October 12, 2017

Mr. Steve Keyser
VP of Engineering
Brock USA
3090 Sterling Circle, #102
Boulder, CO 80301

PO # 5029

RE: 31395-Brock PowerBase Transmissivity Results
Deriving Field Transmissivity from Laboratory Test Results
Using the Characteristic Flow Equation

Dear Mr. Keyser,

Transmissivity tests were performed on seven PowerBase specimens with varied flow channel geometries in order to analyze the effect of the geometry on the flow capacity using the Characteristic Flow Equation.

The Characteristic Flow Equation was determined for each specimen, both based on the superficial velocity with gradient versus flow rate in ml/s and on the interstitial velocity with pressure in pascals versus the flow velocity in m/s. The superficial CFE plots were used to adjust the measurement data for “zero” intercepts and extrapolate the data for very low gradient values. The internal velocity CFE plots were used to compare specimen results and establish qualitative relationships between the specimen geometries and the CFE coefficients.

D 4716 Transmissivity Testing

Seven specimens of the Brock PowerBase were tested in accordance with ASTM D 4716, using 12-inch by 12-inch test specimens, and hydraulic gradients of 0.1, 0.3 and 0.5 under a compressive force of approximately 100 psf.

The flow rates were measured by using a stop watch to time the rise of the water in a clear acrylic tube that is correlated to the volume of the collection container. Over 7 liters of water was collected for the 0.1 gradient measurements, and over 14 liters for the 0.3 and 0.5 gradients. The hydraulic gradients were measured with open manometers.

The Characteristic Flow Equation-Superficial Velocity Plots

The transmissivity results are first plotted with the hydraulic gradient on the y-axis, and the flow rate in millimeters per second on the x-axis. The Excel Trendline function was used to plot the best fit 2nd order polynomial through the three data points.

If the resulting polynomial curve did not intersect the y-axis near zero, then the hydraulic gradient values were adjusted to shift the Y-intercept to intersect the origin. This adjustment is treated as a “correction”, as the change in the gradient is much less than the associated measurement resolution. The final Superficial Characteristic Flow Equation is the 2nd order polynomial, with the y-intercept set equal to zero using the adjusted data.

Once the final Superficial CFE’s are formulated, the flow rate at a gradient of 0.005 was calculated with the following equation and the linear term coefficient C1 and the 2nd-order term coefficient, C2:

$$Q_{i=0.005} = \frac{\sqrt{4 \cdot C2 \cdot 0.005 + (C1)^2} - C1}{2 \cdot C2} \qquad \text{EQN. 1}$$

The measured and adjusted data, the CFE plots, the derived CFE coefficients, and the estimated flow rates at the 0.005 gradient are attached for each of the seven specimens.

Inertia-Unit Analysis of the CFE’s

In order to try to relate the observed differences in the test specimen results with the differences in their geometry, the inertia-unit analysis of the CFE’s was performed. This normalizes the data to the actual velocity of the water in the flow channels.

The first step in the inertia-unit analysis, is to determine the critical interstitial flow area for each test specimen. This controlling internal flow area is taken as the minimum cross-sectional area encountered as water travels in the flow direction. For these seven specimens, the minimum flow areas are rectangular channel shapes.

The flow rate values in milliliters per second are then converted to flow velocities in meters per second based on the measured minimum cross-sectional flow areas. The adjusted hydraulic gradients from the Superficial Flow Rate analyses were converted to equivalent differential pressures in Pascals.

With the Interstitial CFE's plotted in terms of pascals (y-axis) and meters per second (x-axis), the Darcy Intrinsic Permeability Coefficient, the Forchheimer Beta Coefficient, the number of Inertia Units, and the Inertia Unit Length were determined. These calculations are tabulated in along with the plots of the Interstitial Flow Curves for all of the tests.

Qualitative Observations

Looking at the plots of the Interstitial Flow Curves, there is a tight group except for the two tests performed on specimen "2B'. Specimen 2B is a test specimen from an earlier submittal, and has a different cross-channel geometery, with the cross channels continuous across the sample. This is different than the six specimens submitted for this report, where the cross channels alternate, and are not continuous across the specimens.

The tight groupings is an indication that the flow behavior within the specimens in each group is very similar. The conspicuous difference in the two groups being the much higher inertia head loss for 2B.

The number of Inertia Units over the specimen length ranges from 2.1 to 2.8 for alternating cross-channels, and 3.3 to 3.9 for continuous cross-channels. The expected number of Inertia Units for a straight, through-channel type conduit is 2; one inertia unit of head loss at the inlet, and one at the outlet. The additional head loss beyond "2.0" is due to internal head loss to changes in flow inertia.

This observation is very important because if nearly all or at least a majority of the inertia head loss occurs where water enters and exits the test specimen, then this portion of the lab head loss should be "subtracted" from the tests in order to estimate the field transmissivity. This is equivalent to subtracting "1,000" from the measured C2 coefficients.

The estimated "Field Flow Rates" at a gradient of 0.005 are calculated and tabulated next to the flow rate estimates of the lab specimens at 0.005 gradient. Note that the Field flow rate

.

Conclusions

This study has concluded that there is additional head loss caused by the laboratory set-up due to entrance and exit losses that are a substantial portion of the total head loss for lab scale testing. The most representative test specimens are 3,4 and 6, with possibly 4 being the optimum due to the also repeating geometry in the flow direction. The calculated lab flow rate at a gradient of 0.005 for this specimen is 36 ml/s, while the field flow rate is 52.5 ml/s.

Our recommendation is to use the following procedure for determining the field transmissivity of products with similar, "through-channel" type flow geometries:

1. Select test specimens such that the resulting flow channel pattern would be repeated left and right of the test specimen, and that no channels are open against the loading tray side walls. This may involve slightly reducing the actual specimen width to eliminate non-repeating half-channels if necessary.
2. Perform standard transmissivity tests on specimens that are 12-inches long (not 14-inches per the standard).
3. Use hydraulic gradients of 0.10, 0.30 and 0.50.
4. Apply a compressive stress of 100 psf.
5. Use a collection method that involves timing the collection of at least 5 liters of water for the 0.10 gradient tests, and at least 10 liters for the other two gradients.
6. Measure the cross-sectional flow area and convert the Superficial CFE to the Interstitial CFE. Subtract 1,000 from the resulting C2 coefficient to get the "Field Transformed CFE Coefficients". Use these Field Transformed CFE coefficients to calculate the field flow rate estimate for any desired gradient.
7. Confirm the conclusions presented herein by performing a transmissivity test on a 6 ft long test specimen.

We trust that this report has fulfilled its intended purpose. Should there be any questions or if we may be of further assistance, please do not hesitate to call.

Sincerely,

Richard S. Lacey, P.E.
Senior Engineer
Geosynthetic Services Division

TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

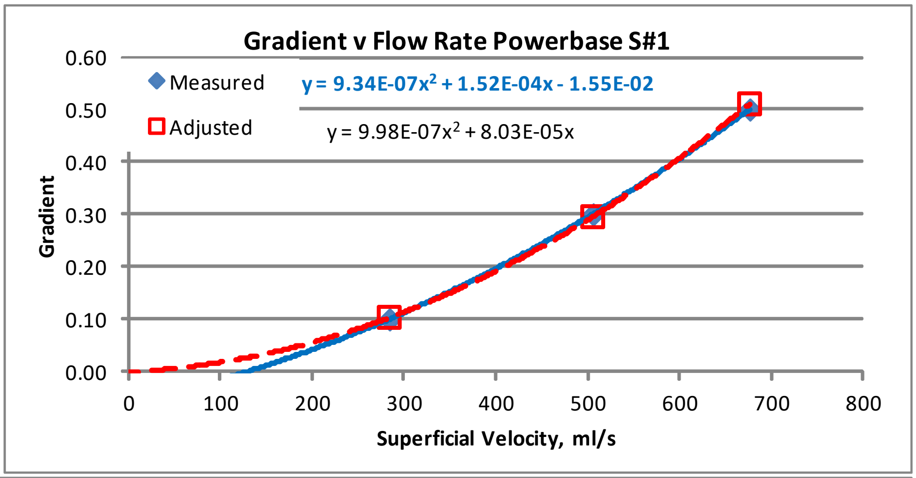
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 1

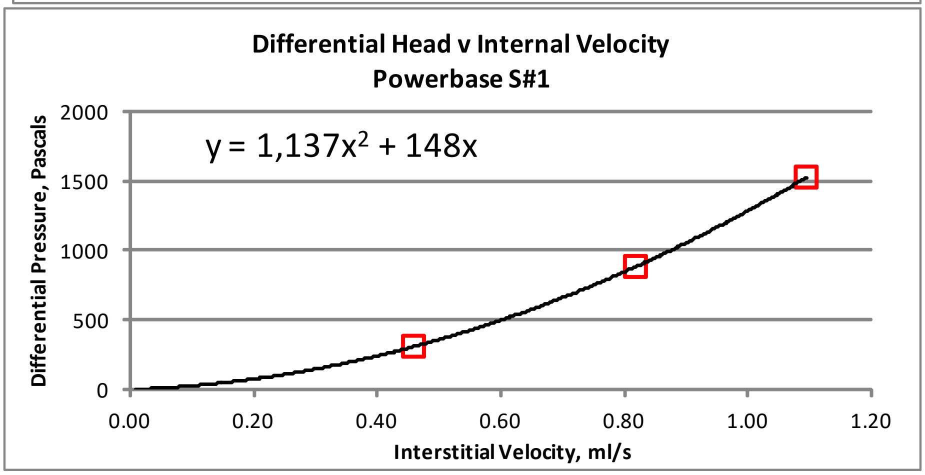
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	21.80	674		0.510
0.50	14700	21.70	677	**676**	0.510
0.50	14700	21.75	676		0.510
0.30	14700	29.20	503		0.295
0.30	14700	29.00	507	**505**	0.295
0.30	14700	29.10	505		0.295
0.10	7350	25.60	287		0.103
0.10	7350	26.10	282	**283**	0.103
0.10	7350	26.10	282		0.103

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 41 ml/s

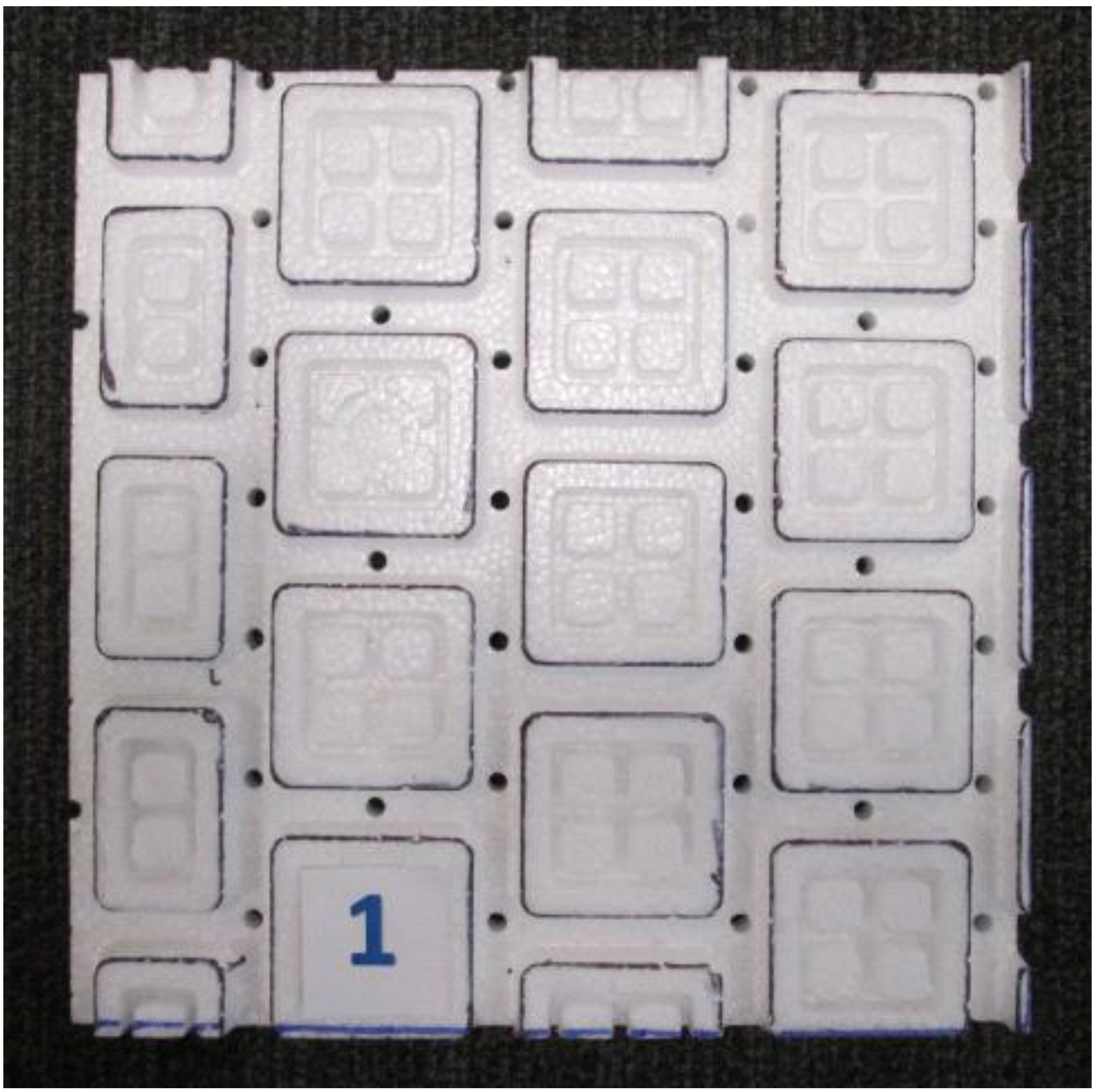
C2= 9.98E-07 C1= 8.03E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 1



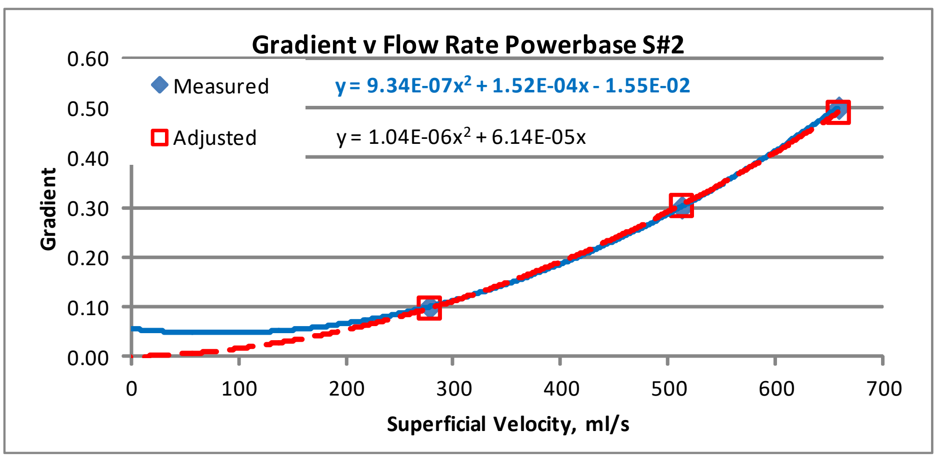
TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

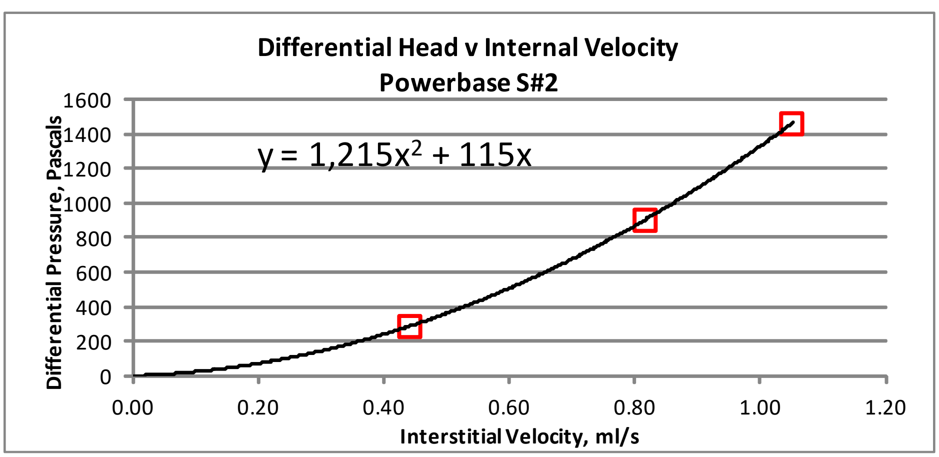
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 2

Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	22.10	665		0.490
0.50	14700	22.50	653	**657**	0.490
0.50	14700	22.50	653		0.490
0.30	14700	28.80	510		0.303
0.30	14700	28.70	512	**511**	0.303
0.30	14700	28.75	511		0.303
0.10	7350	26.50	277		0.097
0.10	7350	26.60	276	**277**	0.097
0.10	7350	26.55	277		0.097

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFI

Extrapolated Flow Rate at Gradient : 0.0050 46 ml/s
C2= 1.06E-06 C1= 6.14E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

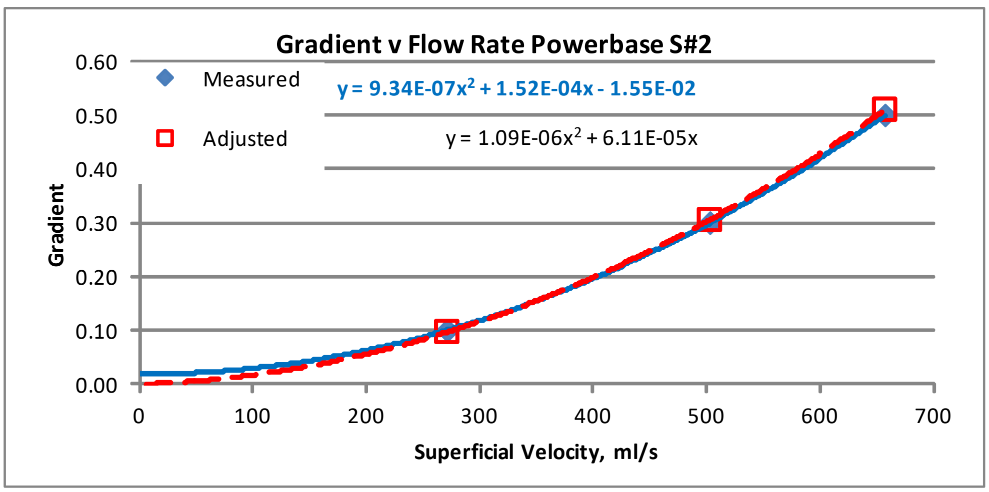
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 2

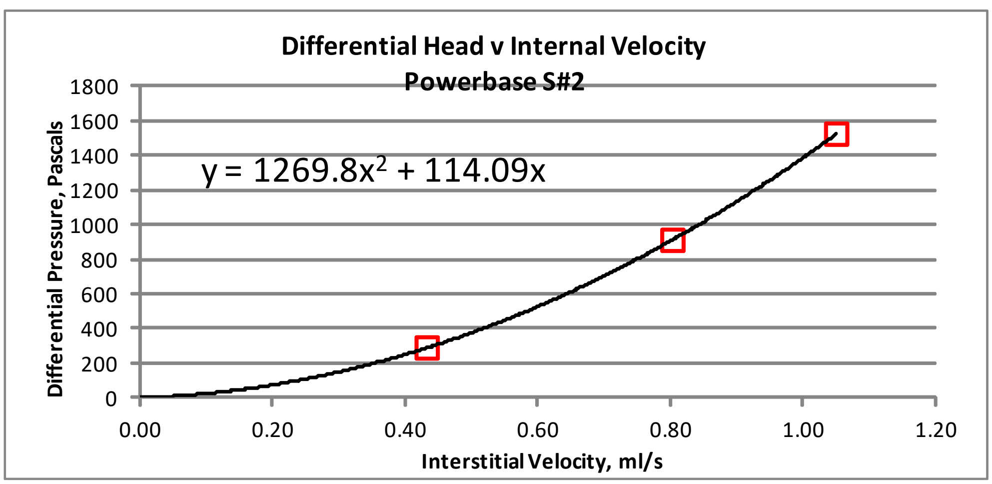
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	22.40	656		0.510
0.50	14700	22.40	656	**657**	0.510
0.50	14700	22.30	659		0.510
0.30	14700	29.10	505		0.305
0.30	14700	29.40	500	**503**	0.305
0.30	14700	29.20	503		0.305
0.10	7350	26.80	274		0.097
0.10	7350	27.50	267	**271**	0.097
0.10	7350	27.00	272		0.097

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 45 ml/s

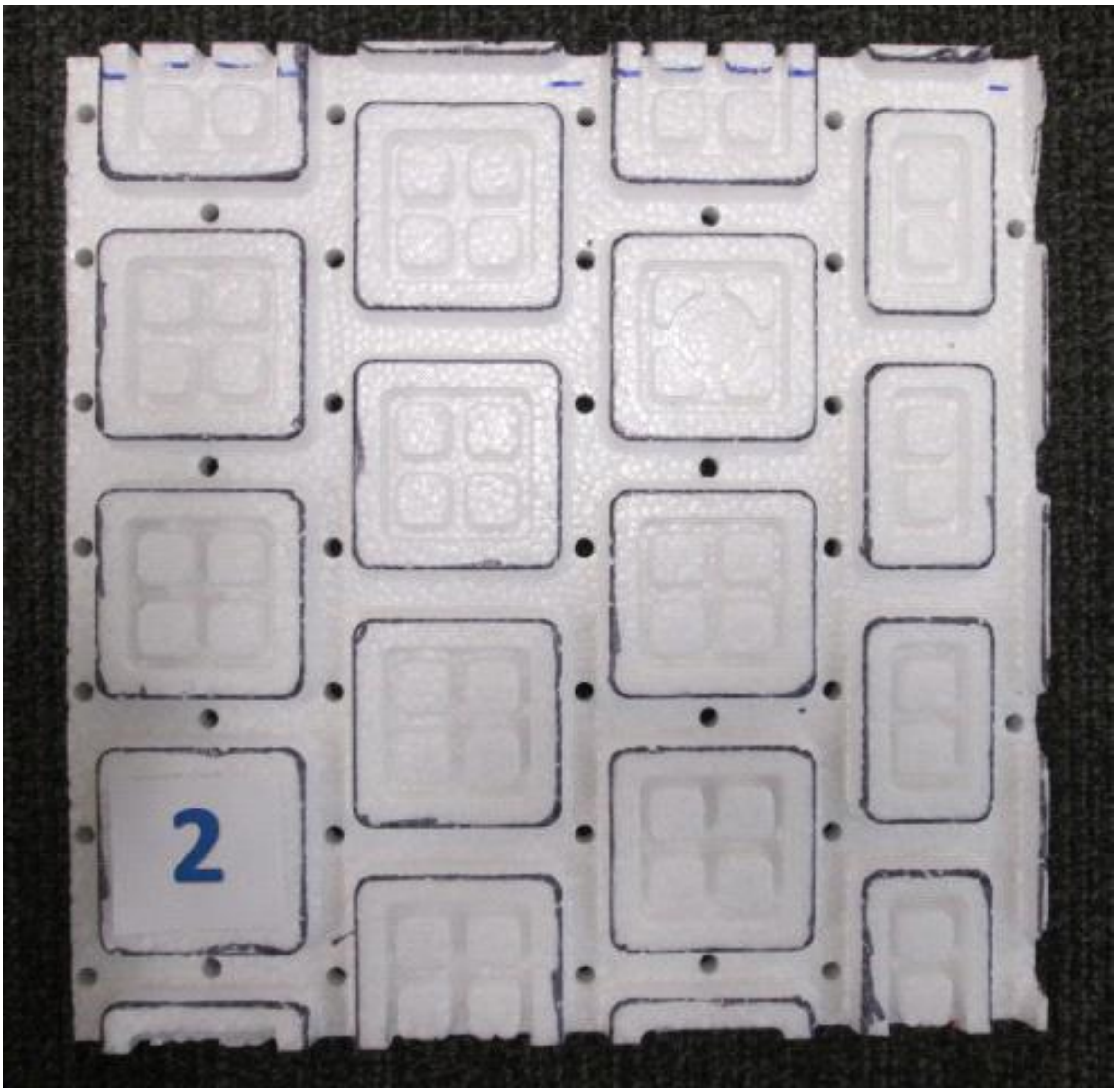
C2= 1.09E-06 C1= 6.11E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material:	Brock PowerBase
TRI Log No.:	31395
Specimen No.	2



TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

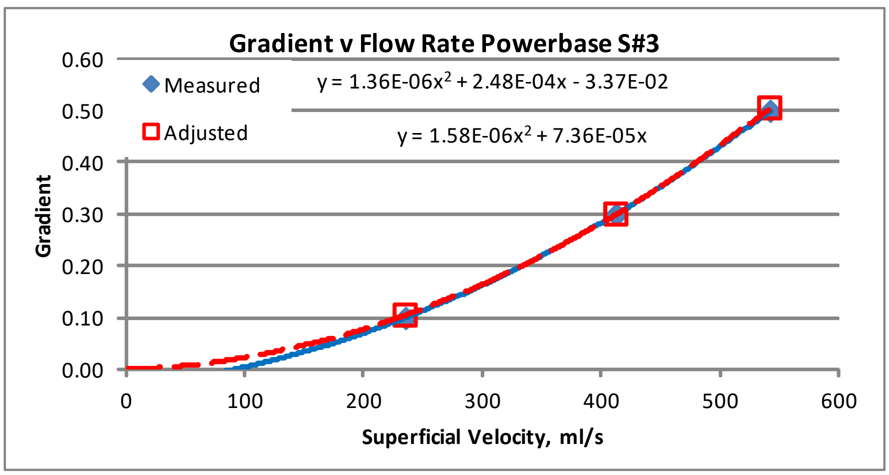
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 3

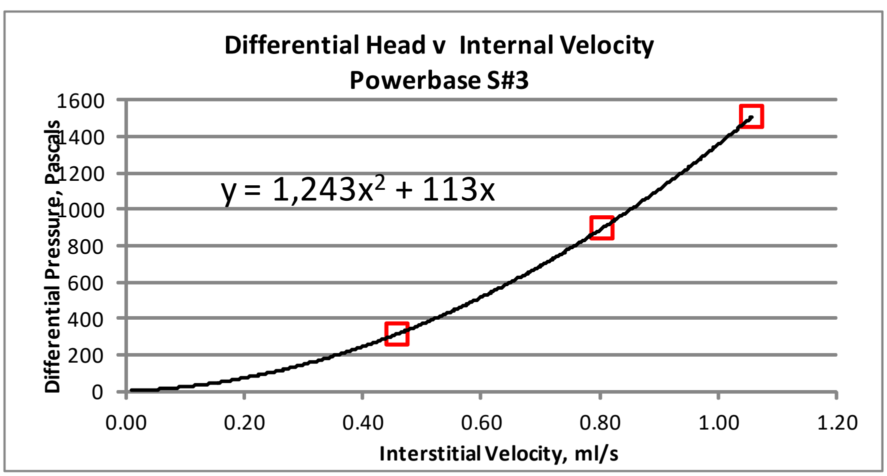
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	27.00	544		0.505
0.50	14700	27.20	540	**542**	0.505
0.50	14700	27.10	542		0.505
0.30	14700	35.60	413		0.300
0.30	14700	35.60	413	**413**	0.300
0.30	14700	35.60	413		0.300
0.10	7350	31.40	234		0.105
0.10	7350	31.00	237	**236**	0.105
0.10	7350	31.20	236		0.105

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 38 ml/s

C2= 1.58E-06 C1= 7.36E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 3

TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

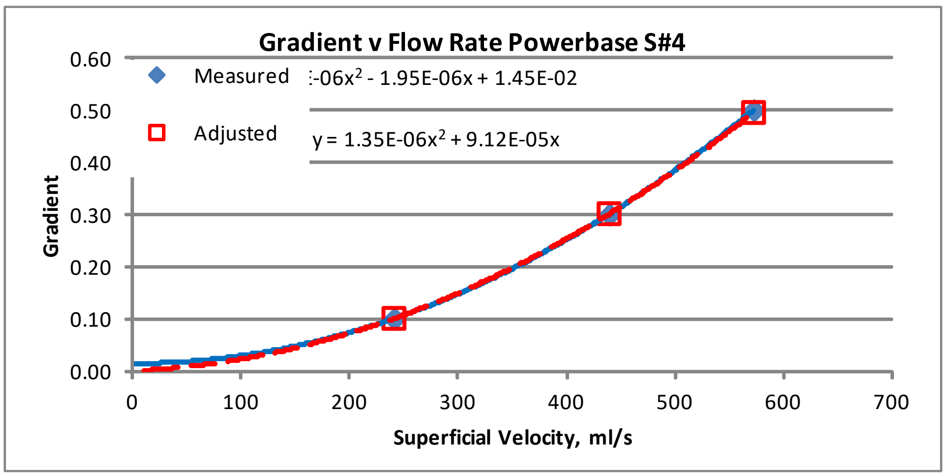
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 4

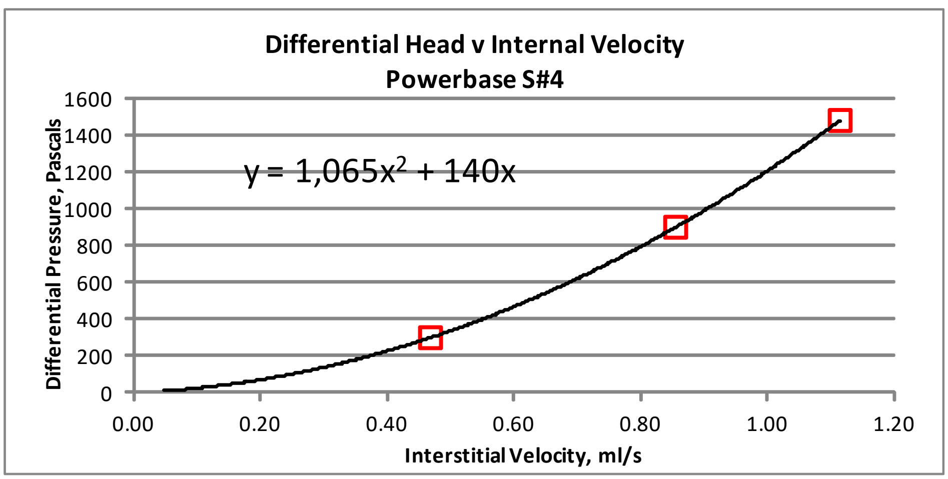
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	25.90	568		0.495
0.50	14700	25.50	576	**572**	0.495
0.50	14700	25.70	572		0.495
0.30	14700	33.60	438		0.301
0.30	14700	33.40	440	**439**	0.301
0.30	14700	33.50	439		0.301
0.10	7350	30.50	241		0.100
0.10	7350	30.90	238	**240**	0.1000
0.10	7350	30.30	243		0.100

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFI

Extrapolated Flow Rate at Gradient : 0.0050 36 ml/s

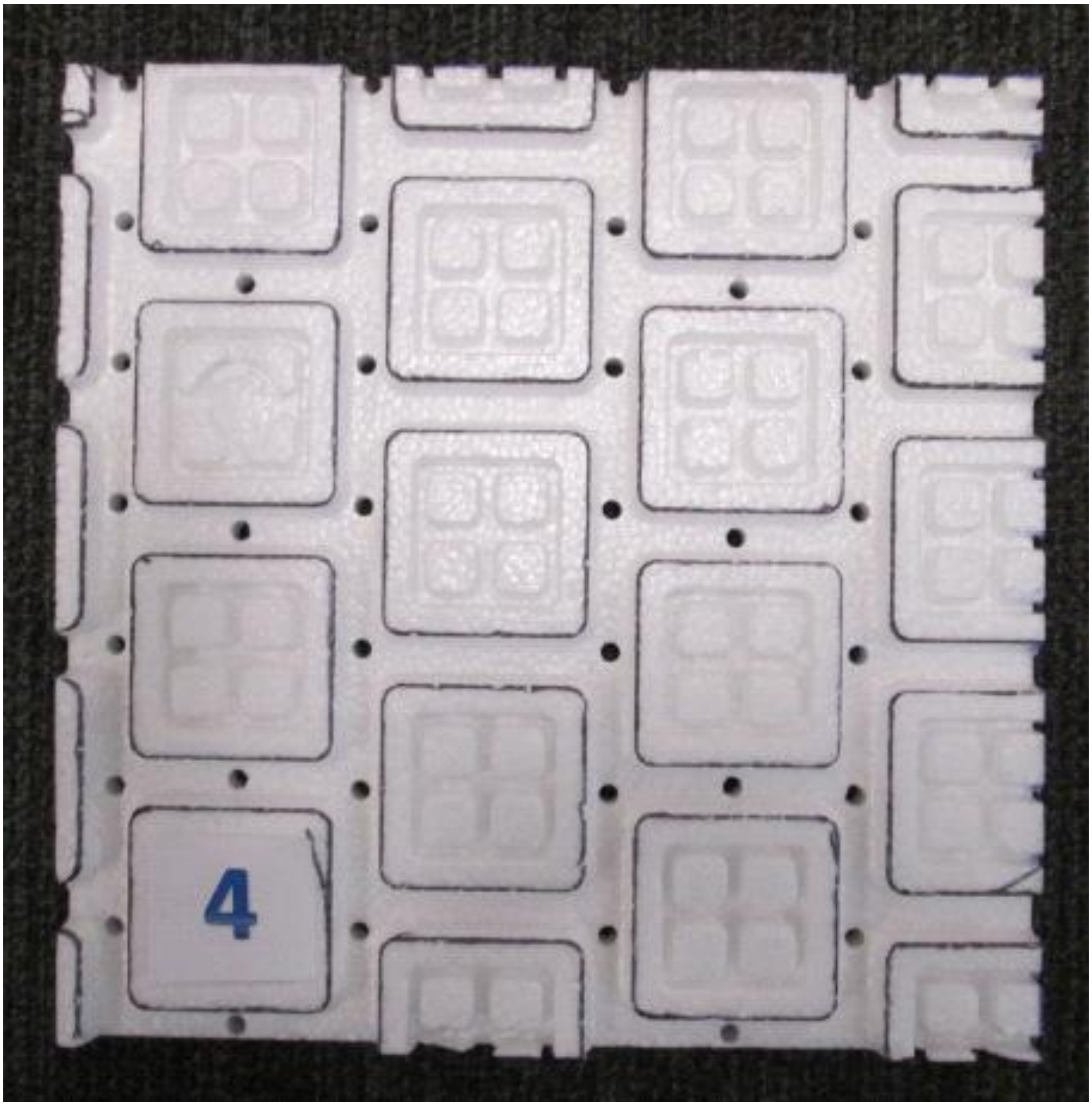
C2= 1.35E-06 C1= 9.12E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 4



TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

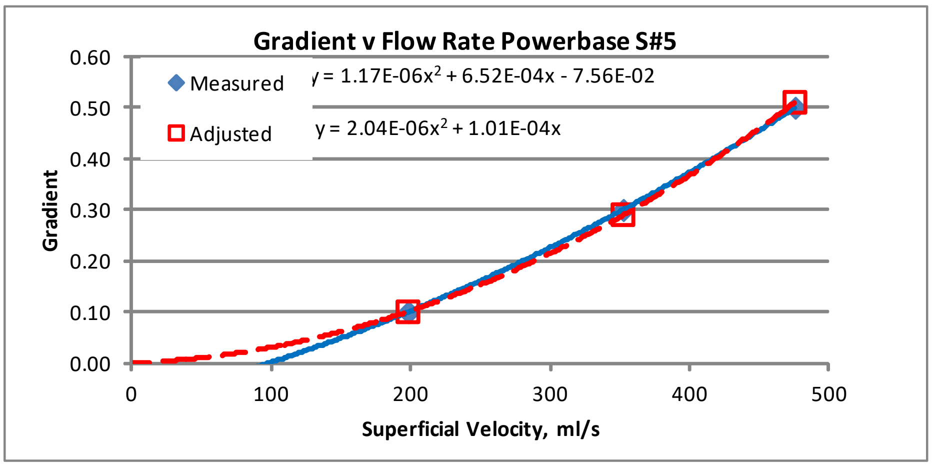
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 5

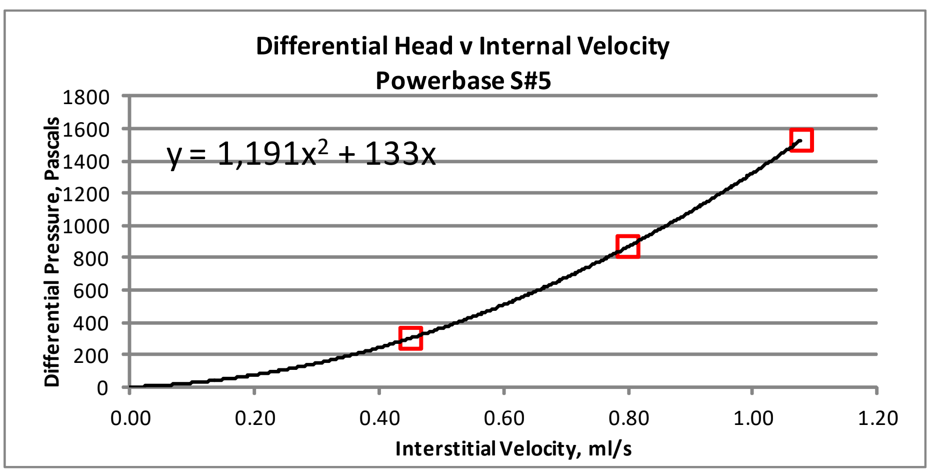
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient	Average Flow Rate Test 1
0.50	14700	30.9	476		0.510	
0.50	14700	30.8	477	**476**	0.510	499
0.50	14700	31.0	474		0.510	
0.30	14700	41.7	353		0.290	
0.30	14700	41.4	355	**353**	0.290	370
0.30	14700	42.0	350		0.290	
0.10	7350	37.2	198		0.100	
0.10	7350	36.9	199	**198**	0.100	197
0.10	7350	37.0	199		0.100	

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 31 ml/s

C2= 2.04E-06 C1= 1.01E-04





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

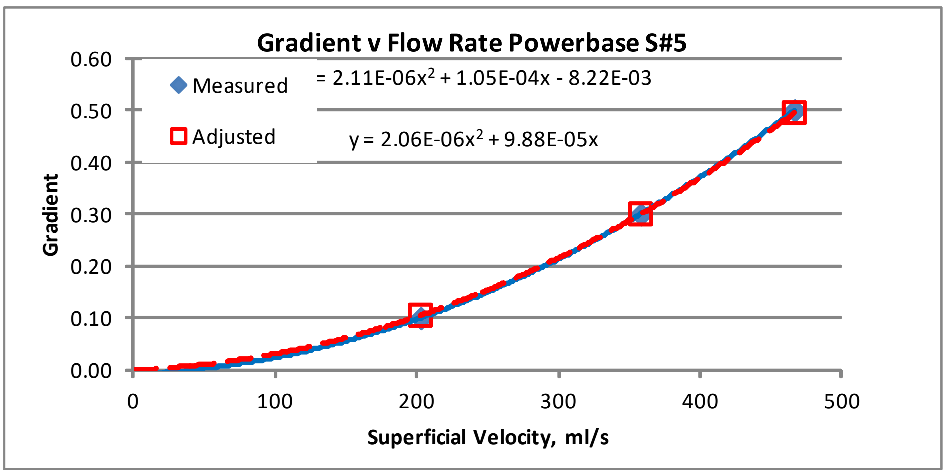
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 5

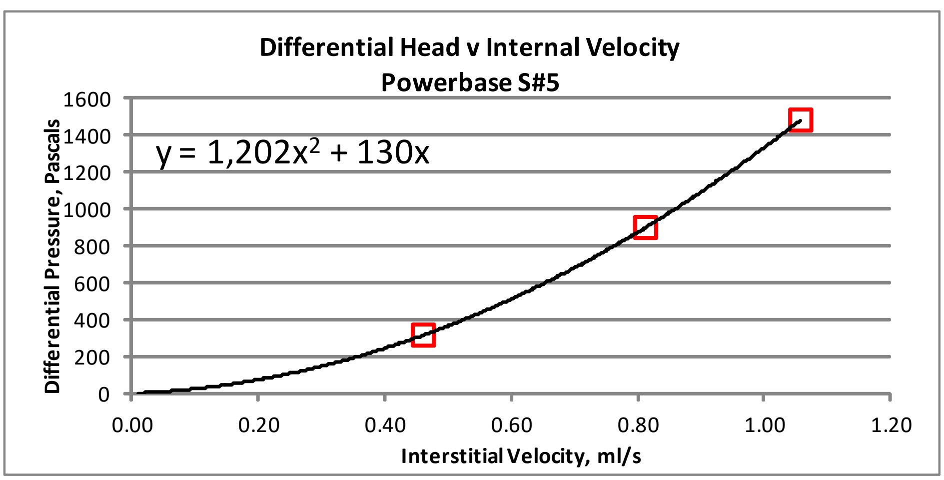
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient	Average Flow Rate Test 1
0.50	14700	31.40	468		0.495	
0.50	14700	31.60	465	**467**	0.495	499
0.50	14700	31.50	467		0.495	
0.30	14700	40.90	359		0.300	
0.30	14700	41.20	357	**358**	0.300	370
0.30	14700	41.00	359		0.300	
0.10	7350	36.00	204		0.105	
0.10	7350	36.40	202	**203**	0.105	197
0.10	7350	36.20	203		0.105	

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 31 ml/s

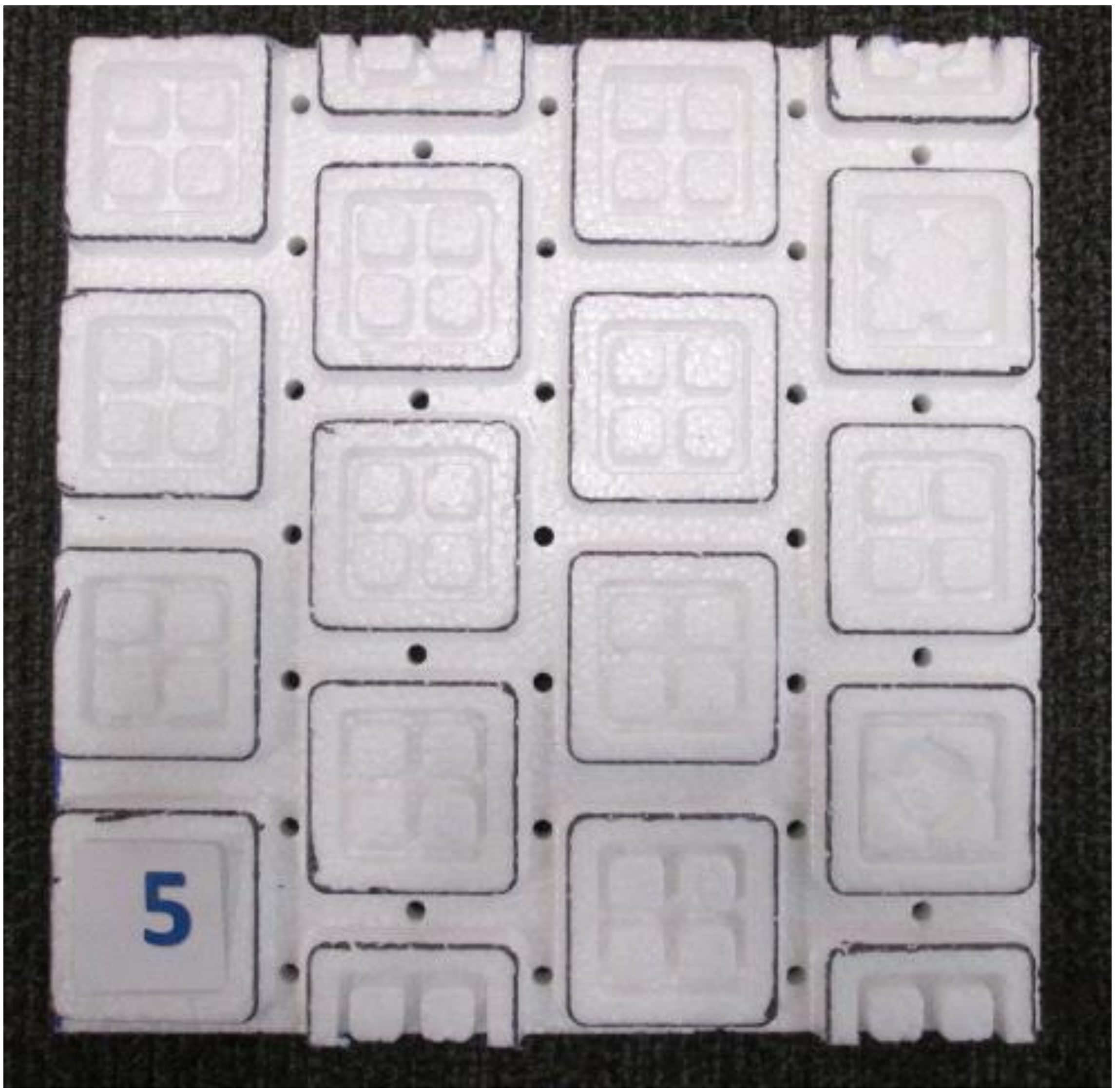
C2= 2.06E-06 C1= 9.88E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material:	Brock PowerBase
TRI Log No.:	31395
Specimen No.	5



TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

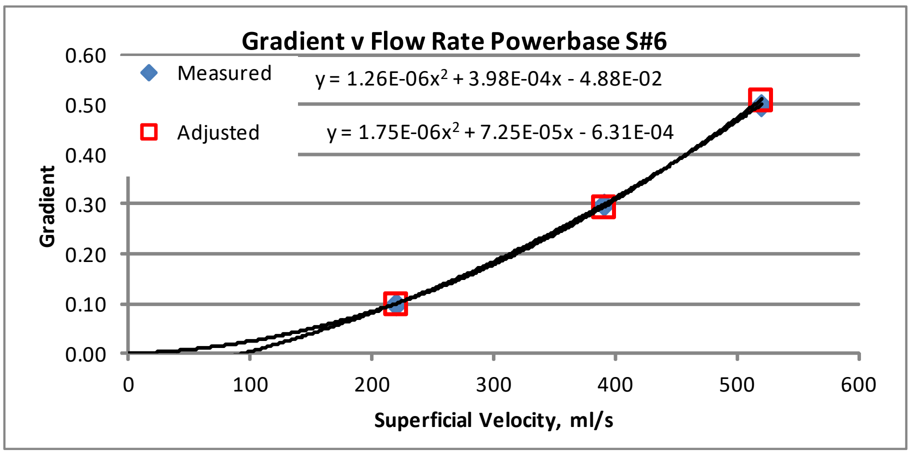
Material: Brock PowerBase
TRI Log No.: 31395
Specimen No. 6

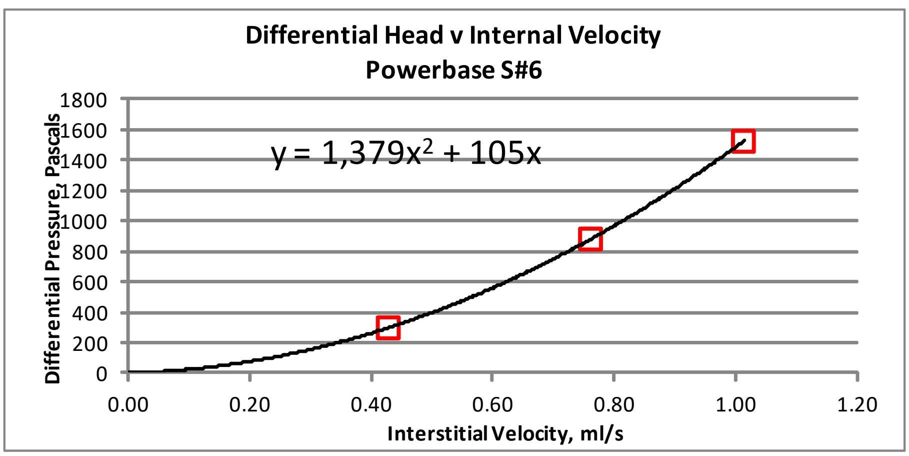
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	28.40	518		0.510
0.50	14700	28.10	523	**520**	0.510
0.50	14700	28.30	519		0.510
0.30	14700	37.80	389		0.295
0.30	14700	37.30	394	**391**	0.295
0.30	14700	37.70	390		0.295
0.10	7350	33.50	219		0.100
0.10	7350	33.30	221	**220**	0.100
0.10	7350	33.40	220		0.100

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 32 ml/s

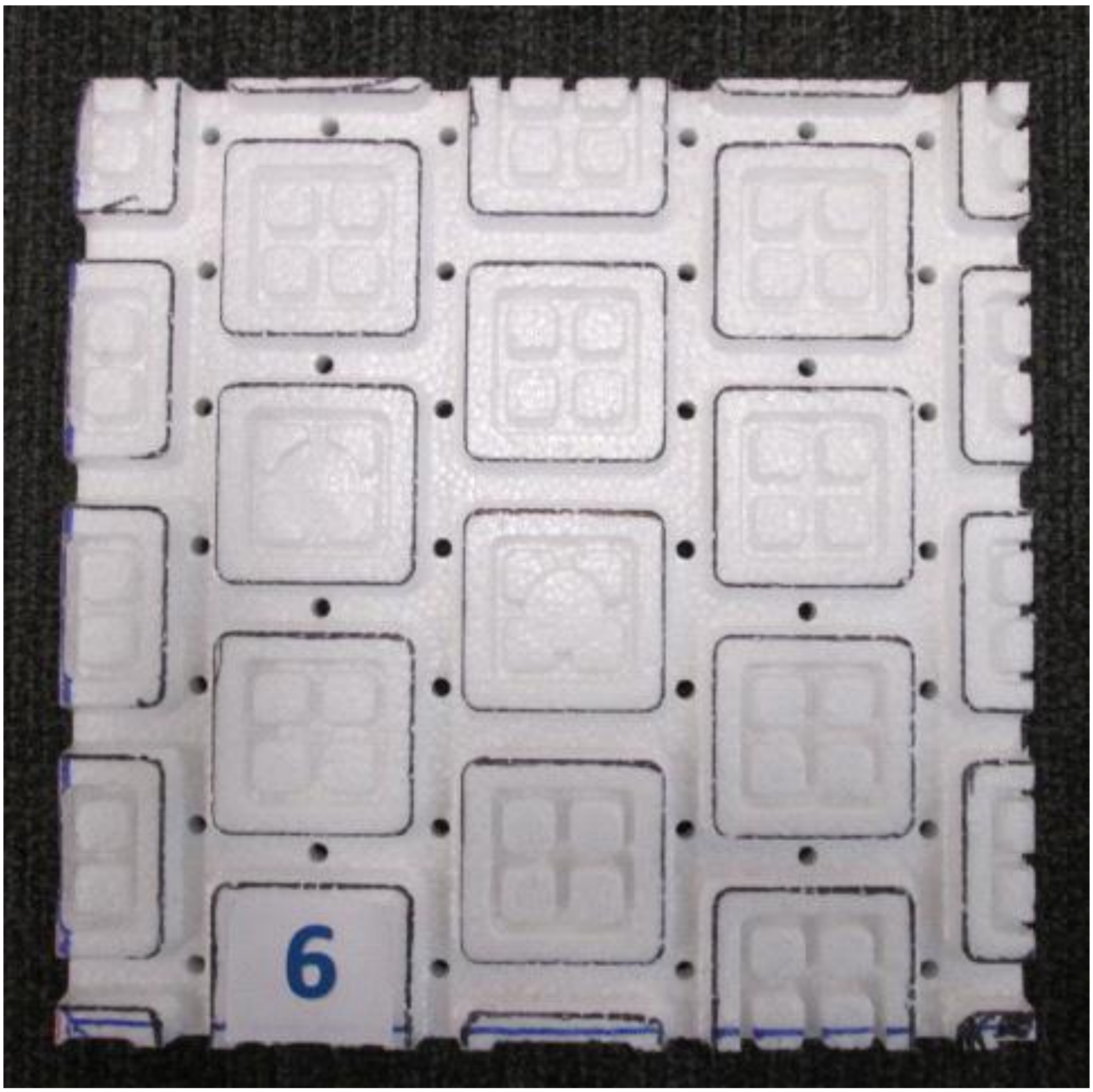
C2= 1.68E-06 C1= 1.00E-04





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material:	Brock PowerBase
TRI Log No.:	31395
Specimen No.	6



TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

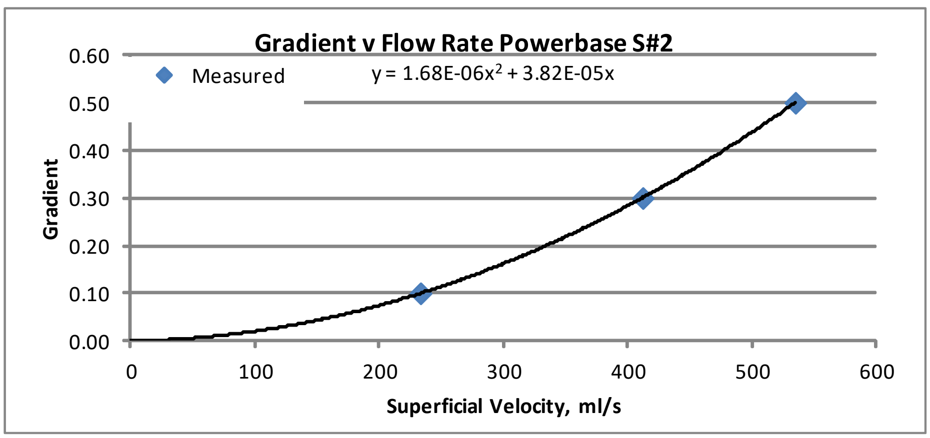
Material: Brock PowerBase
TRI Log No.: 22550
Specimen No. 2B

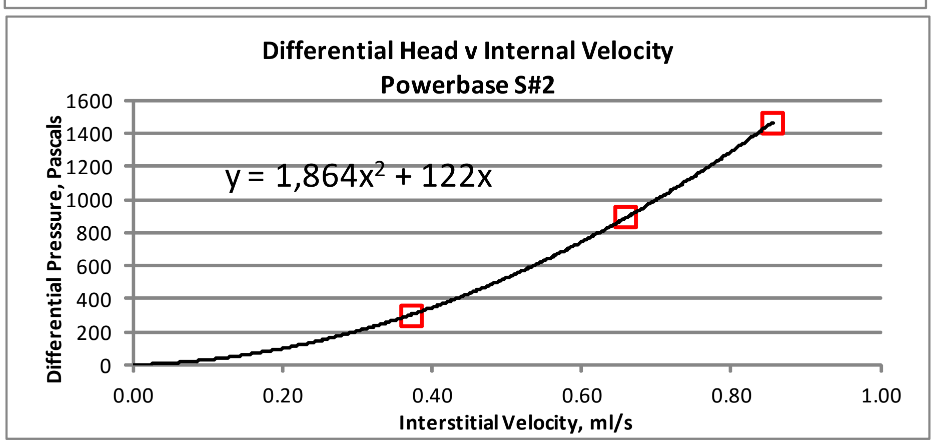
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	27.70	531		0.490
0.50	14700	27.10	542	**535**	0.490
0.50	14700	27.70	531		0.490
0.30	14700	35.60	413		0.300
0.30	14700	35.80	411	**412**	0.300
0.30	14700	35.70	412		0.300
0.10	7350	31.60	233		0.100
0.10	7350	31.70	232	**233**	0.100
0.10	7350	31.40	234		0.100

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 44 ml/s

C2= 1.68E-06 C1= 3.82E-05





TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

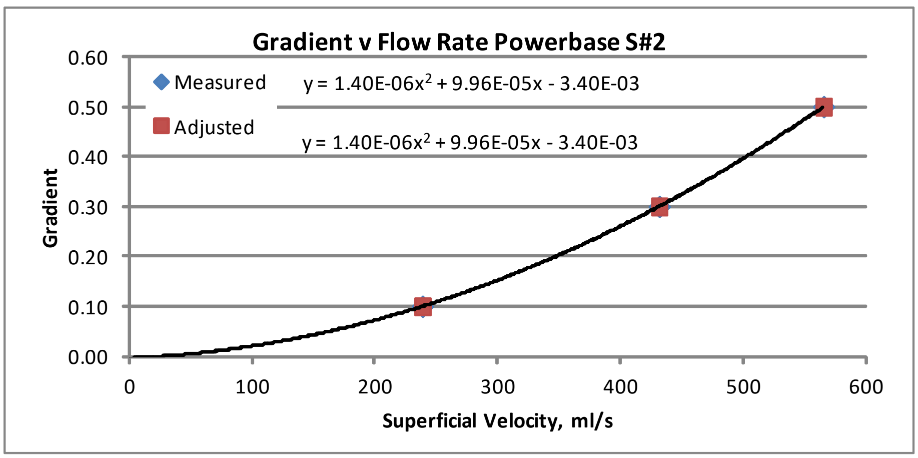
Material: Brock PowerBase
TRI Log No.: 22550
Specimen No. 2B

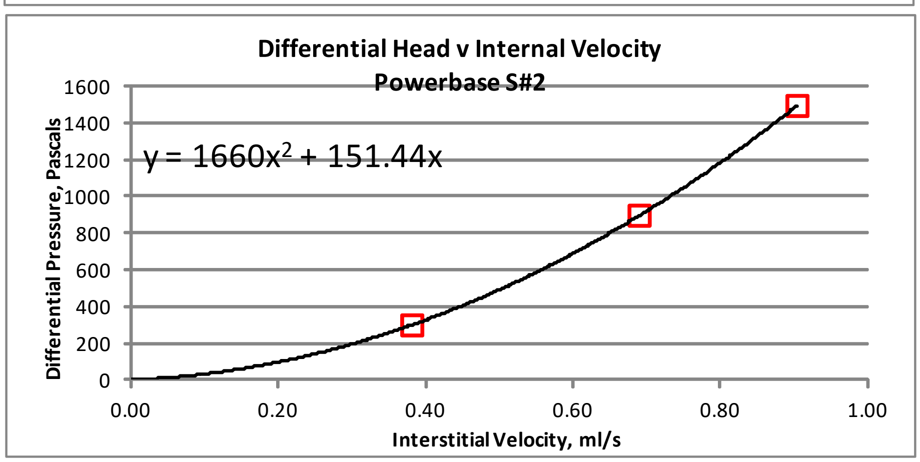
Measured Gradient	Measured Volume ml	Measured ElapsedTime s	Flow Rate ml/s	Average Flow Rate	Adjusted* Gradient
0.50	14700	26.20	561		0.500
0.50	14700	25.80	570	**565**	0.500
0.50	14700	26.00	565		0.500
0.30	14700	33.90	434		0.300
0.30	14700	34.40	427	**432**	0.300
0.30	14700	33.90	434		0.300
0.10	7350	30.80	239		0.100
0.10	7350	30.80	239	**239**	0.100
0.10	7350	30.80	239		0.100

*Gradient adjusted within ± measurement uncertainty range to generate "0" y-intercept for CFE

Extrapolated Flow Rate at Gradient : 0.0050 44 ml/s

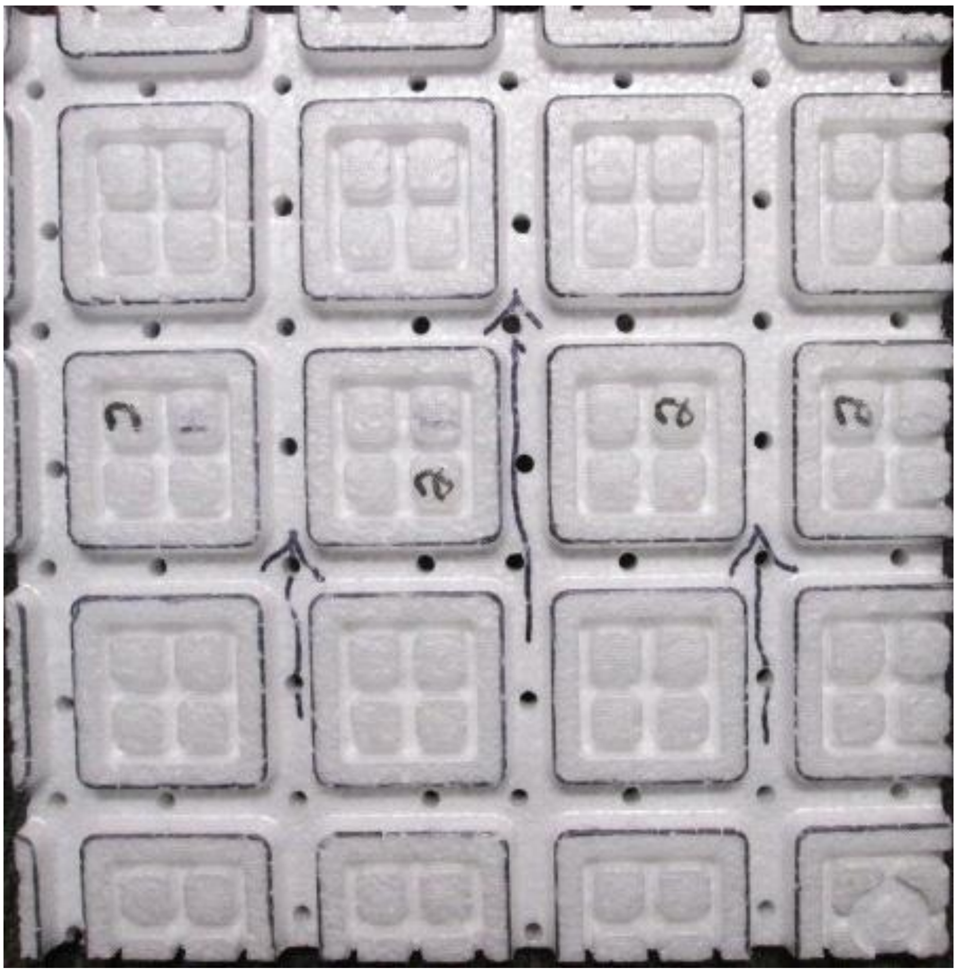
C2= 1.68E-06 C1= 3.82E-05





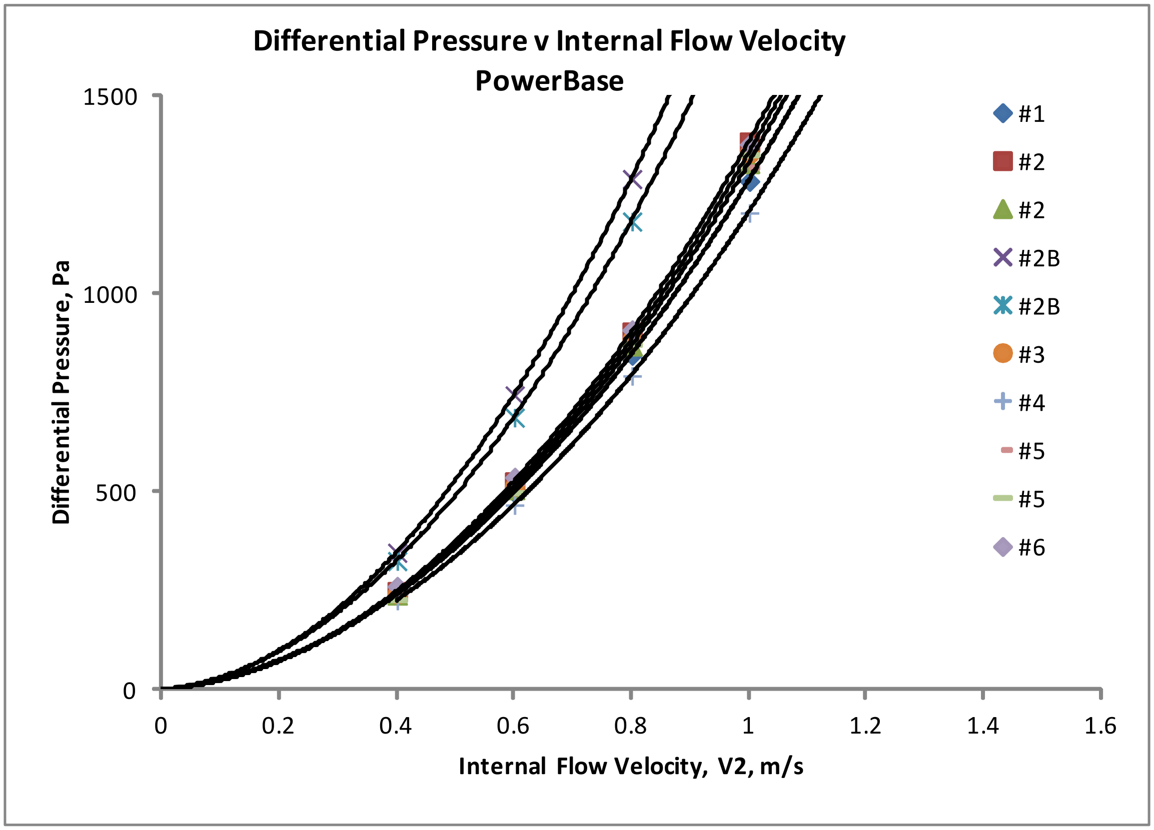
TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material:	Brock PowerBase
TRI Log No.:	31395
Specimen No.	2B



CHARACTERISTIC FLOW EQUATION
INTERSTITIAL VELOCITY ANALYSIS
TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

Material: PowerBase
TRI Log No.: 31395



Spec. No.	Est. A2 m^2	C1	C2	$\beta_\delta L$*	K_D	β_δ	Li mm	Li in
1	6.18E-04	148	1137	2.3	2.1E-06	7.5	134	5
2	6.25E-04	114	1270	2.5	2.7E-06	8.4	120	5
2	6.25E-04	115	1215	2.4	2.6E-06	8.0	125	5
2B	6.25E-04	122	1864	3.7	2.5E-06	12.3	82	3
2B	6.25E-04	151	1660	3.3	2.0E-06	10.9	92	4
3	5.13E-04	113	1243	2.5	2.7E-06	8.2	122	5
4	5.13E-04	140	1065	2.1	2.2E-06	7.0	143	6
5	4.42E-04	202	1119	2.2	1.5E-06	7.4	136	5
5	4.42E-04	51	1301	2.6	6.0E-06	8.6	117	5
6	5.13E-04	172	1206	2.4	1.8E-06	7.9	126	5
Ave Excl. 2B:		132	1195	2.4	2.68E-06	7.9	128	5

* $\beta_\delta L$ = the number of inertia units over the specimen length tested.

CHARACTERISTIC FLOW EQUATION
FIELD TRANSFORMED INTERSTITIAL VELOCITY PLOTS
TRANSMISSIVITY TEST RESULTS
BROCK USA
ASTM D 4716

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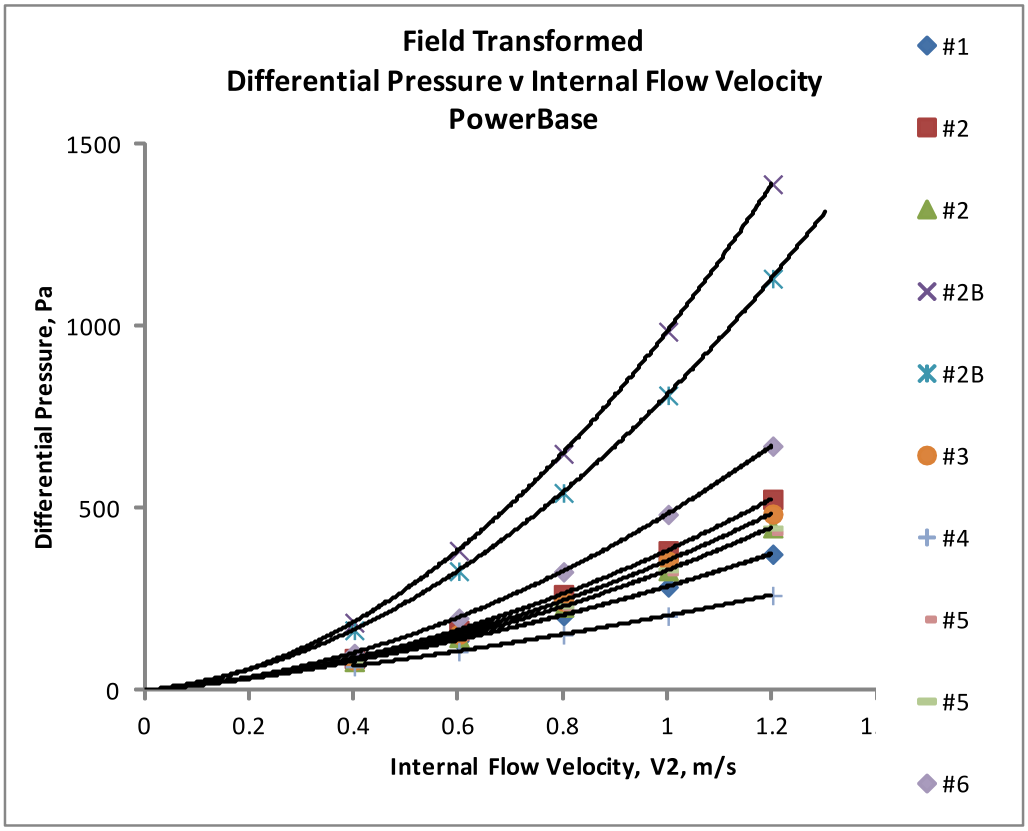

Spec. No.	Est. A2 m^2	Transformed Interstitial C1	C2	Estimated Field Flow Rate at 0.005 grad.	Estimated Lab Flow Rate at 0.005 grad.
1	6.18E-04	148	137	57.6	41.0
2	6.25E-04	114	270	65.8	46.0
2	6.25E-04	115	215	67.8	45.0
2B	6.25E-04	122	864	49.3	44.0
2B	6.25E-04	151	660	46.8	44.0
3	5.13E-04	113	243	55.3	38.0
4	5.13E-04	140	65	52.5	36.0
5	4.42E-04	133	191	43.6	31.0
5	4.42E-04	130	202	44.1	31.0
6	5.13E-04	105	379	53.3	32.0