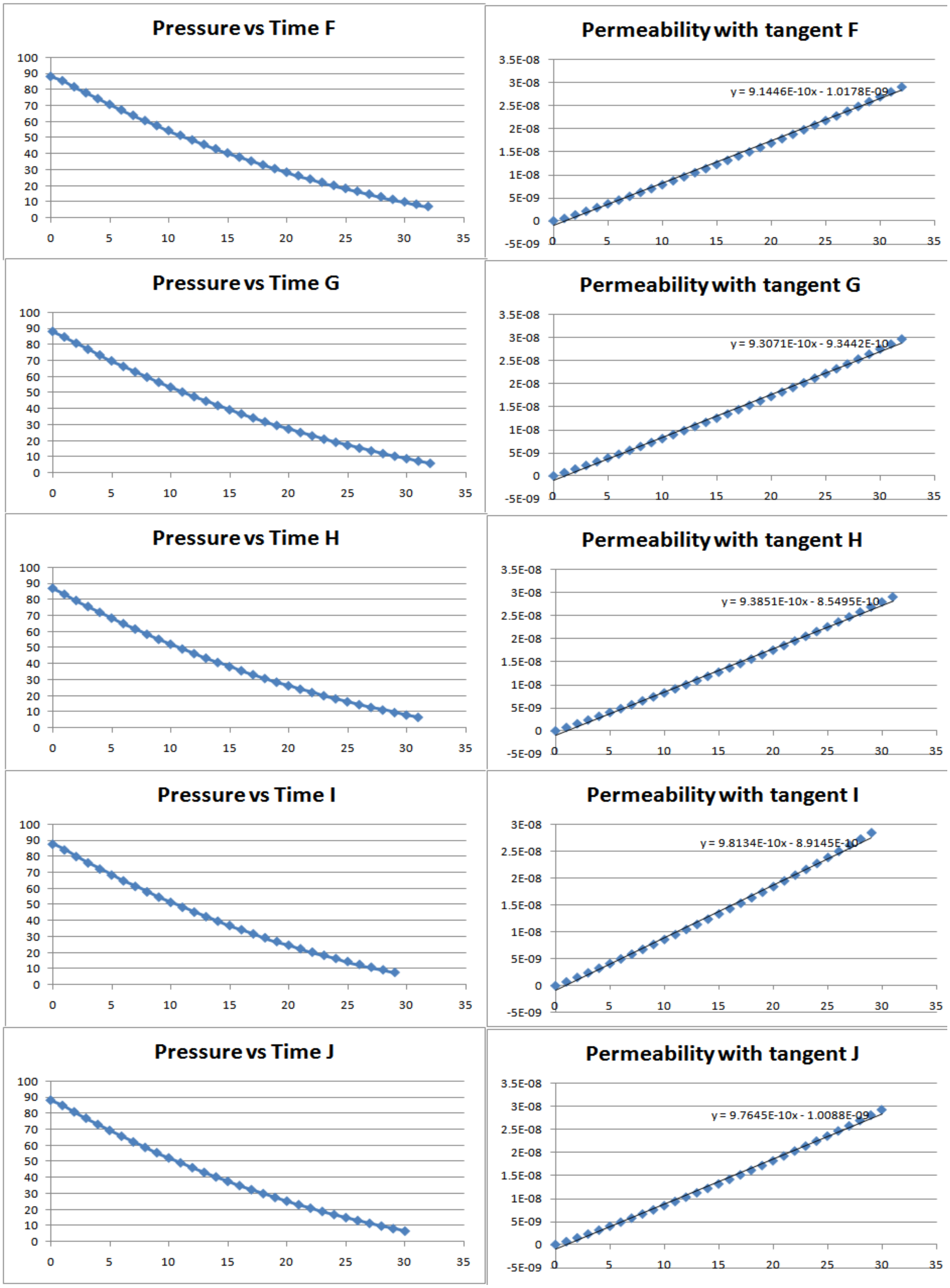


Figure 3.4: Pressure vs. time and permeability with tangent trend line for samples A-J

3.4 Porosity

As earlier on mentioned, in this research there were four ways to calculate the porosity. For uniform samples and binary mixtures it's not necessary to visualize the porosity because it's one (average) value. In practice the porosity is not constant through the sample because the glass beads are not 100% identical and the way in which the glass beads settle differ in each test a little bit. But the variation in porosity is so small that it's safe to assume one value for the porosity.

For the two two-layered samples, 2 and 3, it's possible to display both porosities for each layer. Also, in the case of sample 2 there is a third porosity, namely the transition zone one. This can be seen in figure 3.5. In figure 3.6 the porosity distribution for sample 3 is displayed.

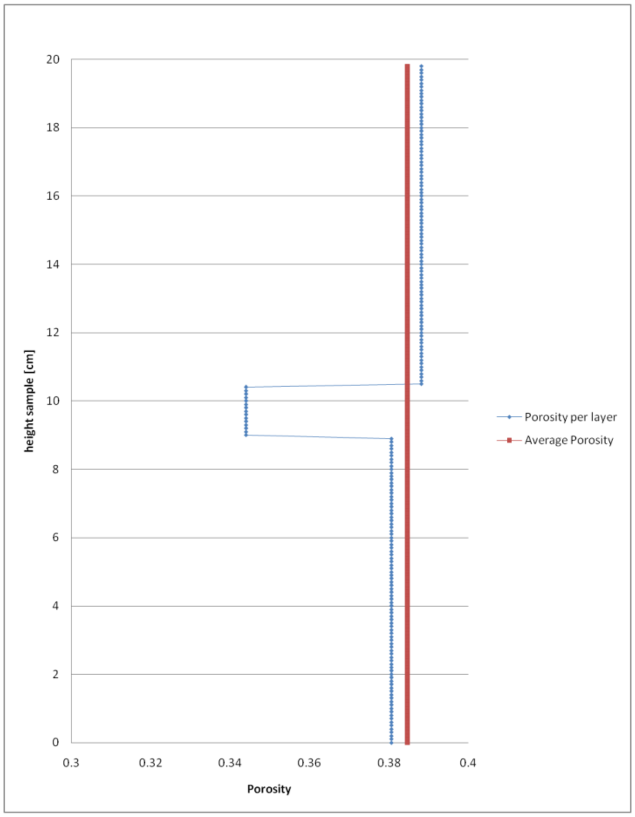


Figure 3.5: Porosity distribution of sample 2

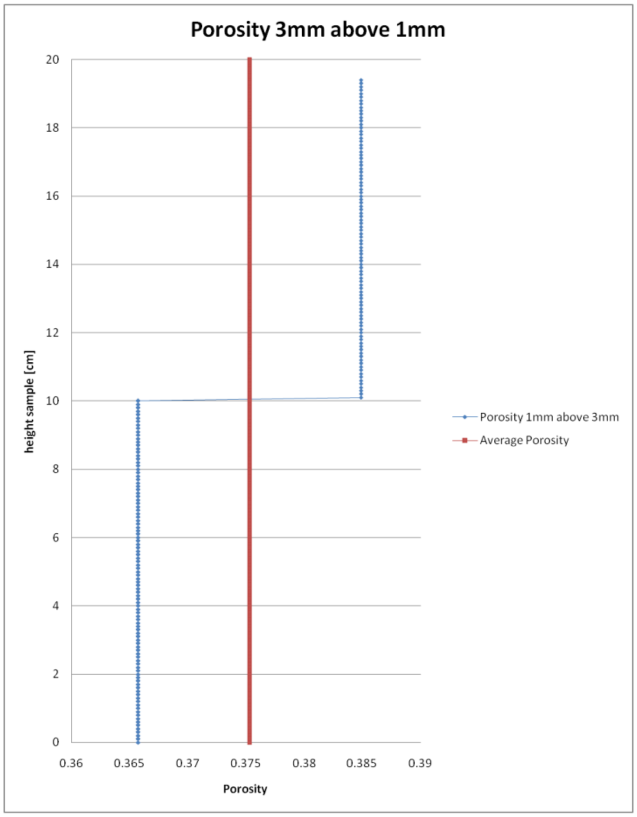


Figure 3.6: Porosity distribution of sample 3

How the porosity of the transition zone in sample 2 is calculated is shown in appendix E as earlier on mentioned. The straight lines shown in both figures 3.5 and 3.6 are theoretical calculated porosities. In practice one should expect a more ribbed behavior through the sample.

In the coarsening upward sequence it's safe to assume that there are no transition/mixed zones occurring between the layers, because the coarser beads are on top of the fine ones. Unfortunately it's really hard to measure the length of the transition zones in the fining upward samples because one can't see how far the fine beads settled in the coarser beads underneath. This makes porosity calculations impossible in those samples. This is displayed in the porosity distributions curves for samples A and J by figure 3.7 respectively figure 3.8 on the next page.

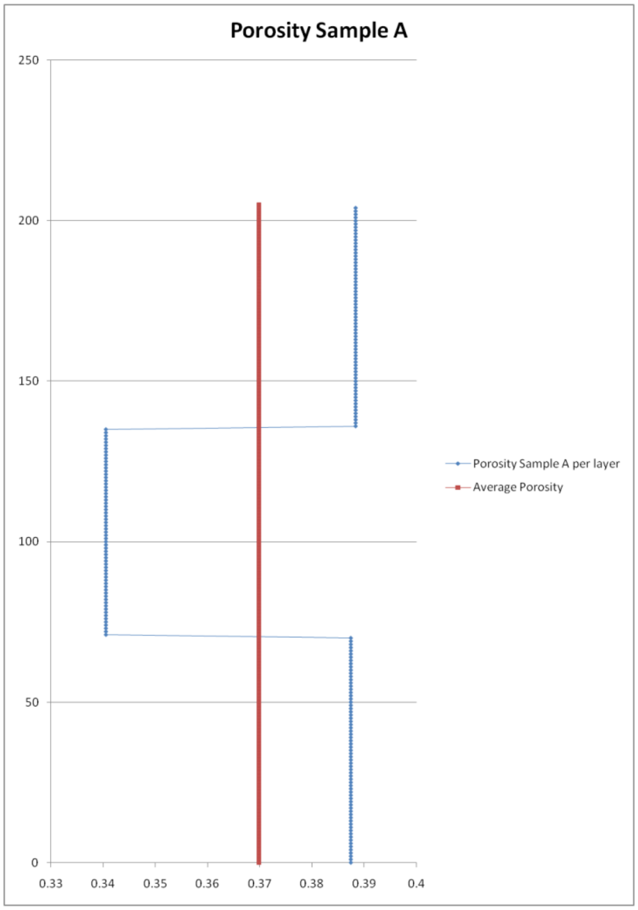


Figure 3.7: Porosity distribution sample A

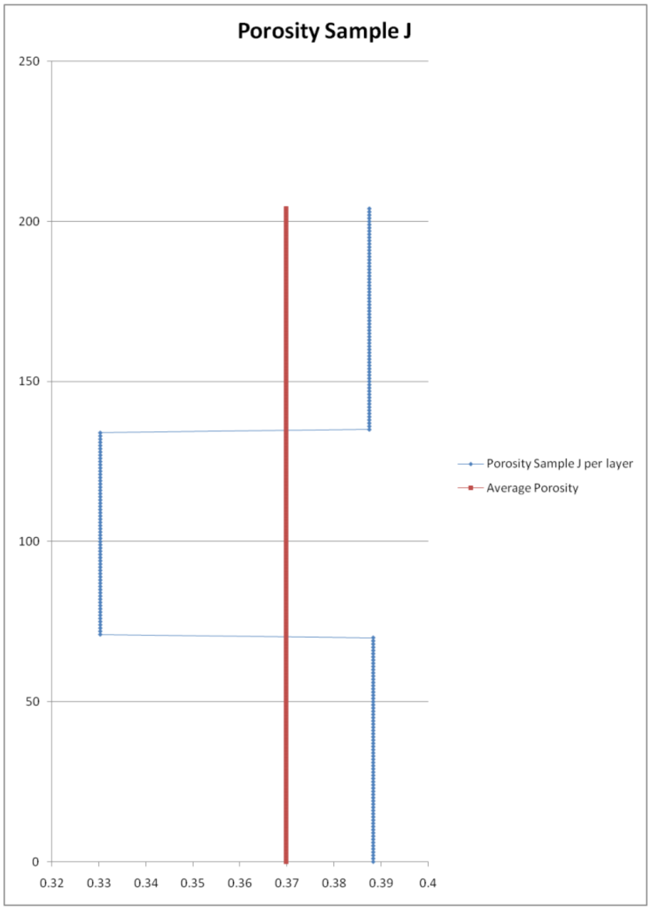


Figure 3.8: Porosity distribution sample J

It must be clear now, that those straight lines in both figure 3.7 and figure 3.8 are theoretical calculated porosities. In practice the lines are more ribbed and in the case of sample A, there is a greater decrease expected because of the existence of a mixed zone between the bottom layer and the middle layer.

The porosities for the other samples are displayed in figure 3.9 and figure 3.10 on the next page. It is clear that with uniform samples, like sample 4 and 5, the porosity is about 38%. When the volume percentages of the smaller beads increase, the porosity drops to roughly 33%-34%.

In the case of figure 3.10, one should notice that the average porosity is about 37% for most of the samples or even higher. This is expected because the binary mixed layers, with the lesser porosities, have a length of about 65mm (total length is about 200mm for most of the samples), so the flow of water is just experiencing more difficulty for a small period of time. When comparing sample A and J with sample 6, it is clear that the permeability is higher in the layered samples than in the binary mixture (sample 6) due to higher average porosity.

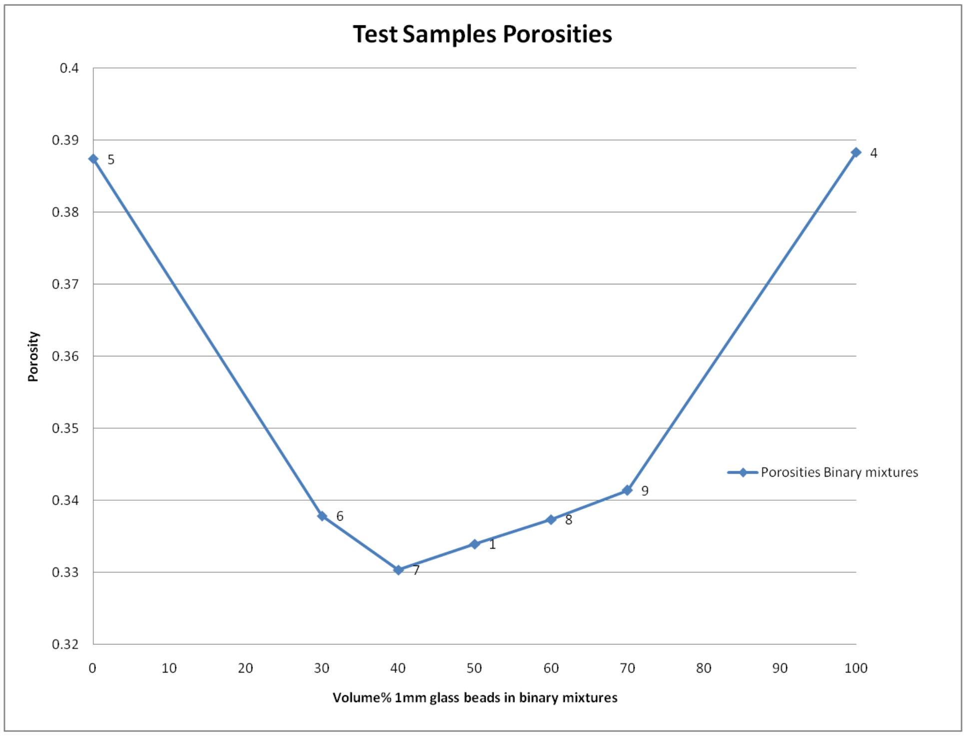


Figure 3.9: Porosities of the binary mixed test samples

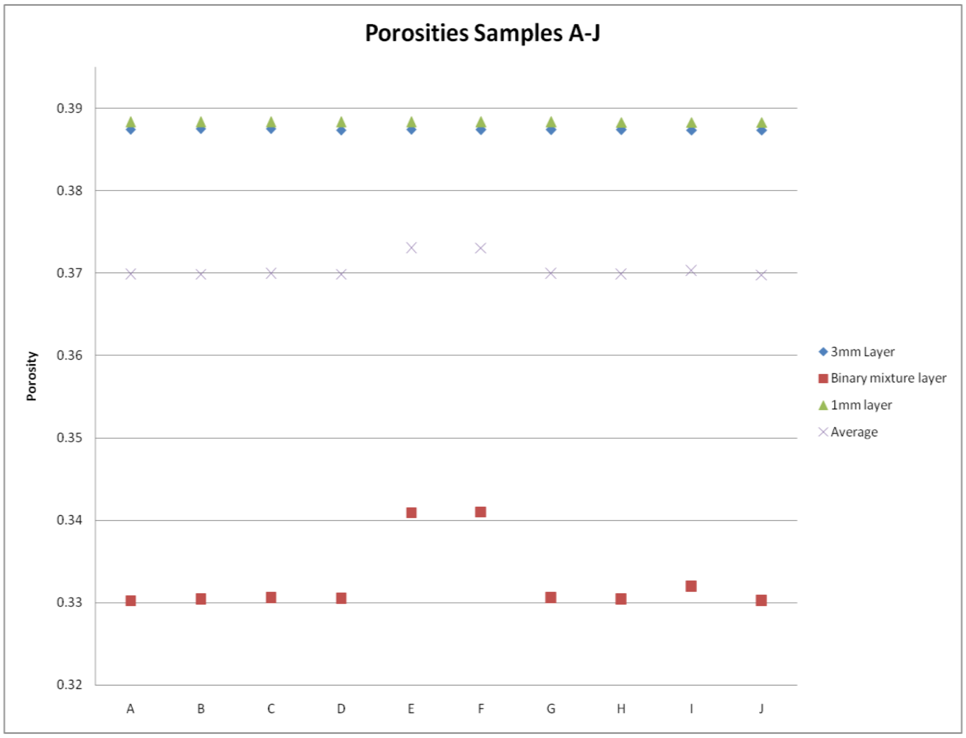


Figure 3.10: Porosities for samples A-J

4. Discussion

The following section will delve in the found results for the permeability's from the falling head tests. The results will be examined further and compared with previous experiments by other researchers. Section 4.1 focuses on the permeability's in the three-layered samples and the found relations. In section 4.2 one can find how the harmonic permeability's is related to the measured permeability by comparing the found results with another study. Section 4.3 will discuss the impact of porosity on permeability. Lastly, the found relations will be linked to general applications in practice in section 4.4.

4.1 Permeability in three-layered samples

As earlier on mentioned, samples A-J show a decrease in permeability as the volume percentage of the ϕ1mm goes up in the binary mixed middle layer. This is expected because the smaller ϕ1mm beads will fill a lot of void space in between the ϕ3mm beads. Again, the permeability's of sample A-J are displayed by figure 4.1 with a distinction made for the fining upward samples (1mm on top) and the coarsening upward samples (3mm on top). Also, the calculated theoretical permeability is displayed in this figure. This will be discussed in the next section.

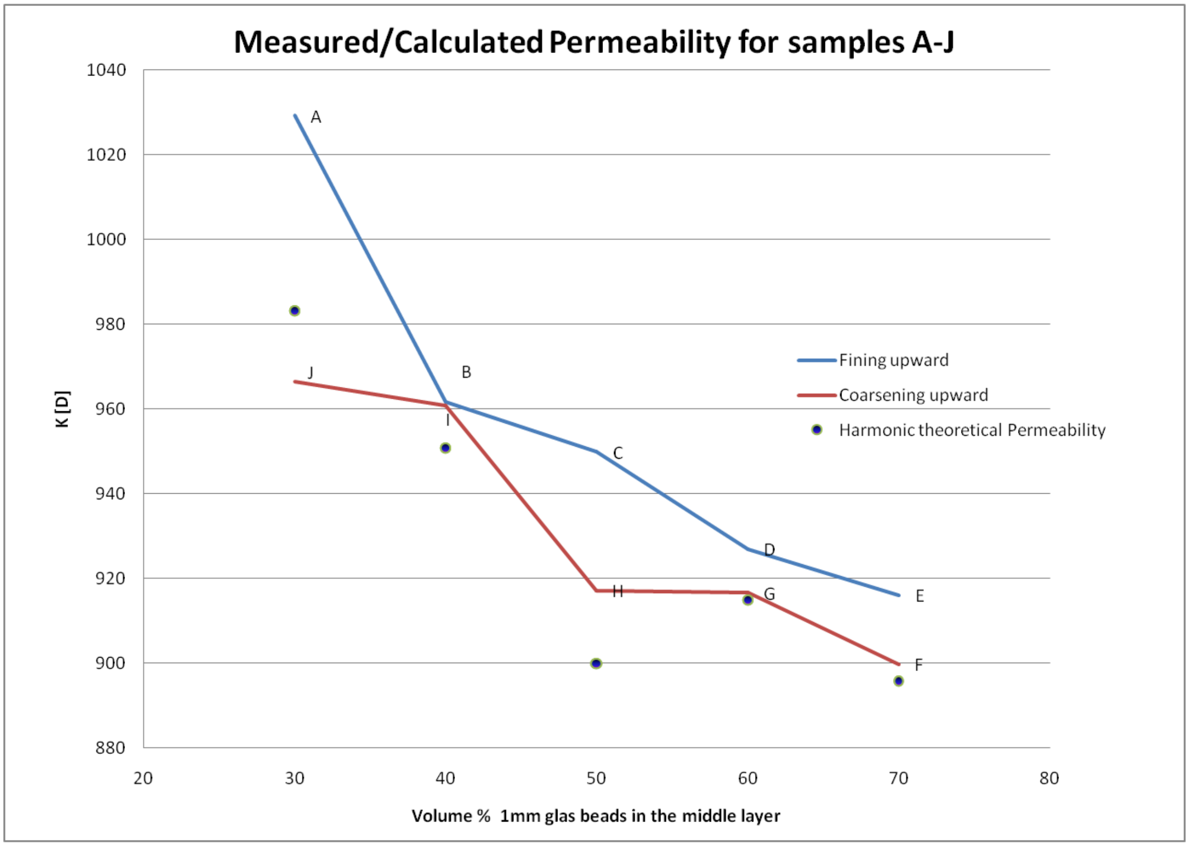


Figure 4.1: Measured/calculated permeability's for samples A-J

Both the binary mixed test samples and the 3-layered samples show a decrease in permeability as the volume percentage of the smaller beads increase. However, the binary mixed layer in the 3-layered samples is much smaller compared to the test samples. The length of most of the test samples was roughly 195mm while the length in the 3-layered sample was roughly 65mm as earlier on mentioned. This caused a smaller permeability interval in samples A-J (1029.25 D maximum/899.73 D minimum) in comparison with the test samples with a wider permeability interval (2067.20 D maximum/ 686.53 D minimum). It seems like the impact of the bottom and top layer in the 3-layered samples on the decrease of the permeability as the volume percentage of fine beads increases can be neglected. It is solely the middle binary mixed layer that acts as the bottle neck for the flow.

This decrease in permeability is also found in other studies. Figure 4.2 display results of the used test samples and results taken from the research of ***Vriesde K. (2015)*** where 1-layered binary mixtures were tested with different volumetric fractions like the used test samples in this study.

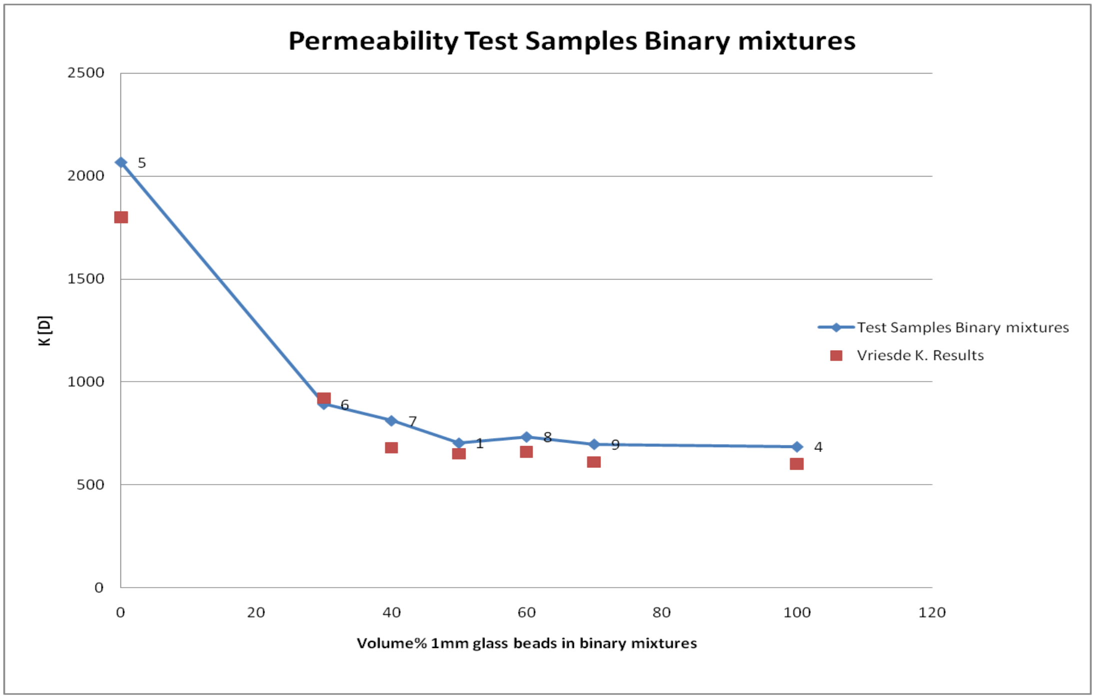


Figure 4.2: Permeability's of binary mixtures **[2]**

Furthermore, there is a questionable behavior in figure 4.1 visible. Namely, the higher permeability values for the fining upward samples in comparison with the coarsening upward samples. One expects that the blue line (fining upward) in figure 4.1 should be below the red line (coarsening upward) according to findings of other studies. This is due the existence of a transition/mixed zone. This expected behavior is shown in figure 4.3, taken from ***Opschoor T. (2016)*** on the next page. This figure shows the porosity and permeability distribution throughout the sample for a 2-layered system with a ϕ1mm- and ϕ5mm-layer. The ratio between those two glass beads is greater than the ratio of the beads used in this research. The occurring of an influencing transition zone is less likeable in the tests conducted in this study, however one still expect lower values for the fining upward samples than for the coarsening upward samples. In table 4.1 are the corresponding fining and coarsening upward samples listed with their specific permeability's and the difference between the two. Subtracting the fining upward permeability values from the coarsening upward values should provide a positive value; in this case it's negative.

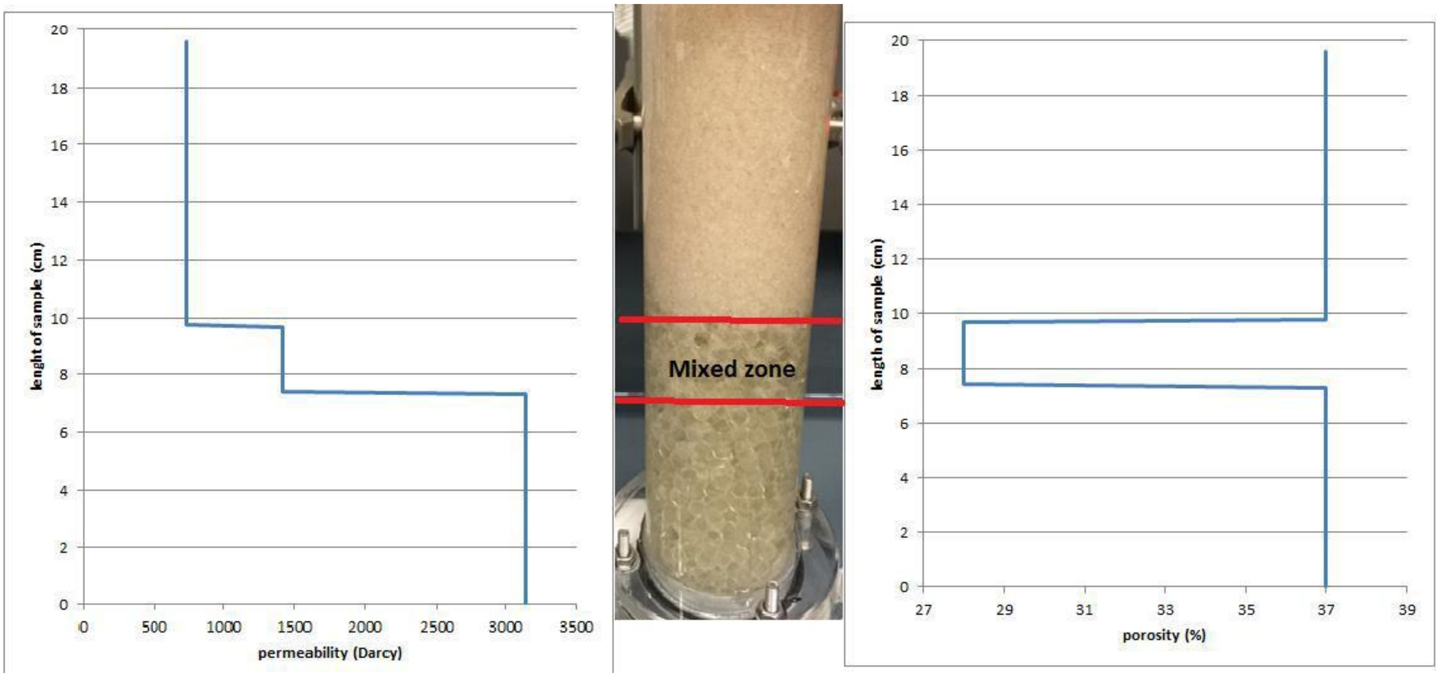


Figure 4.3: Effect of a mixed/transition zone between two layers on the permeability and the porosity **[3]**

Sample fining up	k [D]	Sample coarsening up	k [D]	Difference
A	1029.245592	**J**	966.522227	-62.72336509
B	961.5791544	**I**	960.735471	-0.843683098
C	949.8288197	**H**	917.178333	-32.65048628
D	926.9239439	**G**	916.548329	-10.37561527
E	916.0243849	**F**	899.732457	-16.29192753

Table 4.1: Corresponding fining and coarsening up samples permeability values and the difference between the two

On the other hand, the values in table 4.1 don't differ too much from each other. According to ***Opschoor T. (2016)***, there is no or little mixing between layers with a small ratio of the glass bead diameters. For example, sample A have two transition zones: The first one is between the top layer (consisting of 100% 1mm glass beads) and the middle binary mixed layer (1mm 30% and 3mm 70%). The ratio between those two layers is$\frac{0.3*1+0.7*3=2.4}{1} = 2.4$. The other transition zone is between the binary mixed layer and the bottom uniform layer (consisting of 100% 3mm glass beads). The ratio between those two layers is$\frac{3}{2.4} = 1.25$. To be sure about those results, one must repeat all the experiments by placing a permeable membrane between each layer to avoid mixing between the layers.

4.2 Harmonic permeability vs. measured permeability

In layered samples it’s possible to calculate the average permeability if the specific length and permeability are known of each layer. This is done for all the 3-layered samples and the results are displayed in figure 4.1 and listed in table 4.2.

Sample	Measured perm [D]	Theoretical Harmonic Perm [D]
A	1029.245592	983.2007786
B	961.5791544	950.7990557
C	949.8288197	900.0074547
D	926.9239439	914.9075378
E	916.0243849	895.8171499
F	**899.7324574**	**895.8171499**
G	**916.5483286**	**914.9075378**
H	**917.1783334**	**900.0074547**
I	**960.7354713**	**950.7990557**
J	**966.522227**	**983.2007786**

Table 4.2: Harmonic permeability vs. measured permeability; the value in red is the only value that is greater than the measured permeability. The bold values are the values that can be compared with other studies.

The theoretical harmonic permeability, when the flow is normal to the orientation of the bedding planes, has been observed to deviate from the measured permeability. Referring to *Prakash and Sridharan, 2013* **[5]** on their study about the factors that influence the deviation between the theoretical harmonic permeability and measured permeability, it can observed that the permeability of the exit layer controls whether the measured value of permeability is greater or lesser than the theoretically calculated value. They used multiple 3-layer soil sediments with paper filter in between the layers to avoid mixing in their experiments. The researchers concluded that the measured permeability is either more or less than the calculated theoretically, depending upon whether the exit layer is more or less pervious than the inlet layer respectively.

The samples used in this study weren’t separated with paper filters, but it is safe to assume that in samples F-J (coarsening upward samples) no mixed zones can occur because of the layering of the bigger glass beads above the smaller beads. The bottom layer in those samples consists of a uniform ϕ1mm glass beads with a measured permeability of 686.53 D (test sample 4). The top layer consists of a uniform ϕ3mm glass beads with a measured permeability of 2067.20 D (test sample 5). The exit layer is less pervious than the inlet layer for all the coarsening upward samples. This means that the calculated theoretical harmonic permeability’s must be less than the measured permeability’s. Looking at table 4.2, it’s observed that this is the case for sample F, G, H and I. Sample J shows a not expected higher calculated theoretical value. The cause of this unfortunately can’t be explained.

4.3 Impact porosity on permeability

A decrease in porosity can lead to a decrease in permeability. Figure 3.9 and figure 3.10 have shown the overall porosities for all the samples except sample 2 and sample 3. Samples A-J for instance has an average porosity of about 37%, taking this into account, the effect of the porosity is not clear enough to discuss.

However, when comparing the gained results with the results of ***Vriesde K. (2015)*** and ***Opschoor T. (2016)***, the relation between the porosity and permeability becomes clear. Figure 4.4 shows four types of binary mixtures and their porosities taken from the work of ***Vriesde K. (2015)***. The porosities for each sample are set against the volumetric percentage of each bead size. One can observe that the porosity drop is mostly dependent on the ratio of the glass bead sizes. The drop in porosity is larger at binary mixtures of greater glass bead size ratios. The permeability drops much more for binary mixtures with larger glass beads ratios. This is due to the decrease in porosity because of the transition zones. The consequence of two different glass bead sizes used in this research causes a less clear trend to be visible in the porosities results and the possible influence on the permeability.

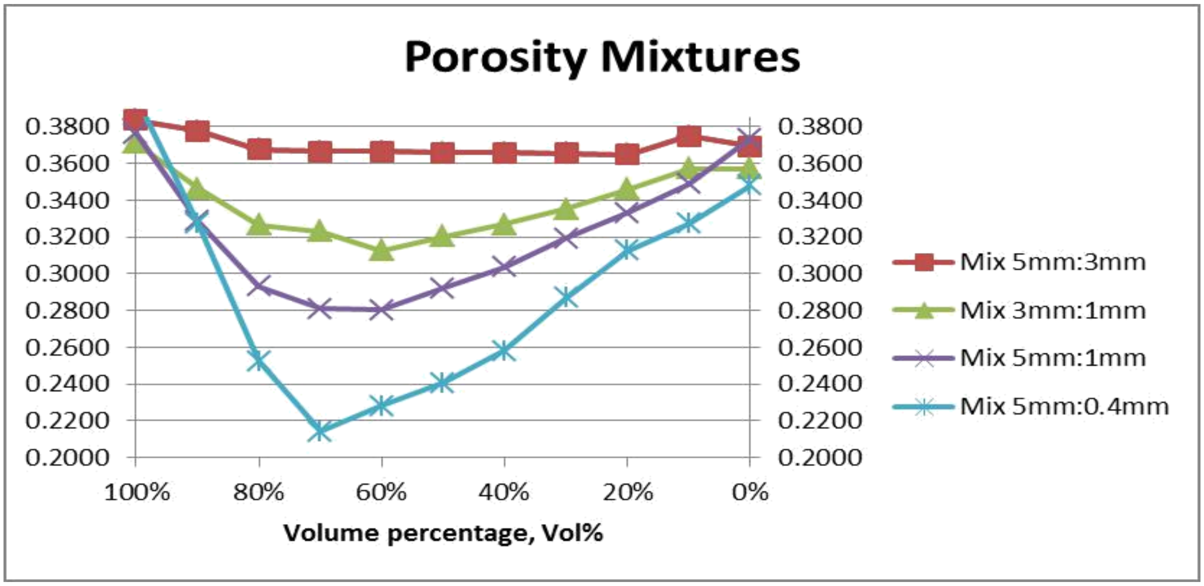


Figure 4.4: Porosity of samples with different volumetric percentages of glass beads **[2]**

Figure 4.5 on the next page taken from the experiments of ***Opschoor T. (2016)*** makes it more clear what the consequence is of the use of 3-layered samples with small ratios between the glass beads. Namely, trends are not clear enough to discuss.

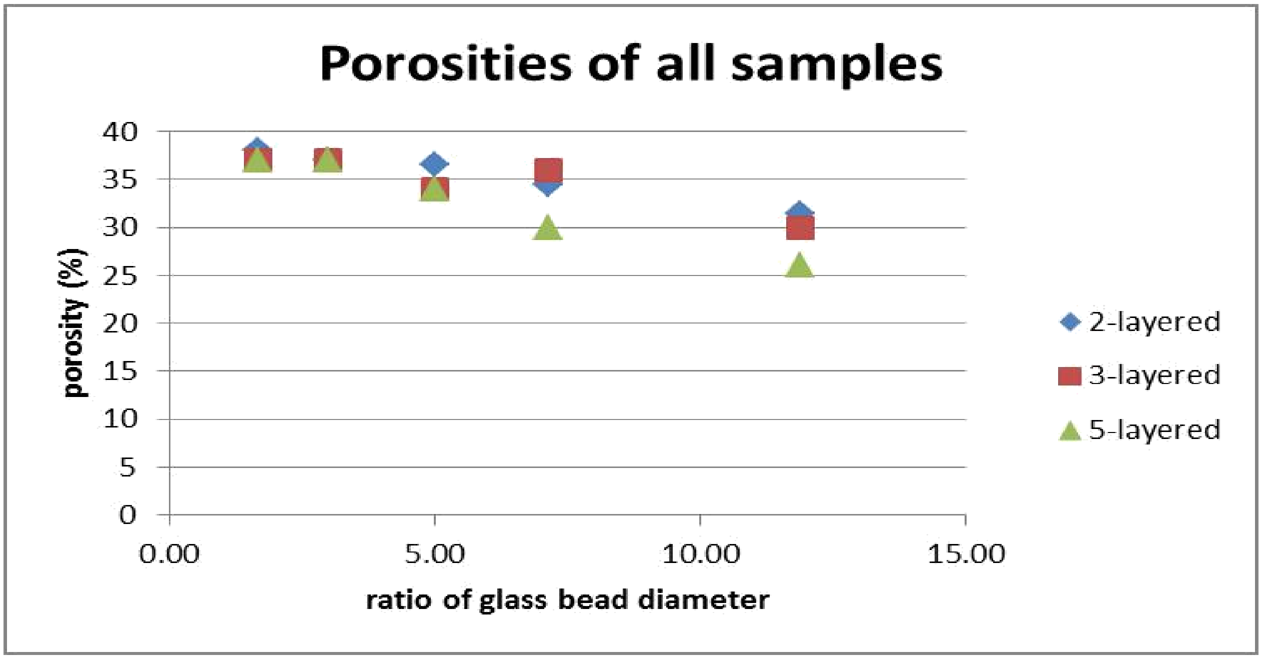


Figure 4.5: Porosities of all samples **[3]**

4.4 Applications in practice

Knowledge about the permeability in fining and coarsening upward formations can influence decision-making in big geo-technical projects. For example, when building embankments one should have an idea about the pore water pressures throughout the soil. This information will determine if there should be water pumped or cement used to keep the stress levels in balance in the soil. If the effective stress decreases to a value below zero, liquefaction could occur with a lot of damage as a result. Pumping water in big projects costs a lot of money, especially when the soil is not really much permeable. It will take a lot of time and in the worst case it can delay the whole project. If the engineer knows that he is dealing with a low permeable soil, he can take measures to increase this permeability. Furthermore, this study shows a decrease in permeability when the grain size decreases. Soils that contain such stratification might be useful for toxic waste storage. There are a lot of applications in practice that need a certain amount of knowledge about the permeability to make sure that safety and profit is guaranteed.

5. Conclusion

The purpose of this research was to determine the permeability and porosity of a simplified model of the fining and coarsening upward geologic stratification. This was modeled with the use of 3-layered samples consisting of ϕ1mm and ϕ3mm glass beads.

The conclusions that can be drawn are:

- At increasing volume percentage of smaller glass beads a decrease in the permeability is visible in both the fining upward samples and coarsening upward samples.
- A possible transition/mixed zone didn’t influence the total permeability of the fining upward samples because of the small ratios of the used glass beads.
- As the exit layer permeability’s are less than the inlet layer permeability’s for the coarsening upward samples the theoretical harmonic permeability’s values are less than the actual measured values.
- The relative positioning of the layers with different values for the permeability and length can influence both the measured permeability and the theoretical permeability.

6. Recommendations

- The samples need to be tested again with the use of paper filters between the layers to make sure that the effect of mixing is not visible for smaller glass bead ratios.
- 3-layered samples consisting of 1mm & 5mm or 3mm & 0.42mm beads with a binary mixed layer in between is an idea for future researches.
- Preparing binary mixtures is difficult because of the varying mass of the different sizes glass beads. It causes not consistent samples. The reproducibility percentage should be specified and taken in account in the error calculation.
- The length and inner diameter of the sample holder are too small for a reliable use and limit the possibilities. The whole setup can be installed on ground level instead.

Bibliography

[1] Katherine Daniels, Permeability experiments, University of Cambridge, cato2

[2] Vriesde K., Permeability of binary mixtures, TU Delft, October 2015

[3] Opschoor T., Permeability of layered glass bead samples, TU Delft, July 2016

[4] Tarek A., “Reservoir Engineering Handbook-Ch. 4: Fundamental of rock properties”, Second Edition, Gulf Professional Publishing, 2001.

[5] K. Prakash and A. Sridharan. 2013. Permeability of layered soils: an extended study. Geotechnical and Geological Engineering 31

Appendix A: Table of symbols

Q = volumetric flow rate [m^3/s]
g = gravitational constant [9.81 m/s^2]
A = area of sample [m^2]
Δp = pressure difference [Pa]
μ = viscosity [kg/m.s]
ρ_{water} = density water [kg/m^3]
L = sample length
P_{total} = total pressure [Pa]
z = gravitational head [m]
h_{column} = height of column [m]
V = volume [m^3]
t = time [s]
k = permeability [m^2 or Darcy]
h = height of water column [m]
h_0 = initial height of water column [m]
φ = porosity [ratio or %]

Appendix B: Permeability testing setup

This setup description has been partly taken from *Opschoor, T., Permeability of layered glass bead samples, TU Delft, July 2016.* It has been modified for own purposes.

Instruction manual for the permeability test

The permeability meter determines the permeability by measuring the pressure that is being exerted by the water column on the glass bead sample. This meter consists of a vacuum pump, a water tube, a sample holder, a square bin and a pressure meter. By using the Bernoulli's principles and the Darcy law the permeability can be determined. The samples are made out of glass beads and the tests are done with demineralized water.

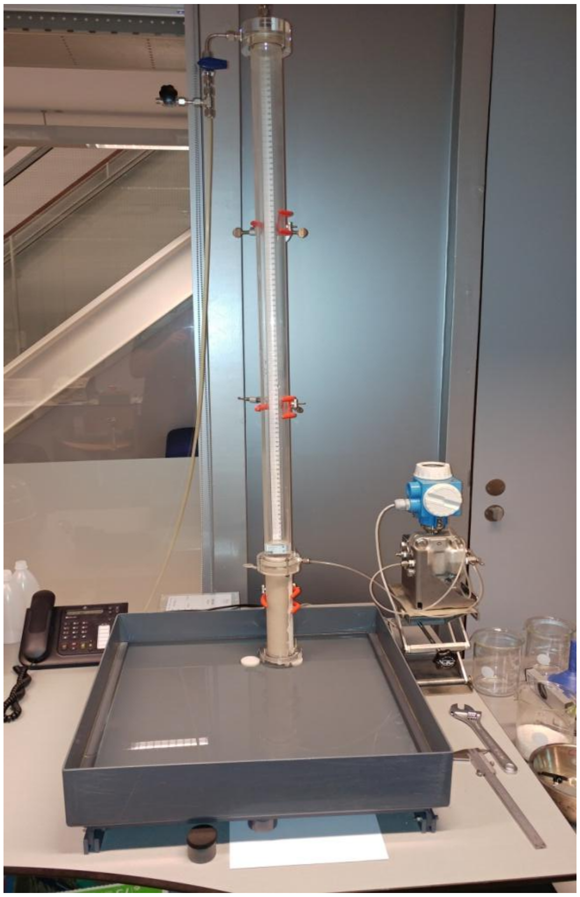


Figure B.1: Testing setup

Preparation of the permeability meter

Measure with a caliper the inner diameter of the sample holder. With this value one can determine the cross sectional area of the holder.

Preparation of the sample

Step 1: Put a measuring cup on a scale and set the weight to zero.
Step 2: Fill the sample holder with the right amount of weight for a predetermined sample. Try not to spill any beads by doing it carefully.
Step 3: Tap on the sample holder with a hammer, such that the grains are compact in the holder. Be gentle when using different grain sizes in the sample, especially when the diameters ratios are large.
Step 4: Put the rubber at the bottom of this sample holder and place the holder back. Make sure the screws are tight enough such that air won't be able to flow in and out of the system.
Step 5: Place the 2 white discs under de sample holder, so it has a stable stance.
Step 6: Make sure that the sample holder is (perfectly) vertical with a water leveler.

Test procedure

Step 7: Measure the water temperature with a thermometer.
Step 8: On top of the setup there are two valves and one knob. The red and blue valves must be closed at first. These are closed when they're horizontal and open when they're vertical. The black knob must be opened. It can be opened by turning it counterclockwise.
Step 9: Turn on the vacuum pump by pressing the green button.

Figure B.2: vacuum pump

Step 10: Open the blue valve by turning it counterclockwise, so it's in the vertical direction as shown in figure B.3. Water will flow through the sample into the column above the sample.

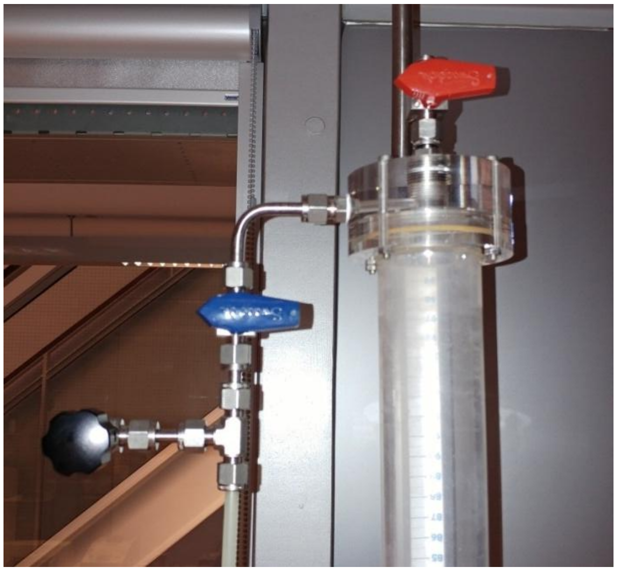


Figure B.3: Valves of the system

Step 11: If the water in the tubes reaches its equilibrium the black knob must be closed a little. Do this by turning the black knob clockwise. Be careful that the water flows into the column at a low rate. When it flows to fast it can cause the sample to be distorted and air bubbles to be sucked into the water column.

Step 12: When the water is at a selected height, close the blue knob. Don't let water flow into the vacuum pump

Step 13: Let the rod of the pressure meter have the same height as the height of the glass beads in the sample holder. This is important for the correct pressure measurements. Figure B.4 shows the correct setup. Make sure the rod is horizontal; check this with a water leveler

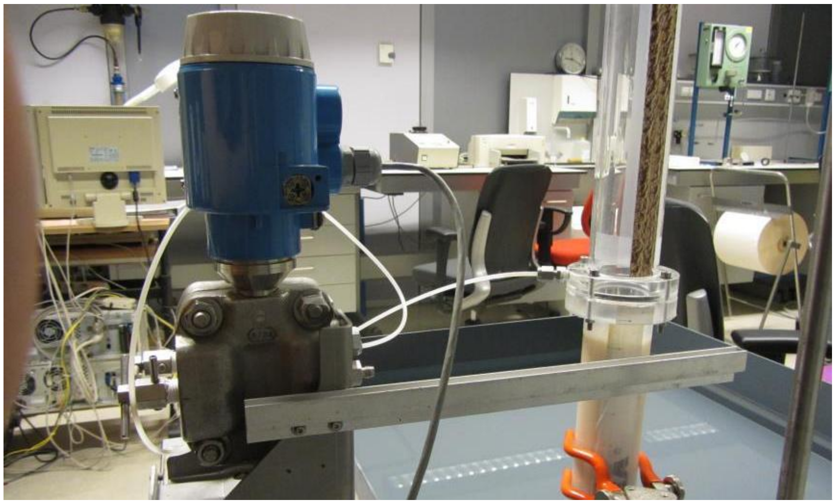
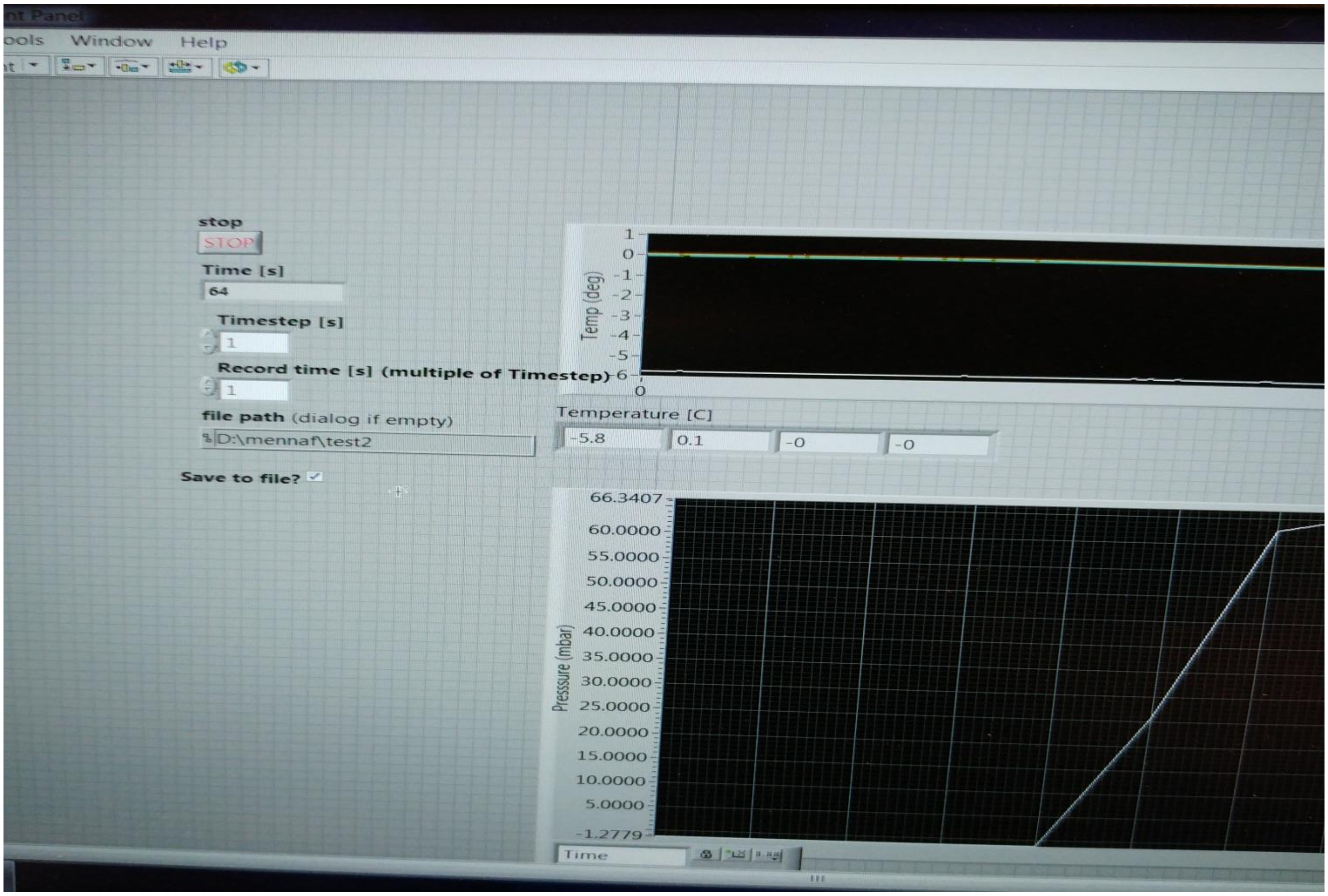


Figure B.4: Rod from the pressure meter is on the same level as the top of the glass beads in the sample holder

Step 14: Start the LabVIEW software on a computer. Run and save the file. Use for the time box value and the record time box the values in figure B.5:



stop

Time [s] 64

Timestep [s] 1

Record time [s] (multiple of Timestep) 1

file path (dialog if empty) D:\mennaf\test2

Save to file? ☑

Temperature [C] -5.8 0.1 -0 -0

Figure B.5: Settings in LabView during measurement

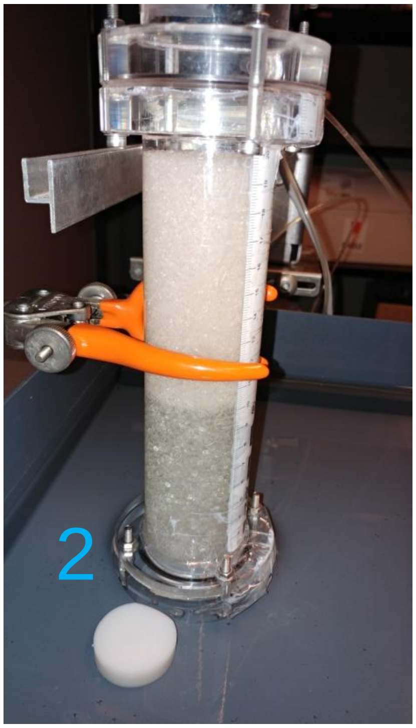
Step 15: Open the red knob in one turn. Water now starts flowing through the sample and data points are measured.
Step 16: Close the red knob before the water level reaches the top of the glass beads in the sample holder.
Step 17: Measure the temperature of the water again.
Step 18: Repeat each test at least four times.

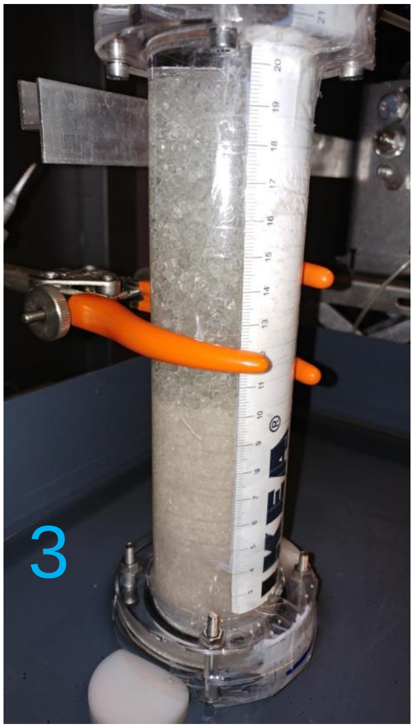
It is important that for each sample that is being tested, the exact length of each layer of beads is measured and noted. This includes both the layer(s) with uniform beads as the binary mixed layer(s).

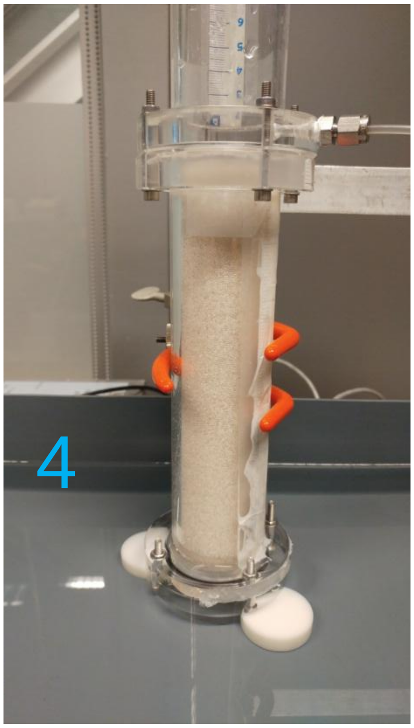
At last, one should change the water in the tank occasionally so it will not get contaminated with dirt or algae.

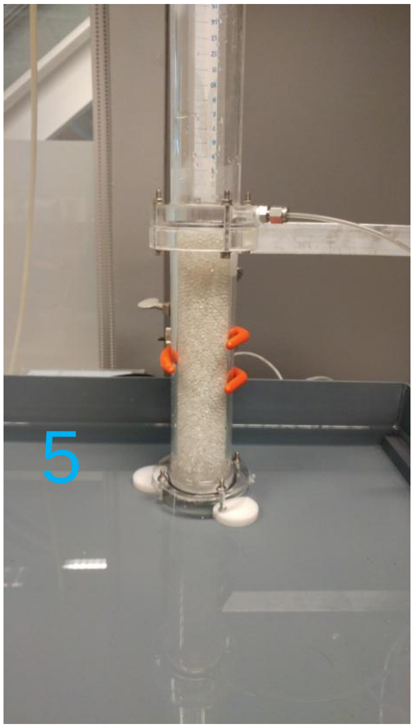
Appendix C: Images of samples

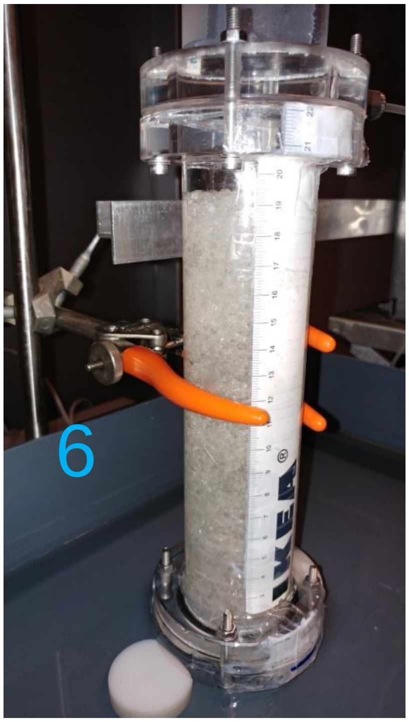
Test Samples 1-9

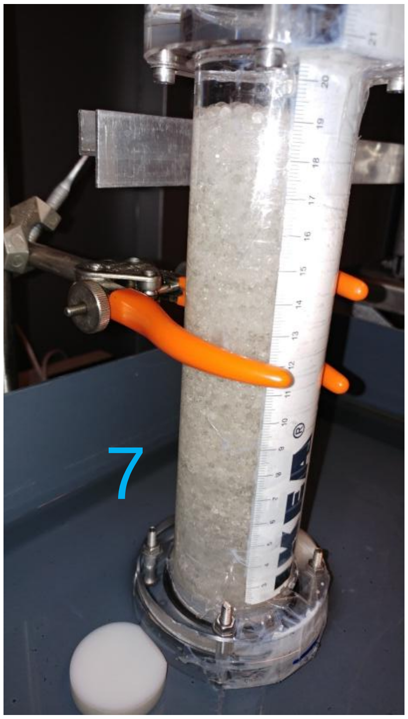


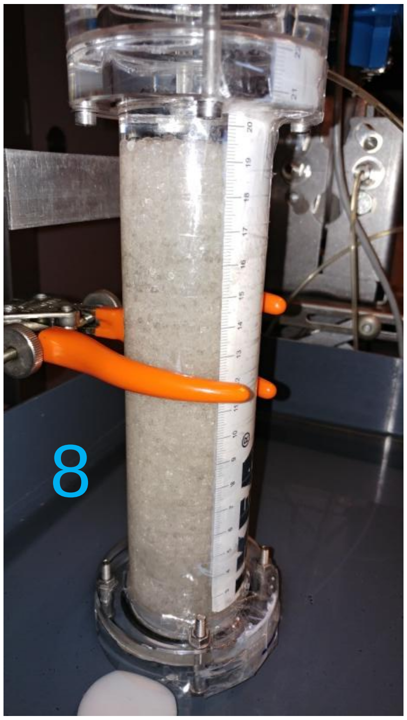


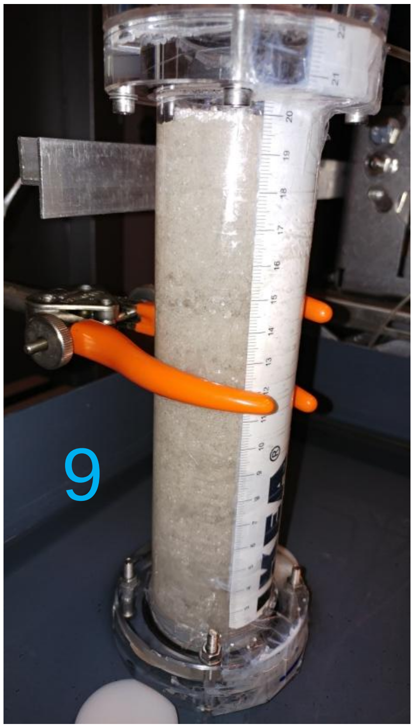




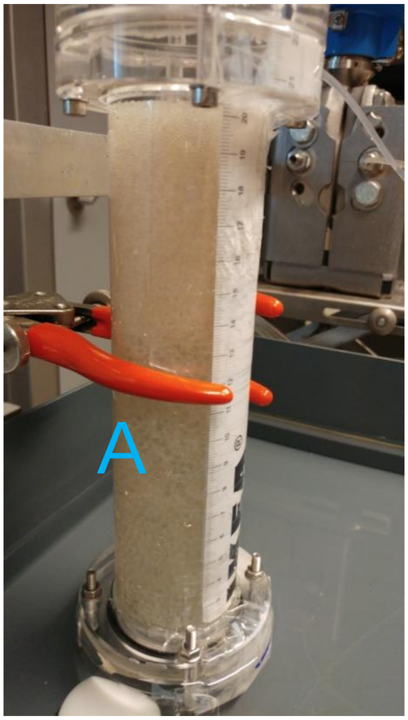


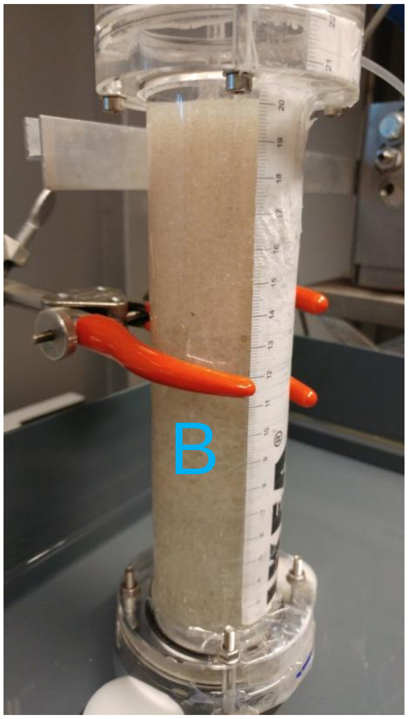


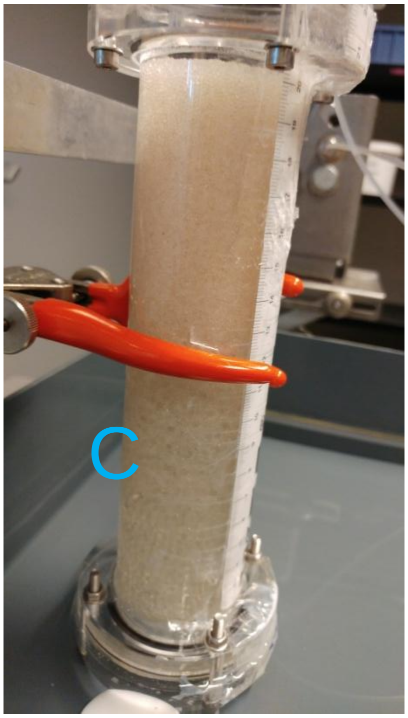


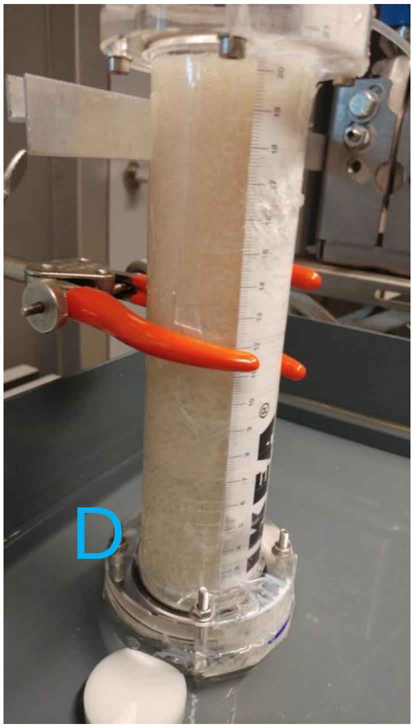


Samples A-J:





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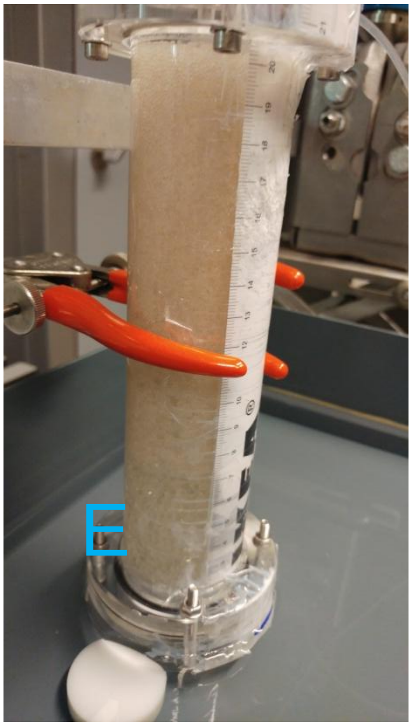
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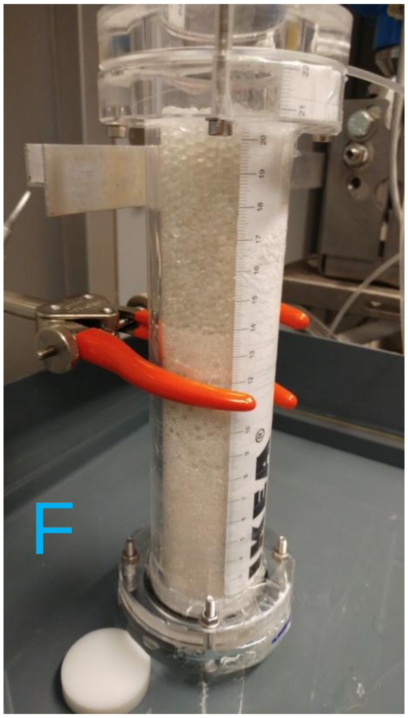
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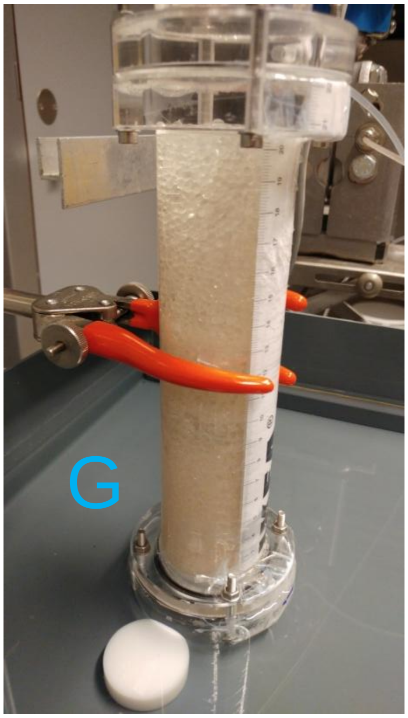
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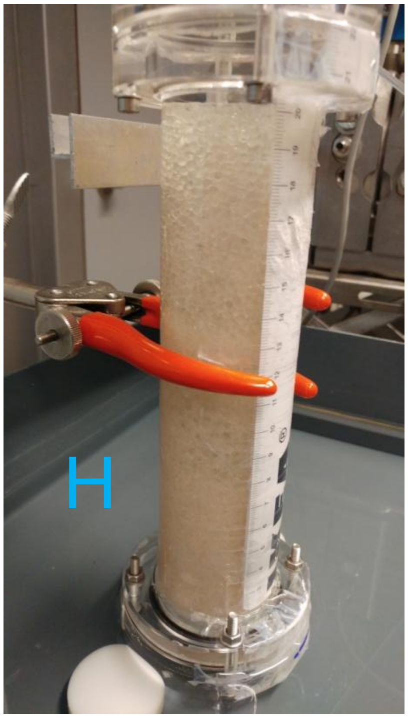
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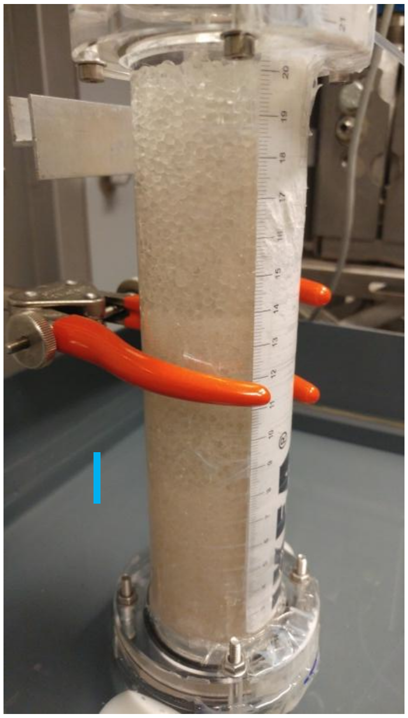
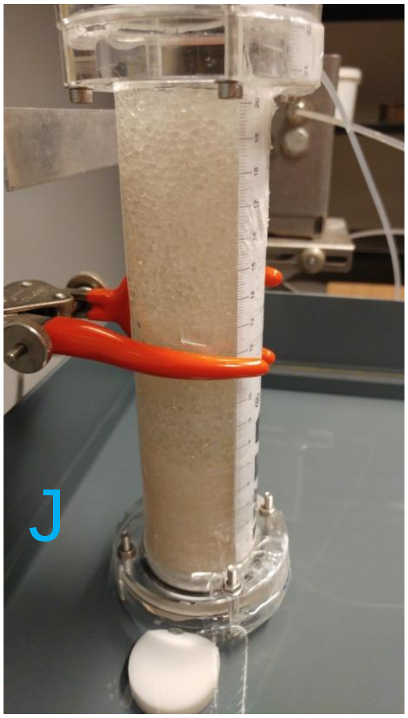

I


J

Appendix D: Error calculation

Each sample is tested four times; this resulted in different values for the permeability. The error and standard deviation are calculated with respectively eq. D.1 and eq. D.2. Table D.1 shows all the measured permeability's for the four tests, the average permeability, the calculated error and the standard deviation.

$$\mathrm{error} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{x_i} - \mathrm{x})^2} \qquad \text{(D.1)}$$

$$\text{standard deviation} = \frac{\mathrm{Error}}{\mathrm{k_{average}}} * 100\% \qquad \text{(D.2)}$$

Sample	test 1 [Darcy]	test 2 [Darcy]	test 3 [Darcy]	test 4 [Darcy]	K average [Darcy]	Error [Darcy]	Standdev [%]
A	1035.259329	1030.541876	1025.781846	1025.399317	1029.245592	4.019849419	0.390562704
B	969.9570567	960.537704	961.6470133	954.1748434	961.5791544	5.614763851	0.583910729
C	958.5441406	956.8002802	953.391239	930.5796189	949.8288197	11.2669943	1.186213144
D	941.7031431	951.870296	907.3980523	906.724284	926.9239439	20.18682686	2.177829907
E	943.4392755	910.5580356	906.2198931	903.8803354	916.0243849	16.00830409	1.747584928
F	914.4572747	908.0401921	894.4779191	881.9544436	899.7324574	12.5449855	1.394301761
G	930.711907	910.0845776	916.1808972	909.2159325	916.5483286	8.606481114	0.939010071
H	938.5097442	909.4355316	914.5690624	906.1989952	917.1783334	12.67215677	1.381645892
I	981.336271	954.8835472	991.5674542	915.1546125	960.7354713	29.52483625	3.073149388
J	976.4463063	971.4641443	955.7217647	962.4566925	966.522227	8.001381962	0.827852867
1	711.005615	703.48856	701.3332504	702.2897712	704.5292991	3.816281498	0.541678182
2	1046.870377	1026.98361	1022.746471	1002.157816	1024.689568	15.88006912	1.549744392
3	1082.707745	1062.986596	1040.463793	1033.230322	1054.847114	19.47197675	1.845952507
4	698.5675065	693.2246672	685.0008979	669.3334392	686.5316277	11.04287077	1.608501389
5	2083.136254	2068.263787	2101.098777	2016.308955	2067.201943	31.5995309	1.528613641
6	944.4833728	892.8876961	912.5993629	822.3751504	893.0863955	44.78427411	5.014551149
7	824.2491922	809.3405946	813.7350341	804.1963527	812.8802934	7.381103172	0.908018466
8	744.1516699	732.7283865	731.2727369	729.333091	734.3714711	5.773634964	0.786200879
9	709.8411477	703.3520222	694.2807406	687.7036425	698.7943883	8.458436277	1.210432771

Table D.1: Error calculation for all the samples. The values in red in the test 4 column differ too much from the other values and that's also noticed in the corresponding error and standard deviation. The yellow shaded cells show a decrease with each test; this is due to better settlement or compacting. The blue shaded cells show also a decrease, but it's less clear, this is due being impatient during the falling head test and distorting the sample by sucking too much water in the column for a moment.

Appendix E: Porosity calculations for sample 2

Test sample 2 consists of a uniform ϕ1mm glass beads layer on top and a uniform ϕ3mm glass beads layer at the bottom. The following section will discuss how to determine the porosity of the mixed zone in this sample. Figure E.1 display this sample schematic:

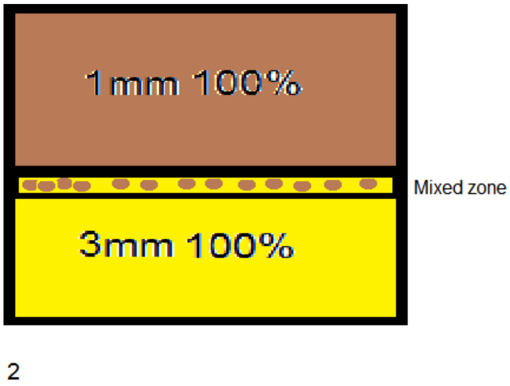
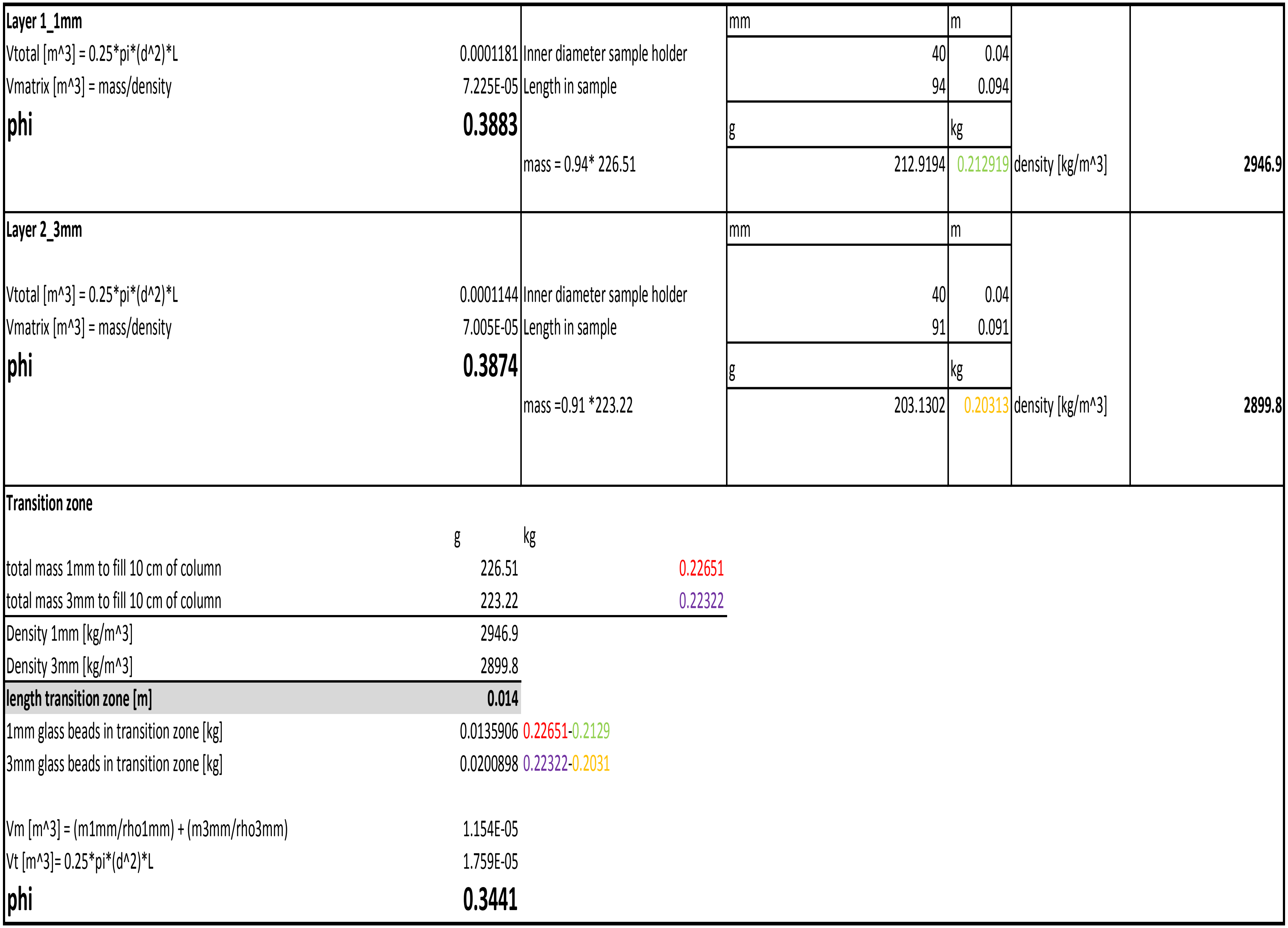


Figure E.1: Schematic image of sample 2

Figure E.2 on the next page shows the steps used for calculating the porosity of this mixed zone. It's a rough estimate, because the length of the transition zone is measured by looking how far the ϕ1mm beads settled in the ϕ3mm layer. This is actually not measurable because it is not possible to see through the beads.



Layer 1_1mm			mm	m		
Vtotal [m^3] = 0.25*pi*(d^2)*L	0.0001181	Inner diameter sample holder	40	0.04		
Vmatrix [m^3] = mass/density	7.225E-05	Length in sample	94	0.094		
phi	**0.3883**		g	kg		
		mass = 0.94* 226.51	212.9194	0.212919	density [kg/m^3]	**2946.9**
Layer 2_3mm			mm	m		
Vtotal [m^3] = 0.25*pi*(d^2)*L	0.0001144	Inner diameter sample holder	40	0.04		
Vmatrix [m^3] = mass/density	7.005E-05	Length in sample	91	0.091		
phi	**0.3874**		g	kg		
		mass =0.91 *223.22	203.1302	0.20313	density [kg/m^3]	**2899.8**
Transition zone						
	g	kg				
total mass 1mm to fill 10 cm of column	226.51	0.22651				
total mass 3mm to fill 10 cm of column	223.22	0.22322				
Density 1mm [kg/m^3]	2946.9					
Density 3mm [kg/m^3]	2899.8					
length transition zone [m]	**0.014**					
1mm glass beads in transition zone [kg]	0.0135906	0.22651-0.2129				
3mm glass beads in transition zone [kg]	0.0200898	0.22322-0.2031				
Vm [m^3] = (m1mm/rho1mm) + (m3mm/rho3mm)	1.154E-05					
Vt [m^3]= 0.25*pi*(d^2)*L	1.759E-05					
phi	**0.3441**					

Figure E.2: Porosity calculations for sample 2