A comparative study: Capillary flow porometry and dry sieving test results for geotextiles

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ABSTRACT: In the USA, dry sieving (ASTM D 4751) is an approved and commonly used method to measure the apparent opening size, O_{95} (AOS) of geotextiles. Although capillary flow porometry (ASTM D 6767) was approved in 2002, it is still not widely adopted, despite it provides the largest pore size (O_{98}) and a complete pore size distribution of a geotextile. The Capillary flow porometry is exempt of most of the experimental issues which affect the repeatability and precision of Dry Sieving test, such as the impact of electrostatic effects and clogging of glass beads within the geotextile. Many soil retention criteria currently used are based on AOS values of geotextiles. Therefore, researchers have been trying to come up with a correlation factor between dry sieving and capillary flow test results. However, different relationships have been established till now due to the limited number of geotextiles used in the various studies, lack of proper calibration and use of equipment with inappropriate ranges of precision. The goal of this study is to compare the results of calibration at three different laboratories using similar materials, wetting liquid and ASTM standard but two different porometers. In addition, six woven and non-woven geotextiles were included in the study to compare capillary flow and dry sieving test results.

Keywords: capillary flow test, dry sieving test, geotextile, calibration, bubble point

1 INTRODUCTION

Recently, the production of geotextiles using different fiber types, manufacturing processes, and formulations has flourished extensively in the market of geotextiles. The most common types of geotextiles widely used, are woven slit film, monofilaments or multifilament, nonwoven needle-punched, and heat bonded. In terms of the performance of these geotextiles as a filter, pore size distribution is an important property of geotextiles. In addition to the difference in fiber types, the pore size distribution and filtration properties are affected by the variety in manufacturing process.

In the North America, Dry Sieving test (ASTM D 4751) has been used as an approved and commonly used method to determine the apparent opening size (O_{95}) of a geotextile. Several standard specifications such as AASHTO M288 and GRI-GT13 use this method as a reference to use for filtration criteria. The other commonly used techniques to evaluate the largest pore openings and pore size distribution of geotextiles are: Hydrodynamic Sieving (CGSB 148.1 n°10), Wet Sieving (SW-640550-83), and Capillary flow test (ASTM D 6767). Only Capillary flow test provides the largest pore opening as well as a complete pore size distribution of a geotextile. The detailed information and accuracy obtained by this test makes it more attractive to the geosynthetics testing laboratories to run instead of using other tests to achieve the same information. In addition, using ASTM D 6767 to get the physical properties of a geotextile can potentially save valuable personnel and time resources of the laboratories rather than using a set of other ASTM methods combined.

Since 1996, very few capillary flow test studies (Vermeersch, et al. (1996), Bhatia et al. (1996), Lydon, et al. (2004), Aydilek, et al. (2006), Elton, et al. (2007), Przybylo (2007), Blond et al. (2015) and Tencate (2015)) have been carried out. However, in these studies different devices based on the capillary flow test principles have been used. Some of the devices were made by the researchers themselves and others were made of by the commercial companies like Coulter Corporation and Porous Materials, Inc (PMI). Two versions of Porometer manufactured by Coulter, Coulter Porometer I and Coulter Porometer II, were used by Vermeersch, et al. (1996) and Lydon, et al. (2004). Different versions of PMI manufactured devices have been used to perform capillary flow test. These devices included PMI Automated Perm-Porometer (Model No. APP-200) by Bhatia, et al. (1996); PMI automated device CFP-1500 AEDLS-2C by Przybylo (2007); Capillary Flow Porometer (CFP-1003A) by Kiffle, et al. (2014). In addition, researchers have used different types of wetting liquids in the capillary flow tests. Due to the variation in the liquid, standard methods and lack of calibration, no conclusive results have been found from the previous studies.

Due to several disadvantages of dry sieving test such as electrostatic effects and clogging of glass beads within the geotextiles, this method does not provide the accurate AOS values (Koerner (1990), Bhatia et al. (1996), Giroud (1996), Blond et al. (2015)). However, many soil retention criteria are based on AOS values of geotextiles. On the contrary, capillary flow test provides the largest pore size (O_{98}) and a complete pore size distribution of a geotextile. Therefore, for several years, researchers have been trying to come up with a correlation factor between dry sieving and capillary flow tests. However, due to the lack of calibration in the range of precision in the equipment and limited number of geotextiles, different relationships have been established till now (Bhatia et al. (1996), Elton et al. (2006), Aydilek et al. (2006), Blond et al. (2015), Tencate (2015). Bhatia et al. (1996) and Tencate (2014) found that the measured bubble point, O_{98} obtained by the capillary flow test is consistently smaller than the AOS (O_{95}) obtained by the dry sieving test. However, Aydilek, et al., (2006) could not find any consistent relationship between capillary flow and dry sieving tests.

Hence, a study has been taken to perform the capillary flow test using ASTM D 6767 to calibrate the test equipment with two thin metallic plates with circular holes. The calibration results were evaluated by a comparison at three different laboratories, Syracuse University, Texas Research International (TRI) and State of the Art Geosynthetic laboratory (SAGEOS)-CTT Groupe, using same calibration metallic plates and wetting liquid but two different equipment. In addition, six woven and non-woven geotextiles were selected to perform capillary flow test in three laboratories and a comparison was established to analyze the precision of both capillary flow and dry sieving test results.

2 CAPILLARY FLOW TEST PRINCIPLES

ASTM D 6767 was followed by three laboratories to perform the capillary flow test. Capillary flow test is a standardized test which is used to determine pore size distribution of both woven and non-woven geotextiles with pore sizes ranging from 1 to 1000 microns. This test is delineated in ASTM D 6767-16, "Standardized Test Method for Pore Size Characteristics of Geotextiles by Capillary Flow Test". The capillary flow test is based on the principle that the continuous pores in a geotextile hold a wetting liquid by capillary attraction and surface tension, and they will only allow the liquid to pass when the pressure applied exceeds the capillary attraction of the liquid in the largest pore. Consequently, smaller pores demand higher pressure to discharge liquid, since they have larger solid-liquid attraction. In order to originate the air flow through a saturated sample, it needs a gateway pressure or minimum pressure, which is related to the largest pore size, or bubble point, and the type of wetting liquid. The ASTM D6767 uses the following equation based on the equilibrium of forces:

$$\pi * d * \tau * B * cos\theta = \pi/4 * d\hat{}2 * P \tag{1}$$

Where,
d = pore diameter, microns,
τ = surface tension of the wetting liquid saturating the porous material, mN/m, (dynes/cm),
B = capillary constant,
θ = contact angle in degrees between the wetting liquid and the porous material (cosθ = 1 for a wetted sample with $\theta = 0°$), and
P = Pressure measured, Pa (N/m^2).
If the test liquid used in testing is assumed to be "wetting", or contact angle, $\theta = 0$, the equation is simplified even further:

$$\mathrm{d} = \mathrm{C}{*}\pi/\mathrm{P} \tag{2}$$

C = constant, 2860 when P is in Pa, 2.15 when P is in cm Hg, and 0.415 when P is in psi units. The capillary flow test can be used to measure the complete pore size distribution of a porous material by gradually increasing the pressure and approving steadily smaller pores to be vacant of liquid. The extended method is based on: (a) air is passed through the pores of a dry specimen during the period when any amount of air pressure will be imposed to one side of the specimen; and (b) air will be passed through the pores of a saturated specimen when the capillary attraction of the fluid is exceeded by the air pressure, (c) smaller and smaller pores will pass the air with the increase in air pressure. A complete pore size distribution of a geotextile can be determined using the following equation (ASTM D 6767).

$$\% \text{ Finer} = [1 - (\text{wet flow rate}/\text{dry flow rate})] \times 100\% \qquad (3)$$

2.1 *Capillary Flow Test Apparatus*

A state of the art capillary flow porometer, Geo Pore Pro (GPP 1001A) was used in both Syracuse University and SAGEOS for the capillary flow tests. This device is fully automated and manufactured by the Porous Materials Inc. (Ithaca, NY). The equipment consists of an electronically controlled pressure regulator (0 to 4000 counts), an absolute pressure transducer (usually 689.47 kPa) and a differential pressure transducer (6.89 kPa), 1 part in 20000 resolutions, 0.15% accuracy in readings, two mass flow transducers (0 to 10 cc/min, 0 to 200,000 cc/min), and a sample chamber. PMI porometer's APP CPCS is directed by a computer connected to the device, which controls valves opening and closing. A software "CapWin" is used to analyze the results obtained from capillary flow test and produce a complete pore size distribution. The pressure entering the system is controlled by the regulator, which is defined as counts (0 to 4000), referring to the maximum regulator setting. The amount of pressure incremented with each count depends on the air pressure going into the machine, and regulator range (see Figure 1 (a)).

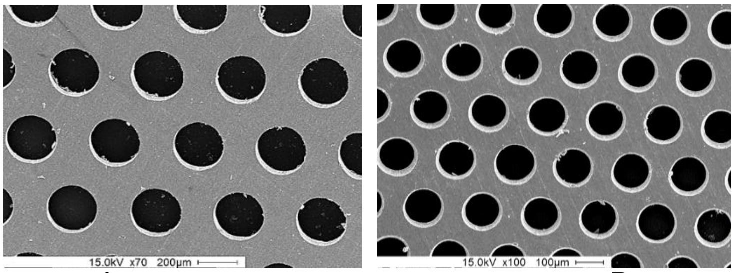
The Capillary Flow Porometer used by TRI laboratory is a touch screen, fully automated device which has a differential pressure sensor of 2.5 kPa with 4095 counts and 0.15% of full scale accuracy. The equipment consists of two flow meters with 3200 count resolution, such as 200 lpm high flow cylinder and 50 lpm low flow cylinder. Two pneumatic test cylinders with 50 mm diameter flow path are connected to operate high flow (on the left) and low flow (on the right). The flow area assures the competent perimeter sealed and prevents lateral pressure loss (see the sideways of TRI Capillary Porometer in Figure 1 (b)).

(a) (b)

Figure 1: Capillary Flow Device: (a) Geo Pore Pro (Syracuse University), (b) TRI Capillary Porometer (sideways)

3 CALIBRATION

To assess the accuracy of the capillary flow test results, calibration of the latest version of PMI equipment- Geo Pore Pro (GPP-1001A), was performed. The GeoPore and TRI device were calibrated using two thin metallic plates. The metallic plates are made of alloy stainless steel and have circular holes with a thick ness of 0.076 mm. These plates are produced by E-FAB Photo Chemical Machining, Engineering, & Fabrication (1075 Richard Ave. Santa Clara, California 95050, USA). Scanning Electron Microscopic (SEM) images (see Figure 2) were taken for both metallic plates and the measured O_{100} obtained from SEM images were recorded as 237-251 microns (A) and 120-130microns (B).



A B

Figure 2: Thin metallic plates (A and B) used for calibration

3.1 *Method*

For the Capillary Flow tests, the following sample preparation and testing procedure was followed.
Sample Preparation:

- Five to eight samples were cut with a measurement of 50.8-mm x 50.8-mm to fit in the sample holder. The samples were selected randomly from the swatch/sheet of the sample.
- ASTM D6767-16 suggests submerging the specimens into tap water for an hour and allow to dry in the standard atmosphere for 24 hours. All geotextiles were submerged in tap water for an hour and allowed to dry for 24 hours in the standard atmosphere. However, the metal plates were not submerged into water, to avoid corrosion.

Wetting Liquid:
Mineral oil was used as a wetting liquid the materials. Mineral oil was purchased from Walmart with a batch number of NDC 49035-035-16 (equateTM). Its surface tension was measured by KRUSS USA (1020 Crews Road, Suite K Matthews, NC 28105, USA). They used the Wilhelmy Plate method to measure the surface tension of the mineral oil. The surface tension of mineral oil was reported as 31.67 – 31.71 dynes/cm.

Shape Factor:
For thin metallic plates with uniform circular holes, a shape factor of 1 was used. However, for geotextiles with irregular pores a shape factor of 0.715 was used (Jena, (2014)).

Contact Angle:
The dynamic contact angle between mineral oil and thin metallic plate A was tested by KRUSS USA (1020 Crews Road, Suite K Matthews, NC 28105, USA). They used the Wilhelmy Plate method to measure the dynamic contact angle and five tests were performed to achieve the accuracy. The receding contact angle between mineral oil and thin metallic plate, A was reported as zero degree. Since both plates are made of same metal, the contact angle was assumed as zero for both A and B.

Cleaning Thin Metallic Plates for Calibration:
The thin metallic plates for calibration were cleaned with Methanol (from PHARMCO-AAPER, Batch no: 12214-03). The following procedure was used:

- A 50.8-mm x 50.8-mm thin metallic plate was soaked in Methanol for 1/2 hour in a shaker and removed. Then the specimen was dried thoroughly for 24 hours and transferred into the Porometer for testing.

Testing Procedure:

- The testing specimens were submerged in mineral oil for a period of 1 hour.
- Test was conducted with Wet up/ Calc. dry and a linear dry curve. The tests were performed in the wet state first and then the sample was pressurized to calculate the dry curve by the software.
- The procedure to set up a sample was: a gasket of 12.7-mm diameter at the bottom – specimen – a 12.7-mm adapter plate – clamp (see Figure 3). Then the chamber cap was placed above the adapter plate to secure the system provided a tight seal around the sample to ensure that no air escaped during the test.
- During testing 3.45 kPa was kept as maximum pressure.
- The test was started, and the pressure was increased at a constant rate. The pressure and flow rate were recorded by the software.
- Each test took approximately 30-35 minutes to complete.
- After the test, the pressure was reduced itself, the holder and adapter plate were removed, and holder was cleaned for the next test.

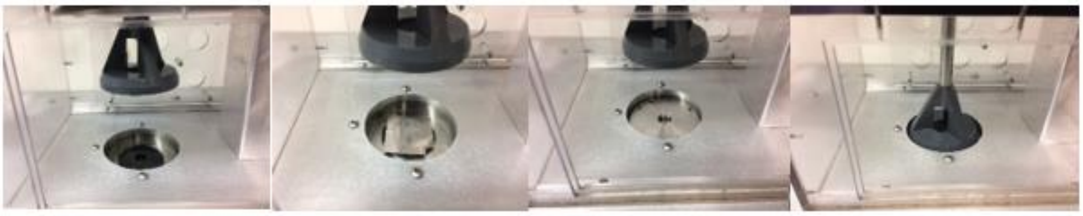


Figure 3. Test set up for thin metallic plates and geotextiles.

3.2 *Results*

The largest pore size (O_{100}) was measured by the Capillary flow test for 2 metallic plates with circular holes. Mineral oil (31.69 dynes/cm surface tension) was used for all tests and a shape factor of 1 was used for uniform holes. Table 1 showed a range of O_{100} values obtained by three laboratories with the manufacturing pore sizes, that were reported as a single number. Standard deviation (STDEVA) of O_{100} was calculated for both SU and TRI results, however, STDEVA could not be calculated for the results obtained from SAGEOS due to the limited number of tests conducted.

Table 1: Capillary Flow Test Results of Calibrating Metallic Plates

Calibration material	Manufacturing pore size (microns)	Syracuse University (SU)		Texas Research International (TRI)		SAGEOS CTT Groupe	
		O_{100} (microns)	STDEVA	O_{100} (microns)	STDEVA	O_{100} (microns)	STDEVA
A	244	275-300	9.28	269-300	10.34	363.69	NA
B	150	160-192.5	11.14	179-191	8.49	189.09	NA

*NA: not available

TRI used a different device and surface tension values of the mineral oil (31.69 dynes/cm) were compared by SU, TRI and SAGEOS results. The results given in Table 1 showed that the results obtained by SU and TRI are comparable. The results obtained by SAGEOS, for plate ‘A’ showed quite a large variation, however, result for plate ‘B’ was almost similar to SU and TRI results. The results obtained by both SU and TRI were slightly larger (14%-18% approximately) than the reported manufacturing values. However, the results obtained by SAGEOS were 20% - 33% approximately larger than the manufacturing pore sizes. The STDEVA calculated for the results of SU and TRI were recorded as a range of 9.28 – 11.14 and 8.49 – 10.34 respectively. Due to the limited number of testing results reported by SAGEOS, STDEVA could not be calculated.

4 CAPILLARY FLOW AND DRY SIEVING TESTS WITH GEOTEXTILES

A research study was undertaken to compare capillary flow and dry sieving test results of six different geotextiles. The selected geotextiles included both woven and non-woven geotextiles from three manufacturers. Based on the capillary flow technique stated in the ASTM D 6767 – 16, pore size distribution of each geotextile was measured. From the pore size distribution, O_{98} (bubble point according to ASTM) is calculated. Dry sieving tests (ASTM D 4751) were performed as well for the selected geotextiles. For each geotextile, 5-10 capillary flow and 5-6 dry sieving tests were conducted. The physical properties of the selected geotextiles are provided in Table 2.

Table 2: Physical Properties of Geotextiles

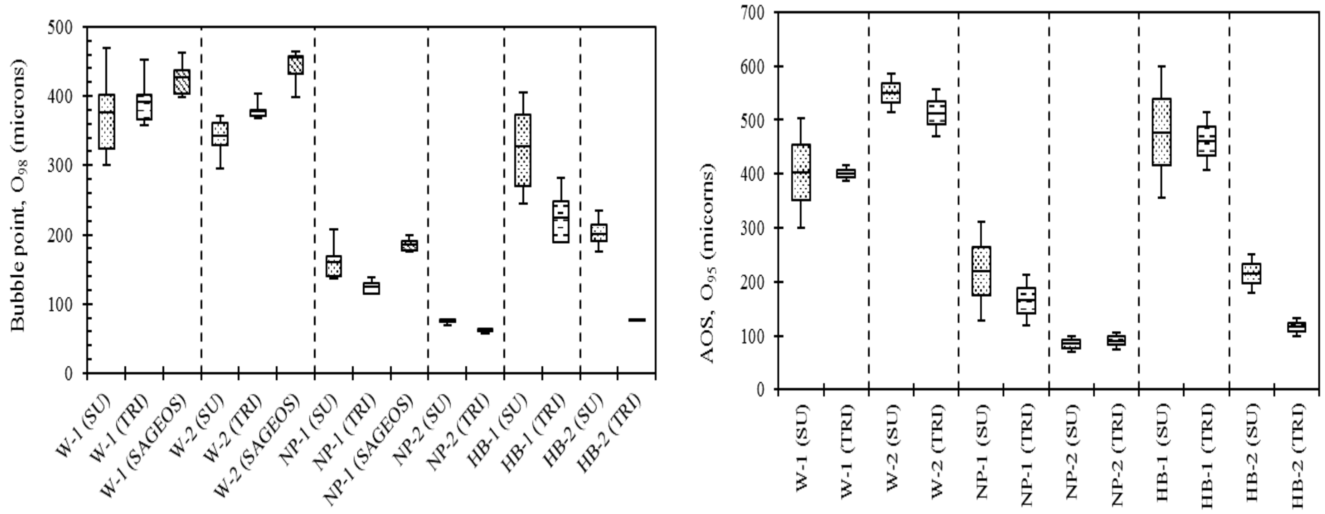
Geotex-tiles	Polymer Type	Weave types	Manufactur-ing process	Mass per unit area (g/m^2)	Thickness (mm)	Permittiv-ity*
W-1	PP	Monofilament	Woven	208-214	0.59-0.63	2.1
W-2	PP	Slit film	Woven	229-234	0.59-0.68	0.6
NP-1	PP	Needle-punched	Non-woven	146-163	0.64-0.89	1.7
NP-2	PP	Needle-punched	Non-woven	270-287	1.29-1.44	0.3
HB-1	PP	Heat-bonded	Non-woven	90-100	0.3-0.38	1.0
HB-2	PP	Heat-bonded	Non-woven	88-108	0.27-0.34	NA

*Reported by the manufacturers, NA: Not available

4.1 *Results*

In Figure 4a and 4b, the bubble point results from capillary flow tests and AOS results from dry sieving tests were plotted for all six geotextiles using box plot and whisker diagrams. The box plot and whisker diagram consist of a box which lies in between first and third quartiles. The middle partition in the box indicates “mean” value of the range. The "whiskers" are straight line extending from the ends of the box to the maximum and minimum values. In SU laboratories, 8-10 capillary flow tests were performed for each geotextile, while in TRI and SAGEOS, 5 capillary flow tests were performed for each geotextile. Therefore, a little variation could be noticed in the range of bubble point results (see Figure 4a). In addition, the testing samples were selected randomly from a large sheet of geotextile, which resulted in some discrepancy in the pore sizes, and as a result, in the bubble point results. If the results were compared only for 5 tests and outliers were removed from the plot, the results would be same for all three laboratories. One woven geotextile (W-1) and one heat bonded geotextile (HB-1) provided larger ranges of both bubble point and AOS results compared to other geotextiles. For dry sieving test, both SU and TRI performed 5-6 tests for each geotextile and the AOS results plotted in Figure 4b are in similar ranges.

SU and TRI results for both O_{98} and O_{95} were plotted in Figure 5. The orange and blue colored markers showed the results of SU and TRI respectively. The bubble point results from both SU and TRI provided a narrow range of pore openings compared to the AOS results, which emphasizes the importance of Capillary flow test. The results of 1 woven geotextile (W-1) and 1 heat bonded non-woven geotextile (HB-1) had more scattered values than other geotextiles. This trend was observed from both SU and TRI results. However, both needle punched (NP-1 and NP-2) non-woven geotextiles, the other woven geotextile (W-2) and heat bonded (HB-2) non-woven geotextile showed a smaller range of both O_{98} and O_{95} results. Figure 5 showed a correlation between O_{98} and O_{95} for the selected geotextiles. The best fitted line plotted provided an equation, $y = 1.23x + 32.075$ (x = bubble point, y = AOS); to calculate an AOS value for each corresponding bubble point value of the geotextile. $R^2 = 0.82$ means 82% AOS values obtained from the test are comparable to the bubble point values. The best fitted line should not be extended below a certain bubble point value (60 microns). Below this limit, the correlation is not valid, because no result exists below the range.



(a) (b)

Figure 4. Box plot and whisker diagram (a) bubble point, (b) AOS.

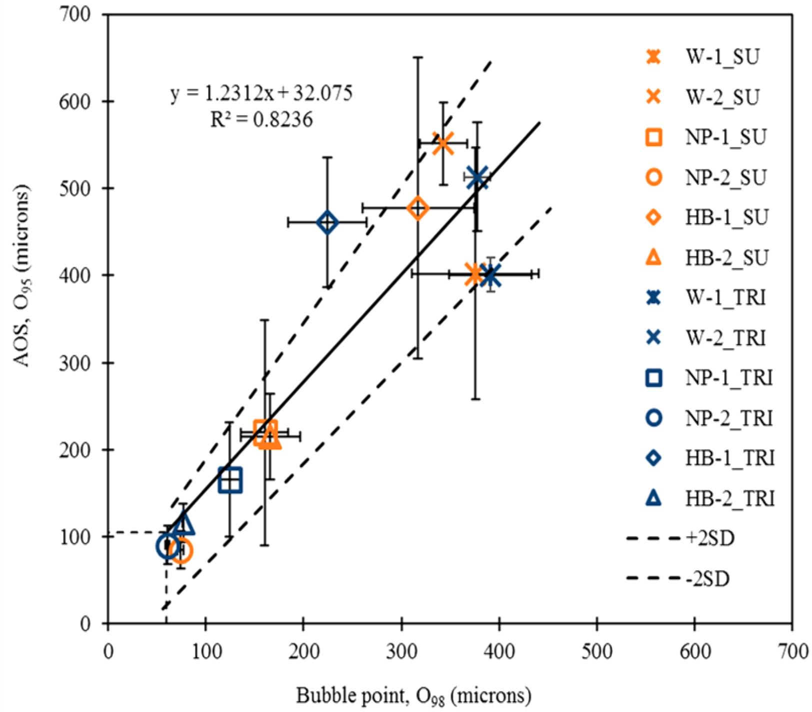


Figure 5. Correlation between bubble point and AOS values.

In Figure 5, the range of AOS and bubble point values were presented with mean +/-2SD (a band around the mean with a width of two standard deviations). According to the three-sigma rule of thumb, mean +/-2SD is called 95% confidence level as well. For each bubble point value, one should expect a range of AOS values within mean±2SD. The equation and positive slope of the best fitted line provided a larger AOS value corresponding to the bubble point value, which validates the previous study conducted by Bhatia et al. (1996) and Tencate (2014). However, the correlation provided in Figure 5 was established based on 6 geotextiles only. Therefore, it should be kept in mind that there might be some deviation for other geotextiles with different fiber types, formulations and manufacturing process; which should be evaluated properly.

4. CONCLUSIONS

A comparison of Capillary flow test and Dry sieving test results from three different laboratories was established with calibration. The cleaning process of calibration metallic plates were discussed in the study. Except one calibration result from SAGEOS with a metallic plate, A1; the other calibration results obtained from SU, TRI and SAGEOS were into the similar range of opening size. The consistency in the calibration test ensured the accuracy of the Capillary flow test.

The comparison in the capillary flow test results with geotextiles were established for SU and TRI. The results showed that capillary flow test provides a narrow range of O_{98} while a large range in the AOS results could be expected from Dry sieving tests. The bubble point results from both SU and TRI provided a narrow range of pore openings compared to the AOS results, which emphasizes the importance of Capillary flow test. Due to the variation in the number of testing, a little difference was noticed in the bubble point results of three laboratories. However, if the results were evaluated for similar number of testing and outliers were removed, the results would be same for all three laboratories. A good correlation (R^2 = 82%) was established between bubble point and AOS values for six geotextiles. A study has been conducted at Syracuse University with 52 different types of geotextiles to compare between capillary flow and dry sieving tests, which was not possible in the previous studies due to the lack of calibration and limited number of geotextiles. The analysis in the SU laboratory is on the way to establish a better correlation very soon.

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