

A Comprehensive Analysis of the Measurement Techniques used to Determine Geotextile Opening Size: AOS, FOS, O_{90} , and 'Bubble Point'

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ABSTRACT

Filtration is a key function of geotextiles. One of the most important properties related to this function is the pore opening size. In North America, this property is determined using ASTM D4751, which involves dry sieving of glass beads through a dry geotextile. However, other opening size measurement techniques are used elsewhere in the world. Eastern Canada uses 'FOS', where water drags glass beads through the geotextile, and opening size defined by sieving the beads passing through the geotextile. Europe uses a wet sieving technique, where high frequency vibrations are used to force the passage of soil particles through a wet geotextile sample. Finally, a technique involving capillary flow has been available at ASTM since 2002. This technique considers the liquid-air surface tension properties and the liquid-solid wettability, and involves drainage of liquid from the geotextile for determination of the entire pore size distribution of a geotextile. Unfortunately, the corresponding results may not compare well, and some of them have very poor between-lab reproducibility. The aim of this paper is to describe these various pore-size measurement techniques, as well as the technical issues which are known to influence the results.

1. INTRODUCTION

There are many geotextiles currently on the market, which are produced using different fibre types, formulations and manufacturing processes. The most common are woven slit films, woven monofilaments or multifilament, nonwoven needle-punched, spunbond, or heat bonded, and circular knits. All of these manufacturing techniques affect the pore size distribution, and therefore filtration properties (Bhatia and Smith 1995).

Since the early 90's, apparent opening size (AOS) as defined by ASTM D4751, is used in North America for determining the opening size of geotextiles. It is referenced in several standard specifications such as AASHTO M288 and GRI-GT13, and used in many filtration criteria used in engineering practice to assess whether a particular geotextile is capable to perform well if used as a filter with a given soil, by comparing an intrinsic property of the geotextile to properties of the soil.

However, there are also other measurement techniques that were developed in Europe or in Canada in particular. These involve different measurement techniques, and may provide different results. This paper describes the measurement techniques which were active and recognized standards at the time of publication of this document. These include ASTM D4751 (AOS), CGSB 148.1 n°10 (FOS), ISO 12956 (O_{90}), as well as ASTM D6767 (bubble point, or BBP).

2. DESCRIPTION OF THE STANDARD TEST METHODS

2.1 Apparent Opening Size 'AOS' per ASTM D4751

Measurement of AOS is based on the concept that the geotextile filter compares to a sieve. The test protocol was developed to determine to which sieve size the geotextile filter corresponds best, using a method that is as close as possible to the method used in geotechnical engineering to determine soil particle size distribution. Instead of sieving unknown particle sizes with known sieves, the test consists in sieving known particle sizes through a sieve with an unknown opening: the geotextile filter.

AOS is thus based on a concept, and involves pieces of equipment, which are common in geotechnical engineering. It can thus be conducted by any geotechnical laboratory capable to run a sieving test per ASTM D422, the sieving technique commonly used to determine the particle size distribution of soils. The single piece of 'complex' equipment needed is a shaker conforming to the requirements of ASTM D422, which is combining a rotating movement and the periodic impact of a hammer to minimize clogging of the sieve, while sieving particles. The sample holder that is necessary to conduct AOS can easily be prepared by repurposing a broken sieve or by machining of a solid piece of plastic and inclusion of a metallic component to minimize the development of static electricity, as shown on Figure 1. The glass beads which are needed to conduct the test can be purchased from glass beads manufacturers at a nominal price, or prepared in the lab using standard sieves. The specimen size corresponds to the diameter of a standard 8 inches sieve.

The intention of classifying geotextiles in categories, similar to sieves, is simple and easily understandable by geotechnical engineers, the main users of geotextile filters. However, there are several challenges which make the reliability of this measurement technique questionable. These challenges, discussed below, range from experimental issues to the method used to analyze the observations.



Figure 1: AOS specimen holder, of the size of a standard 8" sieve

2.1.1 Determination of the 'AOS' based on the observations

In ASTM D4751-12, there are three methods of calculating and reporting AOS, depending on the sections of the standard considered, and these methods do not lead to the same result:

- Section 10.3 specifies how to assign an average value in millimeters calculated from a pass/fail observation on a given sieve, which best reflect the concept of this test as it is presented above.
- Section 11.1 proposes a graphical interpolation. With this method, AOS is the opening of a theoretical sieve for which 5% of the beads would pass through the geotextile, based on the values determined on measurement made with classes of beads immediately larger and smaller to this value. This technique also permits determination of an average, a standard deviation and a coefficient of variation.
- Section 12.6 allows reporting with only the US Standard sieve number, based on the interpolation technique.

Even if the same test procedure as per Section 9 is performed, AOS value will be reported differently depending on the chosen option, but with the current version of the standard, the report will not make any mention of which determination method was used.

Despite this relative confusion, it shall be pointed out that:

- In contract documents, the values specified for AOS are almost always 'smaller than' a specific sieve number and the corresponding opening size in mm, which reflects the idea that the geotextile mimics a standard US sieve. As long as this specified value corresponds to one of the sieve sizes used in AOS determination (i.e. 75, 106, 150, 212, 300, 425 or 600 μm), the three possible values that can be reported as 'AOS' per D4751 will always be on the same side of the limit, except for extremely irregular geotextiles.
- Work has been initiated in ASTM D35 during 2014, in order to clarify the above issue and ensure that only one value can be reported if using the dry sieving technique described in ASTM D4751.

Finally, the application of some of the filtration criteria used in geosynthetics engineering may require specification of a geotextile with an opening size significantly lower than 75 μm . In example, prefabricated vertical drains are always installed in fine grained soils, and may require the use of geotextiles with opening sizes of, say, 60 μm , which cannot be properly measured with AOS, which detection limit is 75 μm .

2.1.2 Practical concerns related to the determination of AOS per ASTM D4751

There are several practical concerns associated with the determination of AOS, which are believed to affect the reliability of the test. The most critical are listed below.

- **The measurement of AOS is based on 5% passing through a sieve.** To put this in perspective, the tolerance on ASTM compliance sieves is 5% with a confidence interval of 66% as per ASTM E11 (i.e. $\pm 6.6\mu\text{m}$ for 150 μm , $\pm 9\mu\text{m}$ for 180 μm). However, when beads identified with a given size are used, i.e. 150 μm , this means that the smallest glass beads may have a diameter of 149 or 156 μm , depending on the sieve used. The 5% passing requirement can thus be met, or not, depending on which actual bead size is used, and which actual opening is dominant on the geotextile.
- **Impact of imprecise preparation of the glass beads.** The above observation is even more critical if preparation of the beads is taken in consideration, i.e. when glass beads are segregated in classes. Clogging of the sieves at this stage will result in the presence of beads from a smaller class in a given class, i.e. beads with a diameter of 125 μm may be found in a class considered to be 150 to 180 μm . This contamination by smaller beads is more likely to pass through the geotextile than the beads of the given class of particles. If this contamination exceeds 5%, this could generate a bias in the results, and possibly lead to the assignation of the AOS to the wrong, larger class of beads.
- **The development of static electricity.** A static electric charge is created when polypropylene or polyester (the most common geotextile materials) contact glass beads. Static electricity depends in particular on the humidity of the room, thus on geographical location and season unless the test is conducted in a room with a controlled atmosphere. ASTM D4751 does not specify to conduct the test in a standard laboratory atmosphere, and provides only very vague recommendations to reduce or eliminate static electricity, such as use of 'static guard' antistatic spray. These recommendations do not consider critical issues such as the thickness of the geotextile, and there are no means suggested to assess the performance of such measures.
- **The impact of static electricity is that glass beads do not pass through the geotextile.** Therefore, the AOS will be assigned to a larger bead size, large enough to overcome static electricity issues. It is not impossible to observe static electricity bias as large as one or two sieve sizes, if not more. Static electricity will have a greater impact on measurements conducted with small beads (i.e. 75, 106 or 150 μm), because the specific surface of 50 grams of glass beads is larger than with coarser beads, leading to a larger opportunity to develop static electricity. Thick geotextiles will also be more prone to generate static electricity problems, because the larger surface of fibers exposed to glass beads.
- **Re-use of previously tested specimens.** If the specimen thickness is less than 2.3 mm (0.091"), the current version of the standard makes it possible to re-use the same specimen several times. There are several geotextiles with thicknesses in the range of 2.3mm, for which observance of this criterion may apply to only a fraction of the specimens, and possibly lead to scattered results. In addition, it is not clear why a value of 2.3mm was selected as a threshold value.
- **Glass beads entrapped within a re-used geotextile specimen may be released** during the sieving a larger bead size. This could potentially lead to a higher quantity of beads passing through the geotextile when it is sieved for the second time. In example, if more than 5% passed through the first sieving, i.e. 50%, the beads from this category may be temporarily retained into the geotextile, and released when sieving on the next bead size. This can affect the results in a similar way than when the glass beads are not precisely prepared, and could lead to an overestimation of the AOS.
- **The standard only poorly defines the motion and tapping arm movement.** As the test is conducted in dry condition, the only energy applied to favor displacement of the beads through the geotextile is the rotation of the sieve column, combined with the impact of the tapping arm. The more energy will be applied by the tapping arm, the more likely will the glass beads move downward, and eventually pass through the geotextile. As a consequence, the use of a sieve shaker that would not be properly set (falling height of the tapping arm) would lead to beads not passing through the geotextile, thus definition of a smaller AOS. This issue is particularly critical with the evaluation of thick geotextiles, offering a large volume of pores for particle entrapment and development of static electricity by friction between the geotextile fibers and the glass beads.

Overall, the experimental issues which have been observed by the primary authors as affecting to affect the results obtained per ASTM D4751 include static electricity, preparation of the glass beads, source of energy used to favor the displacement of the glass beads through the geotextile, among other which are not discussed here (fracture of the beads,...). These experimental issues have a greater impact on thick geotextiles, as well as on those exhibiting a smaller opening size, for the reasons explained above.

It should be mentioned that there are some means to overcome some of these issues, such as controlling the relative humidity of the laboratory atmosphere; never re-use 'thin' test specimens even if the standard allows to do so; always use new, never used glass beads, control their particle size distribution using optical methods (microscope) instead of sieves. However, until these measures are mandatory as per the standard requirement, they will only increase the cost of the test (sometime significantly), and will thus not be used by all laboratories. This could lead to significant differences between results, i.e. when tested by a manufacturer, then controlled by a third party laboratory.

2.1.3 Precision of the measurements generated by ASTM D4751

'Precision and Bias' values are published in standard ASTM D4751. They are based on a study conducted in 1999, with 5 different laboratories, involving one single product of each type. The 'between lab reproducibility' are as high as 63% for needle-punched, 39% for slit films, and 30% for heat bonded fabrics (Table 1).

Table 1. Estimate of precision of different types of geotextiles (from ASTM D4751).

Statistic	Slit Film, Woven	Monofilament, Woven	Needle-Punched, Nonwoven	Heat-Bonded, Nonwoven
Average AOS, mm	0.179	0.142	0.182	0.137
Within Laboratory Repeatability Limit, CV% _{Sr}	8.3	3.4	4.0	5.9
Between Laboratory Reproducibility Limit, CV% _{Sr}	13.9	8.6	22.7	10.8
95% Confidence Limit Within Laboratory, CV% _r	23.4	9.4	11.7	16.5
95% Confidence Limit Between Laboratory Reproducibility, CV% _R	39.1	24.2	63.4	30.2

This table shows that different fibres and bonding can influence the reproducibility and confidence limits of the test. However, even the 'best' repeatability is as high as 24%, which is believed by the authors to be in relation with the experimental issues listed above and remains much too high for a property that is a defines a primary function of geotextile filters.

In order to develop a new set of data focusing specifically on heat bonded geotextiles, a series of tests were ordered to as many as 8 different laboratories, on 5 different heat bonded geotextiles. These products were all manufactured on the same production line but with different masses per unit areas. The corresponding results are presented on Table 2 and Figure 1.

Table 2. Results obtained on heat bonded geotextiles by 8 different laboratories, using ASTM D4751.

Laboratory	A	B	C	D	E	F	G	H(1)	H(2)
Mass (g/m ²)									
90	184	132	196	247	204	--	≤75	206	206
95	175	111	--	--	--	--	≤75	187	198
100	173	104	180	212	178	--	≤75	198	197
115	133	101	166	178	140	140	≤75	167	148
125	92	85	164	106	144	129	≤75	105	103

Sampling of the product was conducted by the manufacturer, in the plant, before any other handling or shipping. The samples received in each lab can thus be considered to be in perfect condition, without any influence of handling in the field. The tests were requested using standard contractual procedures. As a consequence, the values presented on Table 1 and Figure 1 are believed to be representative of the actual market response to the determination of AOS for heat bonded geotextiles.

It can be observed that AOS values range from 75 µm to 250 µm for the lightest grade, and from 75 µm to 163 µm for the heaviest grade.

≤75 µm was reported for all the products by laboratory G. A reported value of ≤75 µm is the smallest dimension that can be observed using AOS, and means that the 'actual' AOS value is in fact lower than or equal to 75 µm. In the laboratory, this result reflects a quantity of glass beads smaller than 2.5 grams (5% of 50 grams) collected under the geotextile when using '75µm glass beads', which are theoretically all passing the 90 µm sieve, and all retained on the 75 µm sieve.

On the other hand, results as high as 247 µm were reported by laboratory D for the same material. This result means that a mass of glass beads smaller than 2.5 grams was passing through the geotextile when using '300µm beads', which are retained on the 300 µm sieve, and passing the 355 µm sieve; and a mass of glass beads greater than 2.5 grams was passing through the geotextile when using '210µm beads' which are retained on the 210 µm sieve, and passing the 250 µm sieve.

Practically, this means that one laboratory did not observe any glass bead with a diameter smaller than 90 µm passing through the geotextile, while another laboratory observed a 'significant' amount of glass bead larger than 300 µm passing through the same geotextile.

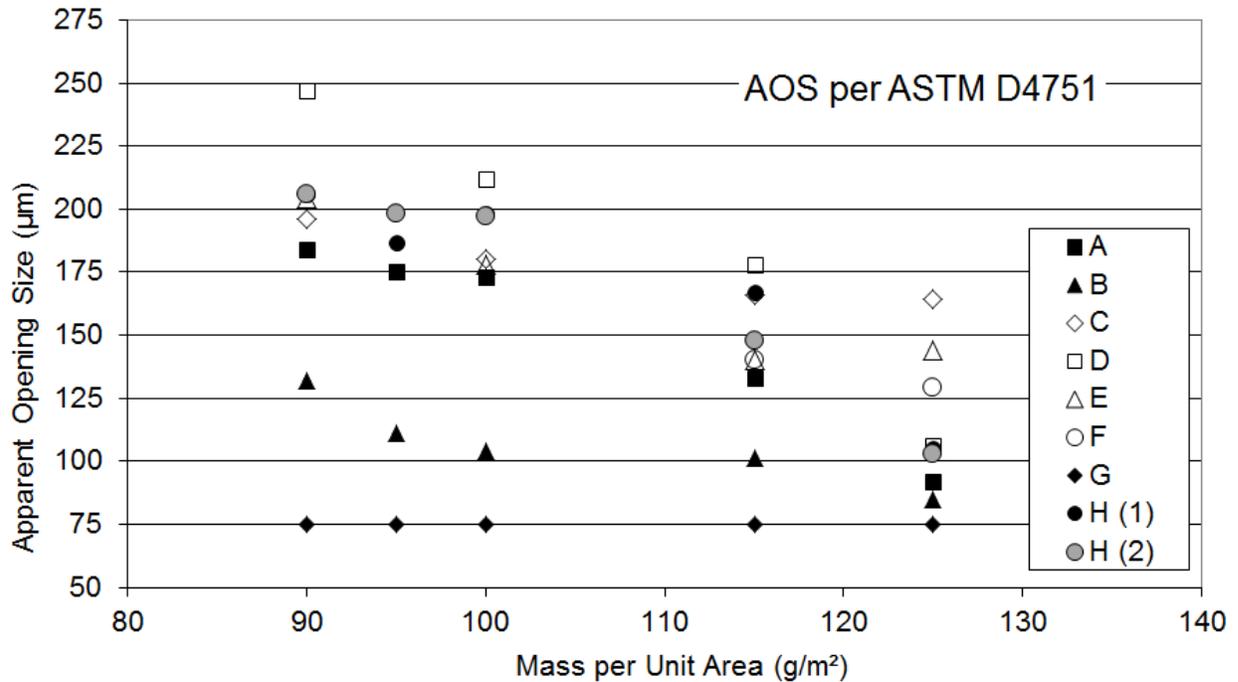


Figure 2: Distribution of the values of AOS obtained by 8 different laboratories on 5 different heat bonded geotextiles

Between the 2 extreme responses observed for the lightest product, the array of reported AOS values is relatively wide, as it is for the whole series of geotextiles. The authors believe that the poor between-lab reproducibility observed herein is the result of the long list of technical and experimental issues presented above.

2.2 Other measurement techniques

2.2.1 Opening Size 'O₉₀' per ISO 12956

The standard developed by ISO TC221 on Geosynthetics involves the same specimen holder as ASTM D4751, but presents several important differences:

- Despite the standard does not exclude the possibility to use glass beads, natural particles are normally used as the reference material sieved through the geotextile.
- A mixture of particles with a uniform distribution through the entire range of particle sizes is used. This mixture shall be cohesionless, not present any gap, and the result is valid only if it is between d_{20} and d_{80} , ensuring that some, but not all the particles pass through the geotextile.
- Water is sprayed on the surface. The quantity of water sprayed shall be small enough to avoid creating a force dragging particles through the geotextile, but sufficient to avoid the development of static electricity.
- Instead of using a sieve shaker to force the passage of particles through the geotextile, a vibrating table with a frequency of 50 to 60 Hz is used.
- Determination of the opening size is made by sieving the particles passing through the geotextile. Considering the passing material as a soil, and the O_{90} of this 'soil' as the largest significant particle, the opening size of the geotextile is considered to be the O_{90} of the particles passing the geotextile.

In principle, this test considers the opening size of the geotextile by looking at the dimension of the particles passing through the geotextile using a set of predetermined experimental conditions. The main difference with AOS, in conceptual terms, is that it does not try to find which sieve the geotextile is mimicking, but more which particles of a soil can pass through the filtration media that is the geotextile, whatever its structure and complexity.

Several of the issues which as known to be problematic with testing per ASTM D4751 are resolved in ISO 12956:

- No static electricity can develop as the test is conducted in humid conditions;
- The tolerance to errors in glass beads preparation, which is critical with ASTM D4751 as a deviation of only 5% can place the geotextile in a different class of product, would only lead to marginal errors with ISO 12956, where a broadly graded mixture of soil is used anyway to conduct the test ;

- It is theoretically possible to measure opening sizes of any dimensions, including smaller than 75 μm , as long as it is possible to determine the O_{90} of the particles passed through the geotextile by sieving. According to the standard, sieves as small as 20 μm can be used, which theoretically permits to determine of O_{90} with values as low as 20 μm . The realism of accurately sieving soil particles or glass beads down to 20 μm shall be verified. However, experience of the primary authors is that sieving down to 45 μm is not a critical issue as long as the weight of particles to sieve is sufficient.

However, this standard also presents a few experimental issues which are identified below:

- The flow of water sprayed on top of the geotextile should be adjusted in order to avoid any water standing on top of the geotextile. This requirement may be difficult to achieve, and an improper setting of the flow rate could affect the test as follows:
- an insufficient flow rate could favor agglomeration of the particles together, water acting as a bonding element between the particles;
- an excessive flow rate could generate standing water, thus to the development of a hydraulic gradient, water then acting as a dragging force.
- The angularity as well as shape of the particles can vary between two laboratories. It is thus theoretically possible to have long, angular particles used in one laboratory, and spherical glass beads used in another one, with both laboratories meeting the standard, but producing different results.
- The frequency of 50 – 60 Hz, with a vertical amplitude of 1.5 mm (3.0 mm total swing movement), has been normalized in the standard as the source of energy used to drag particles through the geotextile. This is not believed to reflect in any way actual field conditions, i.e. mechanisms likely to drag particles through the geotextile. In addition, the authors believe that it is difficult to meet the requirements of ISO 17025 with respect to the verification of the amplitude and the frequency of the vibrations, as there are no tolerances defined in the standard for frequency nor amplitude of the vibration, nor recommended technique to calibrate these test parameters and connect the calibration to a traceability system.

Diederich & al (2012) have investigated the repeatability of O_{90} obtained using ISO 12956 using round robins. Their study was partially based on the results obtained in round robin programs organized for the Norgeospec certification system, as well as by a heat bonded geotextile manufacturer. The corresponding results are copied on Figure 3, for the round-robin evaluation of 5 different types of heat bonded geotextiles, by 10 different laboratories.

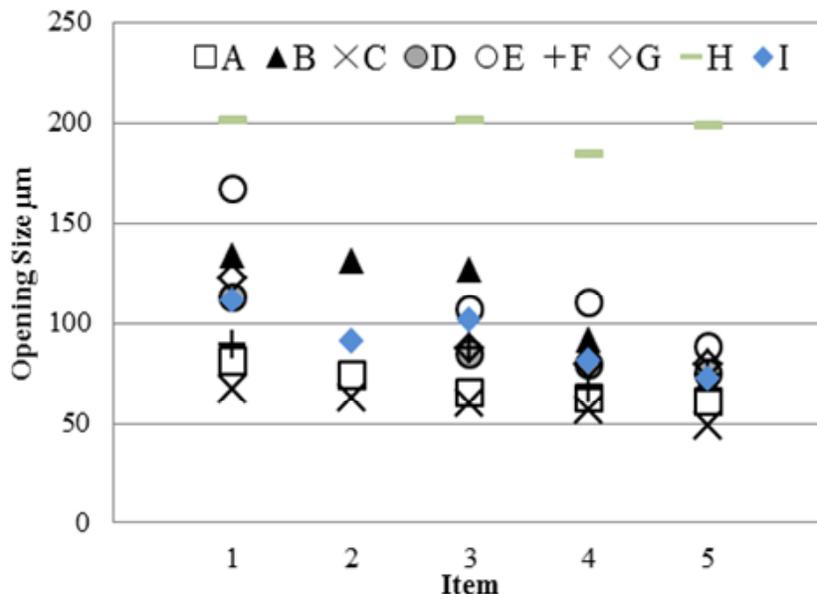


Figure 3: Distribution of Opening Sizes measured according to ISO 12956, from 10 different laboratories (after Diederich et al, 2012)

As what was observed for AOS and reported above, their observation was that the reported values were spread over a very wide range, with a factor of 2 to 4 between the lowest and the highest result, for all the evaluated products. Their conclusion was that the first source of error comes from the standard itself, which leaves too much room for interpretation. It is believed that this statement indirectly refers to the lack of precision of the standard with respect to the experimental issues listed above, and/or the impossibility to control them properly.

2.2.2 Filtration Opening Size "FOS", per CGSB 148.1 n°10

The Filtration Opening Size, or 'FOS', is based on French standard NF-G 38-016, which was used in the 80's, but withdrawn at the time ISO 12956 was adopted in all European (including French) standard specifications. It uses specimens larger than AOS, 12" in diameter instead of 8". A glass beads mixture with a coefficient of uniformity ($Cu=d_{60}/d_{10}$) of 4 is poured on top of the geotextile, which is then exposed to 1000 cycles of immersion / emersion of the geotextile specimen in water. Water thus acts as the force dragging glass bead particles through the geotextile, in a similar fashion than what would be experienced in the field, but with a soil structure remolded after each cycle at the immersion stage, maximizing the quantity of particles likely to be dragged through the geotextile. Example of a FOS apparatus is shown on Figure 4.

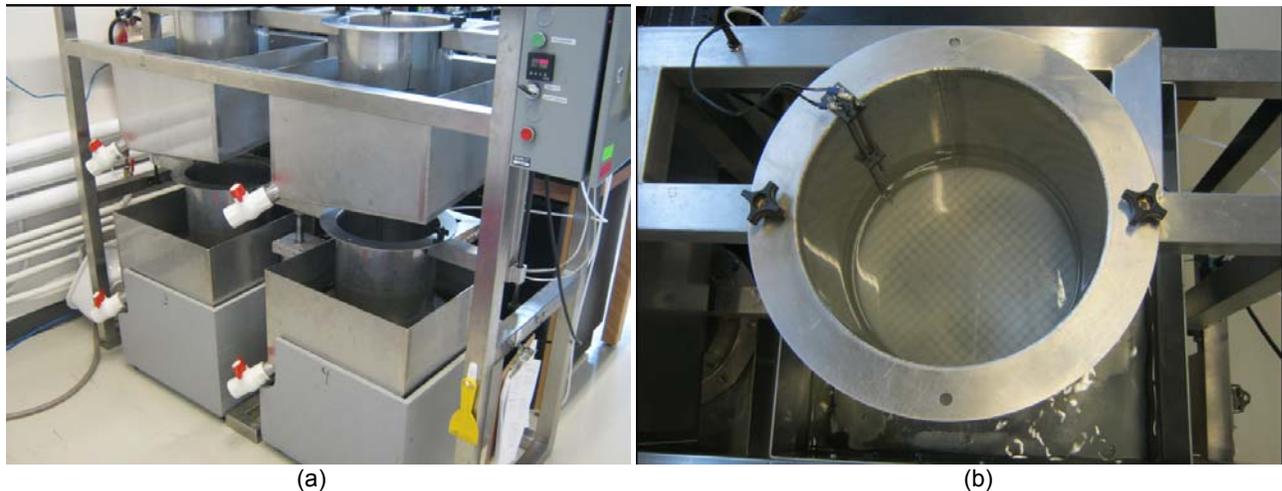


Figure 4: example of apparatus capable to evaluate the filtration opening size (FOS) of geotextiles per CGSB 148.1 n°10. (a): set-up; (b) : view from the top of a specimen holder, showing the geotextile secured between two metallic meshes and covered by the glass beads mixture. Some glass beads that were dragged through the geotextile by the water can be seen in the bottom container (bottom right on the photo).

Just like AOS, this test determines the opening size of the geotextile by looking at the dimension of the particles passing through the geotextile using a set of predetermined experimental conditions. As for ISO 12956, the technical issues which were described above for ASTM D4751 do not exist anymore (static electricity, preparation of the glass beads, possibility to measure opening sizes as low as 45 μm). In addition, the experimental issues which are known to be problematic for ISO 12956 do not exist anymore neither (effect of water on the particles, imprecise definition of the type of particle, use of high frequency vibrations as a dragging force).

However, there are, as for all the other tests, some concerns which have to be considered:

- As for O_{90} , a mixture of particles with a uniform distribution through the entire range of particle sizes is used. This mixture shall not present any gap, as this could influence the measurement should the actual FOS happen to be on the gap itself.
- The test requires the use a particle size distribution with a Cu of 4, which is not very broadly graded, and requires at least 50 grams, and at most 50% of the poured quantity to pass through the geotextile. In other words, it is necessary to know the approximate dimension of the opening size to be measured in order to set-up a test properly to eventually obtain a conclusive test.
- The dimension of the test specimen is large, which makes its use difficult if not impossible for products manufactured or installed in narrow strips, such as PVD sleeves, or filters wrapping drainage pipes.
- For needle-punched, knitted socks and many other products exhibiting a relatively high permeability, it takes at least 16 to 24 hours to complete a series of 1000 cycles with a properly automated apparatus. For geotextiles exhibiting low permeabilities, such as woven slit films, the duration of the test can be extended to several days. In some cases, the test has to be stopped after 1 or 2 weeks, before completion of the 1000 cycles, as a deviation to the standard. Its cost is thus relatively high, compared to tests such as AOS or O_{90} , which require just a couple hours of labor. The test duration happens to be a limitation for the evaluation of low permeability materials, especially for CQC or MQC projects.
- The number of laboratories capable to perform the test is limited, and to the knowledge of the authors, it is currently used in standard specifications in Eastern Canada only. Despite within lab repeatability and reproducibility are known to be excellent based on the primary author's experience, It has not been possible yet to established between-laboratory repeatability data because of the lack of candidate laboratories.

The primary authors believe that this test is the best currently available for characterization of a filtration property of a geotextile, mostly because the force dragging the solid particles through the geotextile is a small water head, which reflects very well the mechanism dragging particles through the filter in the field. However, it is not possible to run it on narrow strips (such as PVD sleeves and filters installed on drainage pipes) and is very challenging for some type of geotextile such as woven slit films.

2.2.3 Pore size distribution / BBP as per ASTM D6767

ASTM D6767 was first published in 2002. It is intended to determine the pore size characteristics of geotextiles by the mean of a capillary flow test. Similar techniques have been used for decades in other industries, such as for air filtration. The capillary flow test has been developed to characterize very small pores, in the range of a micrometer or less, for which no other measurement techniques were available. ASTM D6767 is the first attempt to adapt a capillary flow test to geotextiles, by adapting the dimension of the specimen, the type of fluid used, as well as a few other parameters, calculation and reported values, to the specific characteristics of geotextile filters.

In principle, this test allows determination of the entire pore size distribution from 'O₀', the 'smallest' opening size of a geotextile, to O₉₈, the 'largest' opening size of a geotextile. It is thus not limited to the characterization of the geotextile as a material mimicking a sieve, but provides information on the structure of the pores, i.e. the distribution of pore sizes, their uniformity, etc. In principle, it should permit objective differentiation between woven slit films, knitted socks, heat bonded non-woven, non-woven needle-punched or any kind of geotextile structure, and possibly provide additional tools to possibly explain why some geotextile structures perform better than others in some particular conditions.

The concept of pore size distribution measurement by a capillary flow test is based on the hypothesis that geotextile filters have discrete pores from one side to the other of the geotextile. The bubble point test is based on the principle that a wetting liquid is held in these continuous pores by capillary attraction and surface tension, and the minimum pressure required to force liquid from these pores is a function of pore diameter (after ASTM D6767-11). The higher is the pressure, the smaller are the pores opened to the circulation of air. Analysis of the entire relation linking pressure and velocity can thus lead to the determination of a relation between the open pores of the geotextile, and their surface, thus between the size of a pore and its cumulated surface.

Beyond the possibility to obtain a full pore size distribution for a given sample, this technique presents several other attractive features:

- it permits determination of the opening size of a geotextile in less than 30 minutes, which makes it a very attractive tool for manufacturing quality control, and should bring down the cost of the test.
- Specimen dimension is about 50 mm in diameter, with an effective test surface of about 25 mm in diameter. It can thus be used on samples which would be otherwise difficult (or impossible) to test, such as filters of small diameter drainage pipes or sleeves of prefabricated vertical drains.
- Thanks to the small dimension of the specimen and the short time needed to perform the test, it offers the possibility to have a better vision of the uniformity of the filtration properties across a roll width at a reasonable price.

However, this method completely differs from the three measurement techniques presented above, with respect to the following issues:

- It is an indirect method, which uses hydraulic science to determine the size of a pore, instead of considering the passage of an actual particle through the geotextile filter as all the other measurement techniques do. Actual correlation between the effectiveness of a filter for the retention of particles and whatever number derived from the test thus remains somehow speculative, until demonstrated using experimental data.
- Calculation of the size of a pore involves definition of a shape factor, or tortuosity factor, which is specific to a given structure. This factor defines the relation between the measured pore diameter and separable particle size. The same factor may not be applicable to every pore structure, i.e. woven, knitted, non-woven needle-punched or heat-bonded fabrics. According to PMI (Porous Materials Inc, a leading equipment supplier for this type of measurement), the shape factor can be between approximately 0.71 and 1.0 for many common pore shapes. In other words, the dimension of a spherical particle which can circulate through a pore can be about 1 to 1.5 time smaller than the size of the pore determined by porometry, depending on the shape of the pores. Practically, this means that the opening size determined using a technique involving the passage of glass beads through the geotextile can be 1 to 1.5 times smaller than the opening size determined using this technique, and this factor depends on the product that is being evaluated.
- The measured value depends on the surface tension of the liquid used to perform the test. Evaluations conducted by SAGEOS (internal report, 2014) have shown that changing the viscosity of the liquid, i.e. from 20.1 to 30.7 dynes/cm can lead to a bias in the result in the range of 5%, for non-woven needle-punched geotextile.

- Performing the test requires either a competent operator, with a thorough understanding of the mechanisms involved and the meaning of the reported values. Use of pre-determined, universal settings is hazardous, and can lead to erroneous results if compared to traditional measurement technique (AOS, FOS or O90).

An investigation was conducted on 4 different geotextiles to determine what should be the tortuosity factor, in order for the opening size determined using a capillary flow test to be identical to the value obtained using FOS (CGSB 148.1 n°10). The results are summarized in Table 3. It should be noted that this data-matching was not performed considering AOS (ASTM D4751) primarily because the AOS could not be measured for one of the product (smaller than 75µm).

Table 3: tortuosity factor to apply in order to match BBP / O_{98} (obtained using ASTM D6767) and FOS (obtained using CGSB 148.1 n°10) – fluid used: mineral oil, surface tension 30.7 dyne/cm

Product	thick non-woven needle-punched (polyester)	woven slit film	non-woven needle-punched (polypropylene)	non-woven heat bonded
FOS (CGSB 148.1 n°10)	59 µm	483 µm	104 µm	61 µm
AOS (ASTM D4751)	<75 µm	590 µm	150 µm	101 µm
Tortuosity required to obtain a BBP identical to FOS	0.438	0.673	0.408	0.288
Tortuosity required to obtain a BBP identical to AOS	impossible	0.835	0.585	0.479

It can be observed from the observations in Table 3 that the tortuosity factor that shall be selected to match the BBP obtained with ASTM D6767 to an opening size of the geotextile measured with a classical method is not a constant value, with a factor of 2.4 between the smallest and the highest tortuosity factor. Use of the wrong tortuosity factor could thus lead to a completely erroneous result, i.e. a reported filtration opening size of 236 µm instead of 101 µm for the heat bonded geotextile, should the factor developed for the woven slit film be used!

However, the factors determined for the two non-woven geotextiles were very close one from the other, despite significant differences in weight, opening size as well as polymer. This is consistent with the observations of Vermeersch et al. (1996) who have identified that for non-woven needle-punched geotextiles, there is a very good correlation between FOS as determined using CGSB 148.1 n°10 and the bubble point determined using a technique comparable to ASTM D6767, as shown on Figure 6. Additional investigations should be conducted to confirm that a similar tortuosity factor can be applied to all non-woven needle punched geotextiles, with generated errors in the range of, or lower than the errors generated by other measurement techniques.

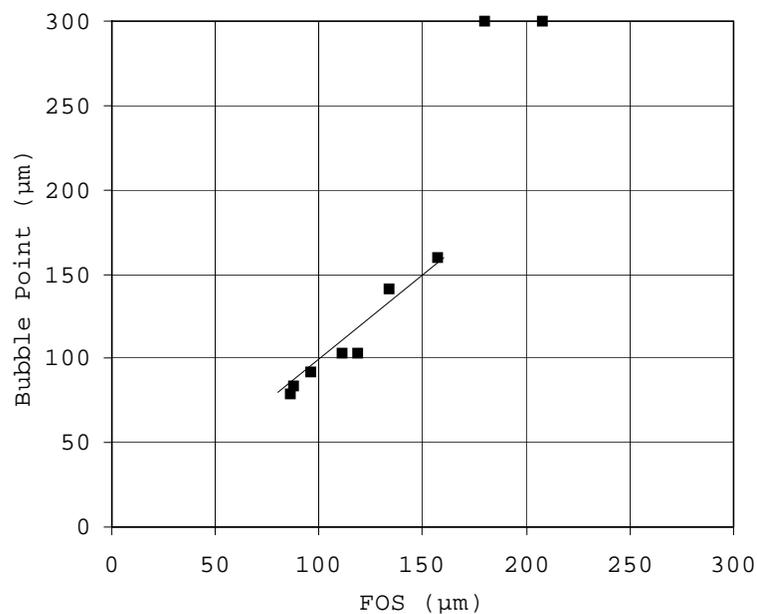


FIG. 6--Bubble point size (O_{max}) versus filtration opening size FOS (after Vermeersch, 1996).

It shall be mentioned that this discussion is limited to the single biggest pore size, as there is currently no mean to assess whether the structure of the smallest pores of a geotextile is the same as the structure of the biggest pores or not.

Overall, it is believed that for the time being, pore size distribution using ASTM D6767 remains an experimental approach, not used yet in any material specification, and difficult (if not impossible) to correlate with performance-based tests such as AOS, FOS or O_{90} . Practically, the correlation between the filtration performance of a geotextile and a value (or set of values) determined by pore size distribution remains unknown, and definition of standard operating conditions applicable to any type of geotextile structure seem to be very hazardous. However, if a tortuosity factor can be determined and considered reliable for a given type of material, ASTM D6767 represents an excellent opportunity for manufacturing quality control, thanks to the short time needed to perform the test, and limited quantity of material required.

3. CONCLUSION

Four opening size measurement techniques were presented. Three of them involve the passage of particles (i.e. glass beads) through the geotextile to determine a characteristic opening size. The fourth one is an indirect measurement technique, where surface tension of a liquid is involved in the determination of the characteristic opening size of a geotextile.

It was shown that AOS, determined using ASTM D4751, presents several experimental challenges which make its repeatability, thus reliability, relatively poor. O_{90} , determined using ISO 12956, presents less experimental challenges but dispersion in the results were still observed in round robin tests. It was not possible to demonstrate this reliability of FOS, determined according to CGSB 148.1 n°10, because there are not enough laboratories capable to perform the test to permit determination of the between-laboratory repeatability. Several improvements should be made to ASTM D4751 and ISO 12956 to maximize their repeatability, these are identified in the paper.

Finally, the challenges associated to the determination of BBP according to ASTM D6767 start with the calculation and theory behind the test, before the experimentation can be actually analyzed. However, this test is believed to be very promising if conducted in conjunction with another test for calibration of the tortuosity factor.

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