Chapter 13

Nanotechnology Formulations and Modeling of Hydraulic Permeability Improvement for Nonwoven Geotextiles

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Additional information is available at the end of the chapter

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Abstract

First, the general concept of nanotechnology formulations used to manufacture geotextiles (GT) is introduced. Separation and filtration functions using geotextiles from nanoclay formulations are introduced as important concepts. Yellow clay was added as nanoparticles to make a polyester formulation in turn to make nonwoven geotextiles to improve the removal effects of toxic and organic components of leachate solutions. Engineering behavior was evaluated to confirm the effects of adding yellow clay. There is a possibility of nanocomposite formulations for geosynthetics in the future. Second, sustainable laminar geotextile composites with different fiber-packing densities were made, and the effects of laminar structures were examined on water permeability. To fabricate these materials, the fiber-packing densities of laminar geotextile composites were discriminated correspondingly. The experimental values of water permeability by permittivity test were smaller than those of the theoretical values due to the loss of hydraulic pressure at the interface between geotextiles. To interpret the water permeability behaviors, structural model of tubes with different fiber-packing densities was applied. Finally, the inlet forms – bell mouth and soft tube structures – of laminar geotextile composite pores were estimated from the loss rates of hydraulic pressure.

Keywords: Nanotechnology formulations, yellow clay, nanoparticles, leachate solution, nanocomposites, laminar geotextile composites, permeability, structural model of tubes, inlet forms, loss rates of hydraulic pressure

1. Introduction

1.1. Nanotechnology to fibers

Nanotechnology is a new technology which can make an ultimately fine material such as a fiber (see Figure 1) by controlling atoms and molecules as small as 10^{-9} m in size, and this technology can be widely used in many industrial situations. Among the many possible nanoproducts, nanofibers could be controlled for fiber length, diameter, surface properties, pore distribution, fiber evenness, cross-sectional shapes, etc.

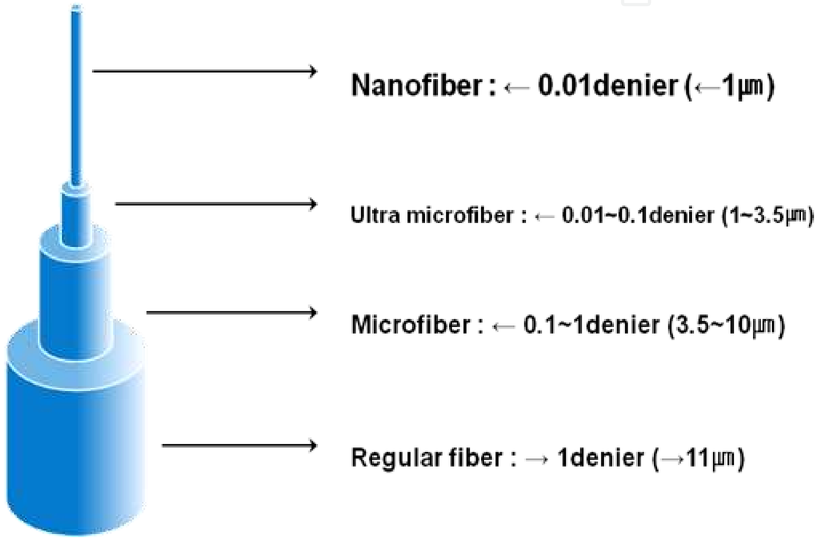


Figure 1. Comparison of nanofibers to conventional standard fibers.

Nanofibers are one of the most advanced materials which can be easily designed with high-performance materials having distinctive properties. New geosynthetic materials which have separation, filtration, and absorption functions and are specifically made could be developed in the field of geoenvironmental applications.(*Koerner, R. M., 2005*) In addition to fibers, nanoparticles (such as nanoclay) can be used to make unique formulations, which can, in turn, be used to make conventional fibers for geotextiles and yarn-type geogrids. As an example of nanocomposite geosynthetics in geoenvironmental applications, it is very important to eliminate the toxic and organic components of various waste leachate solutions. Such capability is not found in the standard manufactured nonwoven geotextiles and hence the functional nonwoven geotextiles need to be manufactured which can absorb the toxic and organic components that may be harmful to personal health and the environment.

It is possible to manufacture these types of functional nonwoven geotextiles by using nanotechnology. Section 2 describes nanofiber technology to gain insight into extremely small-scale manufacturing. Section 3 describes the objective of this study that introduces nanoclay into a polymeric formulation to manufacture a geotextile for use in geoenvironmental applications. Section 4 provides commentary for future applications.

1.2. Nanofiber application methods

Figure 2 shows various aspects of nanofiber manufacturing technology and productivity of nanofibers where it is seen that mass production of nanofibers is possible by modified electrospinning. Electrospinning is the general method used to manufacture nanofibers, which is similar to the melt-blown method, but the current problem is to increase mass productivity.

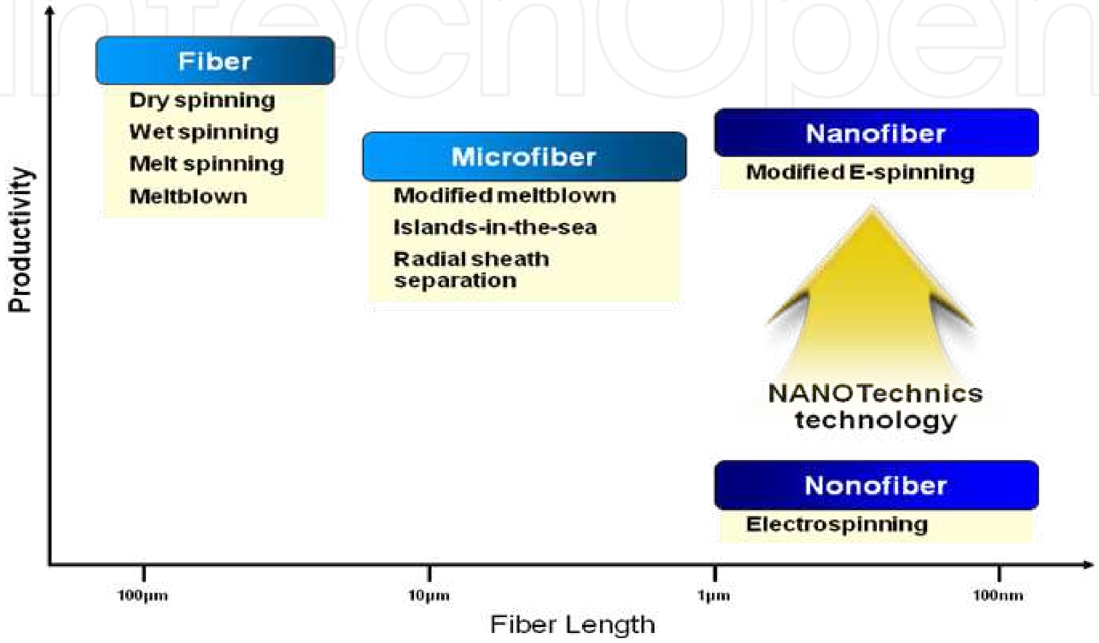


Figure 2. Fiber manufacturing technology and productivity.

In general, regular fibers are widely used to manufacture geotextiles and yarn-type geogrids, but filtration efficiency of microfibers and nanofiber geotextiles would be better than the standard fiber used to manufacture conventional geotextiles. To be considered, it is expected that nanofiber geosynthetics could provide the sustainable filtration function in geoenvironmental applications by their composition structure as shown in Figure 3. If the numbers of filled fibers per unit area increases, the pore size among nanofibers is decreased. Therefore, fine pollutants cannot pass through pores made by nanofibers and the filtration efficiency will be improved. This means that ultrathin geosynthetic filters can be manufactured having a high-quality filtration function to absorb fine impurities and toxic components in both polluted water media and polluted air media (Figure 4). Figure 5 shows the separation concept of a nanofiber air filter by pressure. To optimize this air filter, a higher particle collection and dust retention rate are required. Therefore, hybrid-type air filters must be the optimum, and Figure 6 shows such fiber materials versus fiber length. For hybrid membrane technology (HMT) and expanded PTFE materials, nanofiber layers are accumulated above the general fiber materials as a hybrid material. This is the important result of larger specific adsorption area in the surface of geosynthetics. Figure 7 shows the relationship between separation fields and separation membranes using fiber-related nanotechnology.

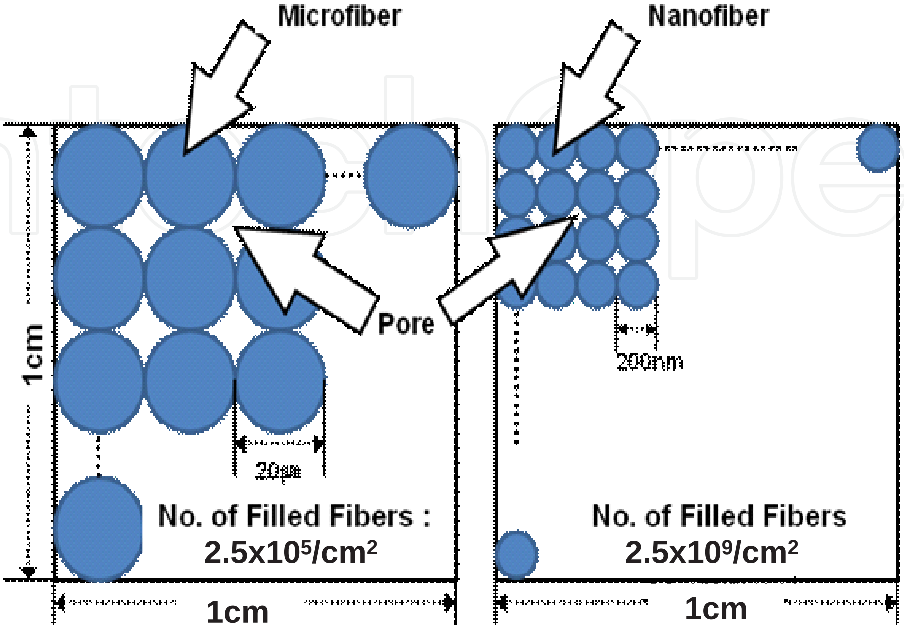


Figure 3. Fiber filling between microfiber and nanofiber per unit area.

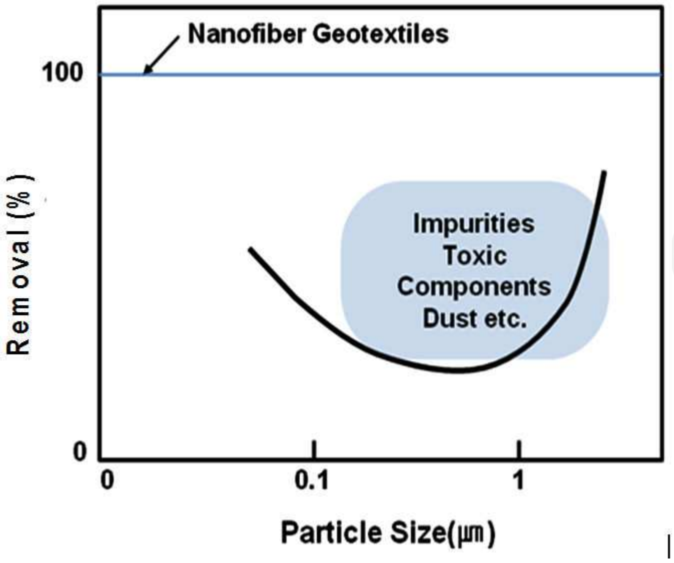


Figure 4. Effect of using a nanofiber geotextile filter.

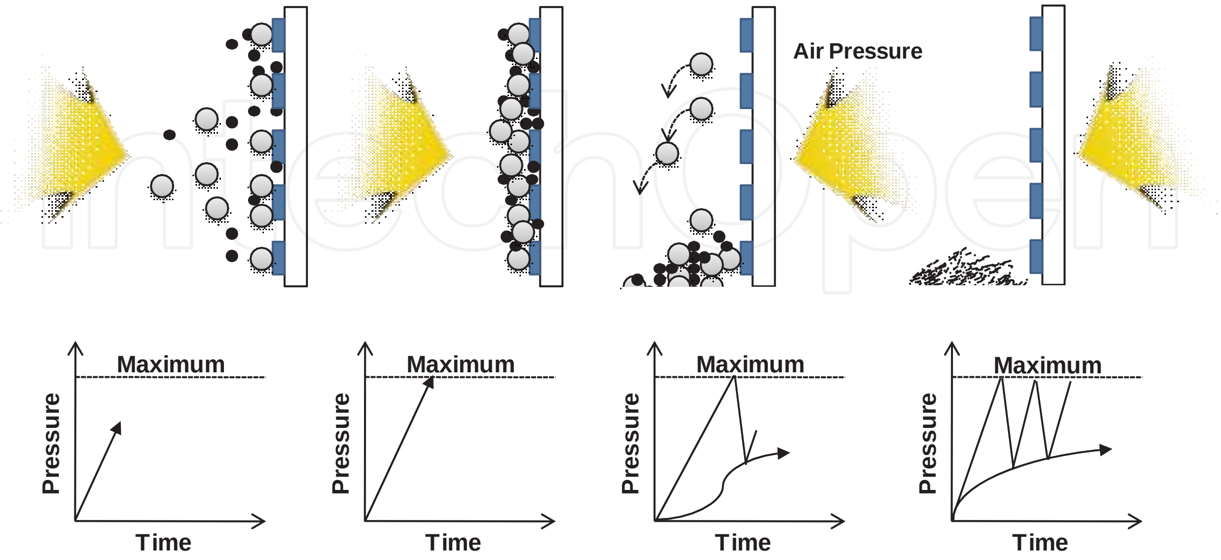


Figure 5. Maintenance of filtration efficiency for nanofiber filters.

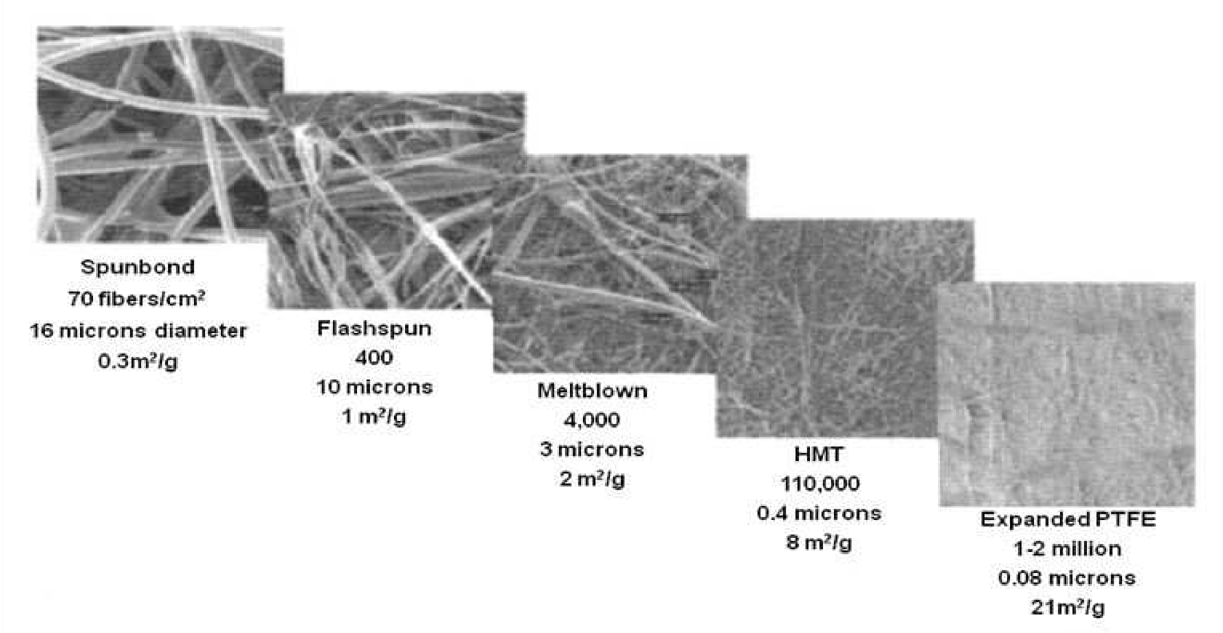


Figure 6. Comparison of fiber diameter and surface area using nanofiber and other fibers.

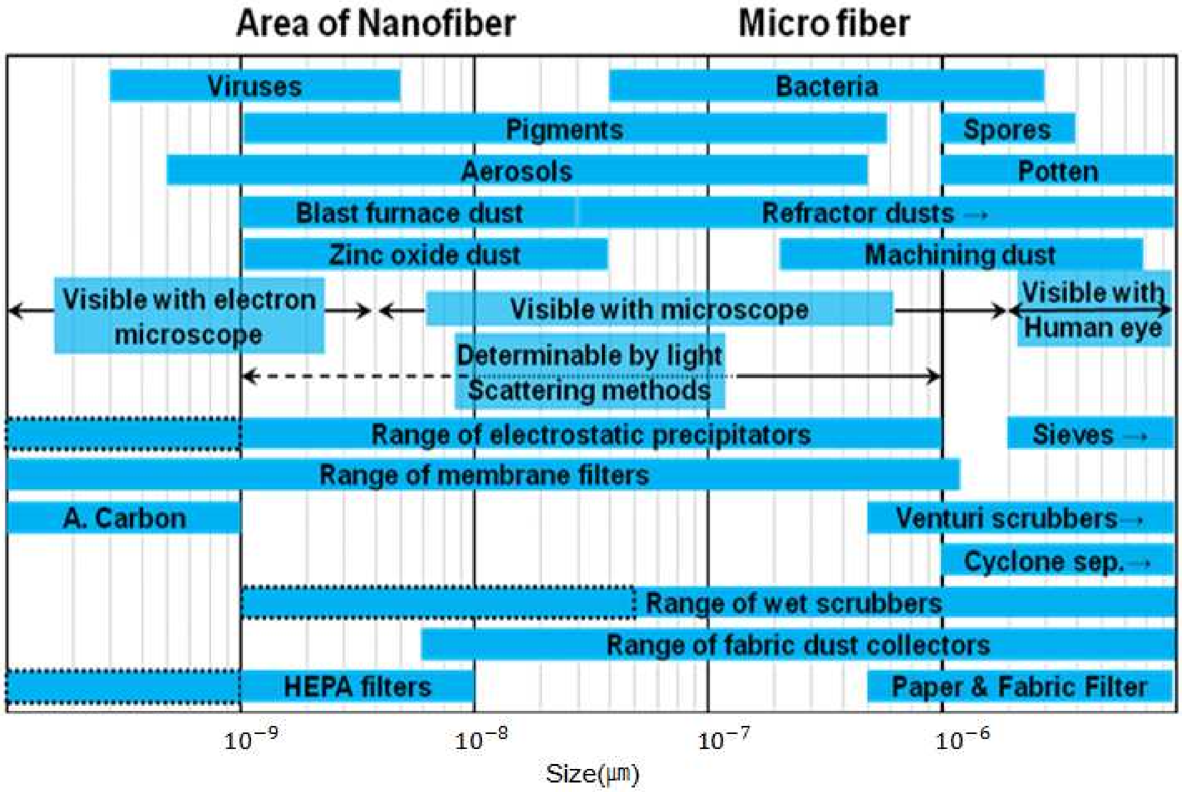


Figure 7. Relationship between separation fields and separation membranes using nanotechnology.

1.3. Nonwoven geotextiles by nanotechnology formulations

1.3.1. Nano clay fibers geotextiles

A related aspect of nanotechnology is to use one or more components of a blending formulation in the nanoscale so as to create a nanocomposite formulation. Having pellets made from such a formulation, standard manufacturing processes can be used to manufacture any type of geosynthetic material. Two to three percent yellow clay nanoparticles have been added to make a formulation in order to manufacture polyester geotextiles. Table 1 shows the specifications of the two types of geotextiles in this study: one with nanoclay (the formulated geotextile (FGT) series) and one without (the GT series). The standard polyester geotextiles were used to compare the performance difference against those with the clay nanoparticle blending formulation.

Table 2 shows the properties of the nanoclay blended to the virgin polyester resin formulation from which it is known that the amount to be added is 2–3%.

Composition	Geotextile Type	Weight (g/m²)	Clay Content (%)
Nanoclay-Formulated Nonwoven Geotextiles	FGT-1	272	2–3
	FGT-2	463	
	FGT-3	784	
	FGT-4	1514	
Traditional Nonwoven Geotextiles	GT-1	284	None
	GT-2	480	
	GT-3	756	
	GT-4	1546	

Table 1. Specifications of the two types of polyester geotextiles.

Component	Loss	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
Content (%)	97.54	1.80	0.07	0.11	0.13	0.01	0.01	0.02	0.01

Table 2. Components of the added yellow clay particles.

1.3.2. Testing protocols used to evaluate engineering performance

Tensile properties of nonwoven geotextiles were tested using ISO 10319 to minimize the deviation between index and performance tests. The modified EPA 9090 Test Method that was proposed by United States Environmental Protection Agency (EPA) was adapted to test the chemical resistance of the geotextiles. The chemical resistance of nonwoven geotextiles in waste leachate solution was evaluated by comparing the strength retention before/after immersion at 25°C, 50°C, 80°C, and for 180 days using ASTM (American Society for Testing and Materials) D 4632. AATCC (American Association of Textile Chemists and Colorists) 30 was used to estimate the biological resistance in the waste landfill leachate. Similar to chemical resistance, the biological resistance of nonwoven geotextiles was evaluated by comparing the strength retention before/after immersion. ASTM D4751-99a was used to compare the apparent opening size (AOS), and ASTM D1987-95(2002) was used to examine the permittivity of nonwoven geotextiles before/after immersion in the waste landfill leachate. (*ASTM D 35 Committee, 2015*) Finally, the adsorption efficiency was estimated to obtain the amounts of toxic and organic components that remained within the nonwoven geotextiles through inductively coupled analysis (ICP) analysis. An actual field leachate was used from the Woonjung-Dong waste landfill site in Gwangju, Korea (Rep.), where food wastes were mainly disposed of. It was seen that the pH value of the leachate solution indicated a weak-alkaline state and the presence of toxic components, for example, Cd and Pb, etc., and many kinds of organic components were included.

1.3.3. Tensile properties

Figure 8 shows the tensile strength of both the nanoclay-blended and traditional polyester nonwoven geotextiles. For the two types (i.e., FGTs and GTs), tensile strengths in both directions (machine direction (MD) and cross machine direction (CMD)) increased with weight but tensile strains decreased with weight. This is a very common trend in tensile properties of nonwoven geotextiles. (*Jewell, R. A., 1996; Holtz, R. D. et al. 1995*)

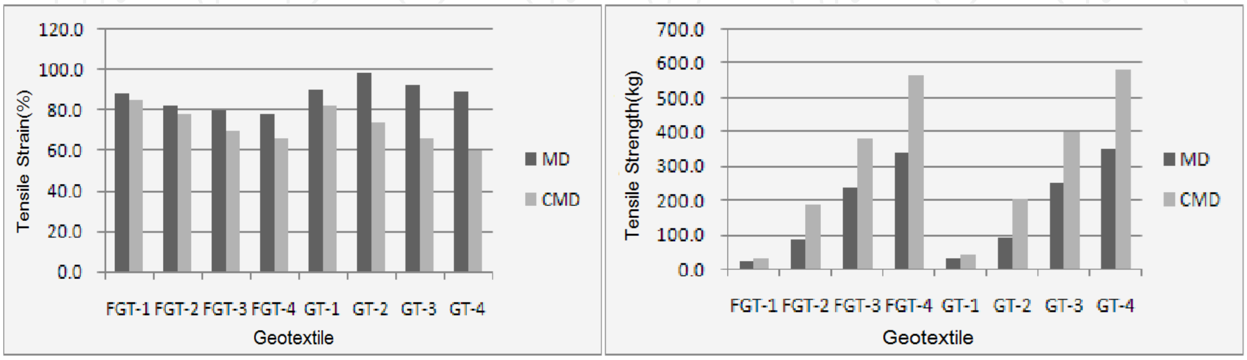


Figure 8. Tensile properties of nanoclay-blended and traditional polyester nonwoven geotextiles (where MD, CMD mean the machine and cross machine directions, respectively).

1.3.4. Effects of chemical and biological degradation

Figure 9 shows the tensile strength retention of both the nanoclay-blended and traditional polyester nonwoven geotextiles before/after immersion in the leachate solution. Tensile strength and strain retention of both types of polyester nonwoven geotextiles (FGTs and GTs) show the similar tensile property and decrease with temperature. These phenomena are shown very clearly at 80°C, and this result would be due to the hydrolysis effect of both polyesters under high temperature in the alkaline state. (*Gugumus, F., 1996*) In addition, the strength retention of polyester nonwoven geotextiles before/after leachate immersion state in the waste landfill site was examined. Figure 10 shows the tensile strength retention in order to explain the biological resistance.

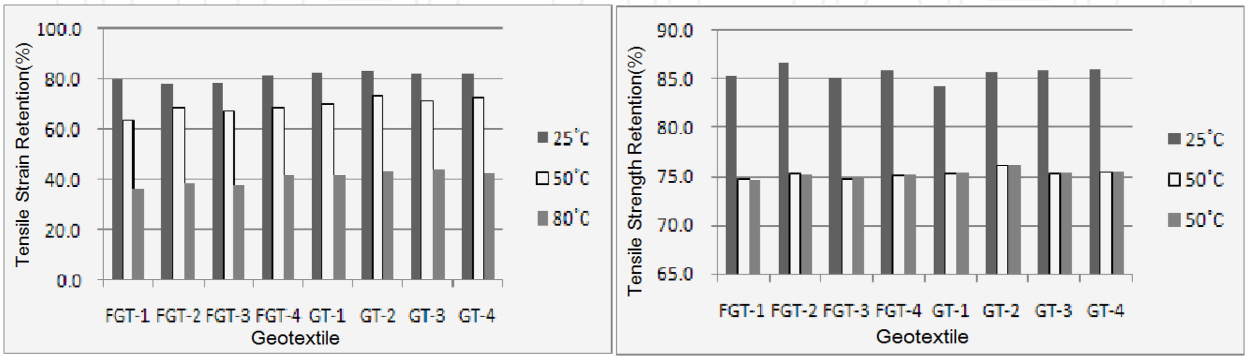


Figure 9. Chemical resistance by tensile property retention of nanoclay-blended and traditional polyester nonwoven geotextiles.

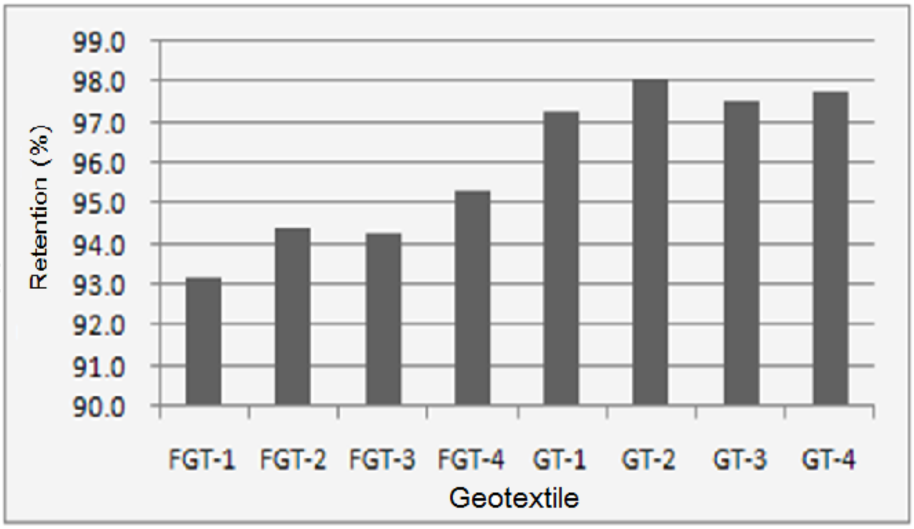


Figure 10. Biological resistance by tensile strength retention of nanoclay-blended and traditional polyester nonwoven geotextiles.

The nanoclay-blended polyester nonwoven geotextiles (i.e., the FGTs) show lower tensile strength retention than the traditional polyester nonwoven geotextiles (i.e., GTs). It is assumed that this means the FGTs were influenced by the components of the leachate solutions in a greater or less amount because of the nanoclay component. However, this does not mean that fungi and bacteria can attack these geotextiles. Figure 11 shows the values of cumulative reduction factors and the allowable tensile strengths of all of these nonwoven geotextiles.

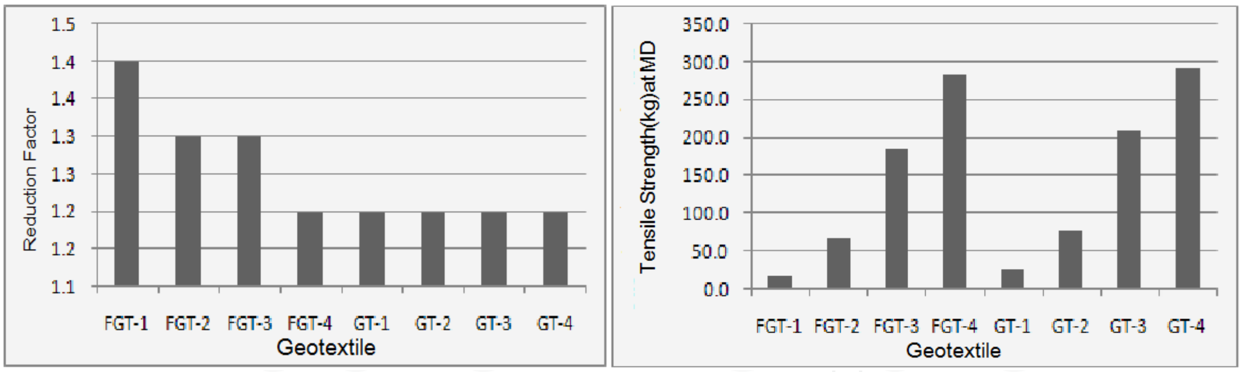


Figure 11. Allowable tensile strength of nanoclay-blended and traditional polyester nonwoven geotextiles.

1.3.5. Hydraulic properties due to clogging phenomena

Clogging means a channel blocking in the nonwoven geotextiles and this is an important cause of decreasing water permeability among soil particles. Usually, AOS does not decrease while clogging has not occurred in the nonwoven geotextiles. Figure 12 shows AOS values of polyester nonwoven geotextiles before/after immersion in the waste landfill site. The nanoclay-blended polyester nonwoven geotextiles (the FGTs) showed relatively small AOS values than the traditional polyester nonwoven geotextiles, which indicates that a significant clogging was formed in the FGTs. Hence, toxic, organic, and floating components in the leachate solution could be simply adsorbed to the nanoclay-blended polyester nonwoven geotextiles.

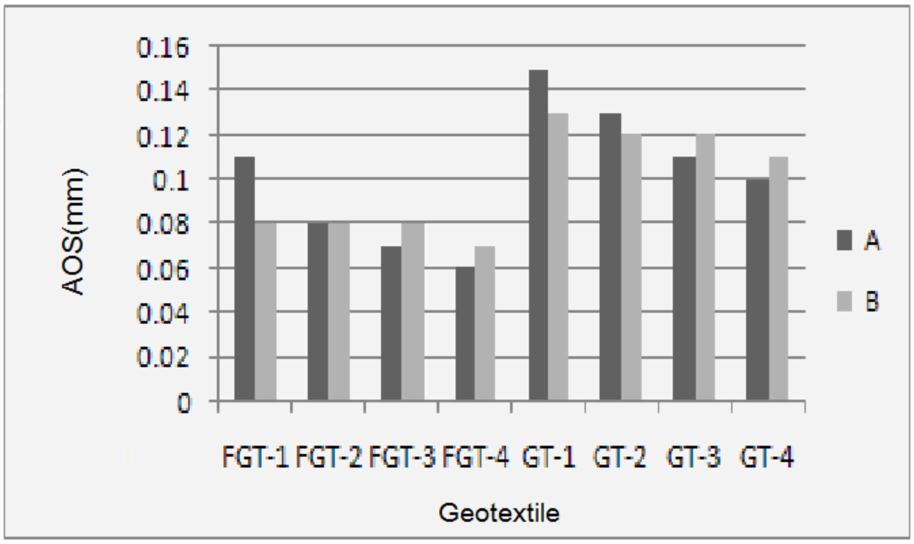


Figure 12. AOS of nanoclay-blended and traditional polyester nonwoven geotextiles before/after immersion (where A, B mean before and after immersion, respectively).

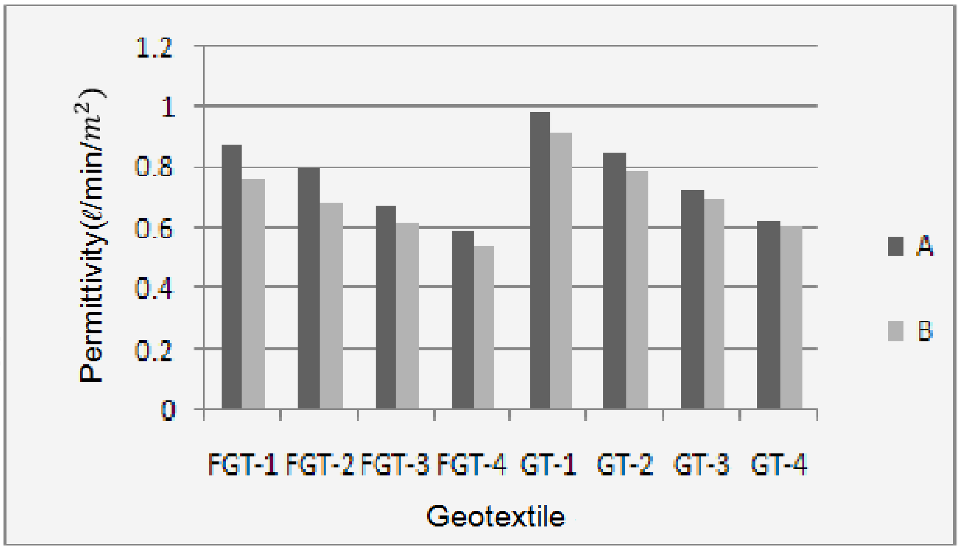


Figure 13. Permittivity of nanoclay-blended and traditional polyester nonwoven geotextiles before/after immersion (where A, B mean before and after immersion, respectively).

Figure 13 shows the permittivity of the polyester nonwoven geotextiles before/after leachate solution in the waste landfill site. As shown in the case of biological resistance, AOS, and permittivity, the FGTs showed smaller permittivity values than traditional polyester nonwoven geotextiles because of clogging effects of FGTs. Figure 14 shows strength retention of the polyester nonwoven geotextiles before/after clogging and the same result was observed. The nanoclay-blended polyester nonwoven geotextiles (the FGTs) show smaller tensile strength retention than the traditional polyester nonwoven geotextiles (the GTs). Figure 15 shows the values of cumulative reduction factors and the allowable permittivity of all of these nonwoven geotextiles.

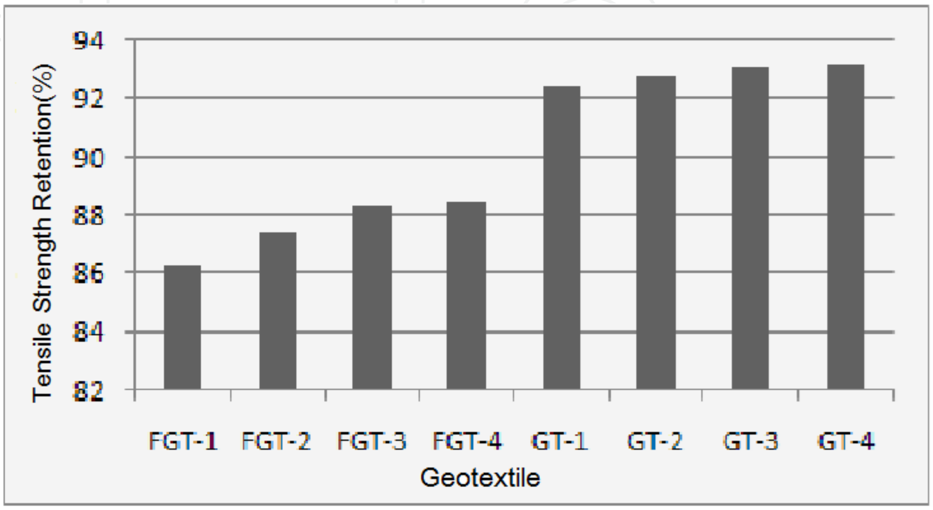


Figure 14. Tensile Strength retention of nanoclay-blended and traditional polyester nonwoven geotextiles after clogging.

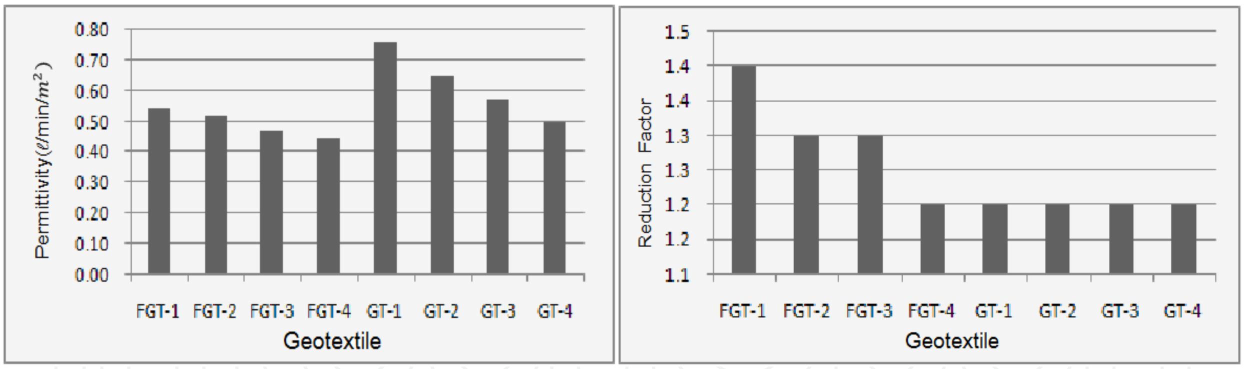


Figure 15. Allowable permittivity of nanoclay-blended and traditional polyester nonwoven geotextiles after clogging.

1.3.6. Adsorption efficiency

Figure 16 shows the adsorption efficiency of hazardous and heavy metal components of nanoclay-blended polyester nonwoven geotextiles. Here, FGTs showed excellent adsorption efficiency compared to the traditional polyester nonwoven geotextiles.

Finally, further study must be conducted to generate a detailed, clear, and quantitative adsorption effect with various nonwoven geotextiles, which have different fiber compositions.

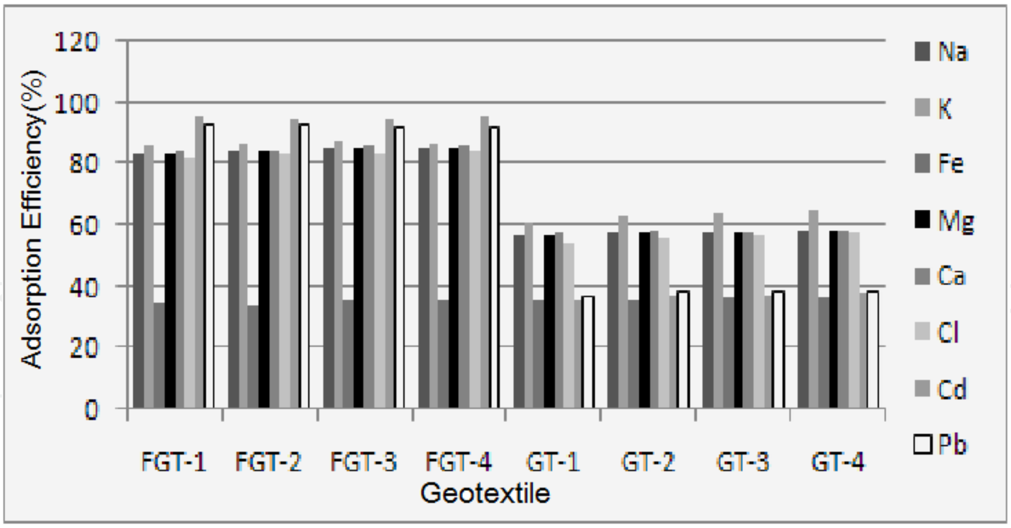


Figure 16. Component adsorption of nanoclay-blended and traditional polyester nonwoven geotextiles.

1.4. Future of nanotechnology applications in geoenvironmental engineering

The following was suggested by Dr. Ian D. Peggs in his article "The Future of Geosynthetics – One Opinion" regarding the manufacturing capabilities for use by the geosynthetics community: (*Peggs, I. D., 2008*)

- Nanoclays and nanofibers already exist for use in the geosynthetics technology
- Carbon and graphite are also related to geosynthetics in that they can be generated from polymers
- Geomembrane manufacturers have three-layer extruders and a few have five-layer extruders suited for the technology
- Multilayer-extruded barrier products are not new, so there exists a technology base
- Geogrids can be made stronger
- Geonets can be made less compressible
- Geocells can be made more rigid
- Stress cracking and oxidation resistances can be increased
- New materials will be involved in bringing new participants and new applications to the industry
- Five-layer geomembranes offer a better opportunity to customize colors (for example) for owners and for better awareness
- Color-coding can also be related to performance characteristics
- Color can be marketed – it was done successfully in HDPE gas pipe and PVC water pipe

- The technology presents an opportunity to make a significant step (not just a small one) toward more specialty products that will be accepted and utilized accordingly

1.5. Conclusion

Though the above list represents a suggestion and recommendation of a geosynthetic expert for nanotechnology geosynthetics in geoenvironmental engineering, it is very important to extend and set up this new application field for advanced geosynthetics. To develop the typical performance of regular geosynthetics, it is very natural and necessary to manufacture nanoparticle formulations and nanofiber geosynthetics as advanced materials and search/extend the new applications to the geoenvironmental engineering fields in the near future. (*Jeon, H. - Y. et al., 2008*)

2. Modeling for hydraulic permeability improvement

2.1. Introduction

Geosynthetics as special functional materials have played very important roles in developing and improving the utilities of geotechnical, environmental, and transportation fields in recent times. Especially among them, woven and nonwoven geotextiles are widely used in 120 specific application areas as described earlier because of their various application functions, such as separation, reinforcement, filtration, drainage functions, etc. (*Ingold, T. S., 1994*) Needle-punched nonwoven geotextiles for subgrade reinforcement do not have a great difference in mechanical properties between machine and cross directions due to the randomly entangled structure of staple fibers at any directions. In addition, nonwoven geotextiles have excellent drainage and filtration functions and pass the liquid and retain the soil on the upstream side for civil and geotechnical applications. (*Holtz, R. D. et al., 1997; Van Zanten, R. V., 1986*) Water permeability of nonwoven geotextiles is influenced by the entangled state of fibers, fiber composition, thickness, etc. For the case of fiber assemblies, such as nonwoven geotextiles, water permeability is influenced by the morphological structure of these in macroscopic viewpoints. In this study, laminar geotextile composites with different fiber-packing densities were made and the effects of laminar structures were examined on water permeability.

2.2. Theory of normal permeability on laminar geotextile composites

Nonwoven geotextiles are a kind of materials with high porosity and have the three-dimensional structure with different fiber orientations. It is assumed that the pore shapes of geotextiles are very narrow and tube typed, and therefore, the permeability of geotextiles depends on the pore-size distribution. The structural model of laminar geotextile composites is considered as an assembly of narrow tubes, which join each other with different fiber-packing densities. Figure 17 shows the two schematic diagrams of laminar geotextile composites and the assembly to have the different fiber-packing densities. From Darcy's law, water permeability of laminar geotextile systems could be written as follows:

$$\frac{Q}{A} = \frac{h}{\frac{T_1 \cdot K_2 + T_2 \cdot K_1}{K_1 \cdot K_2}} \tag{1}$$

where Q = quantity of flow, mm^3

A = cross-sectional area of geotextile, mm^2

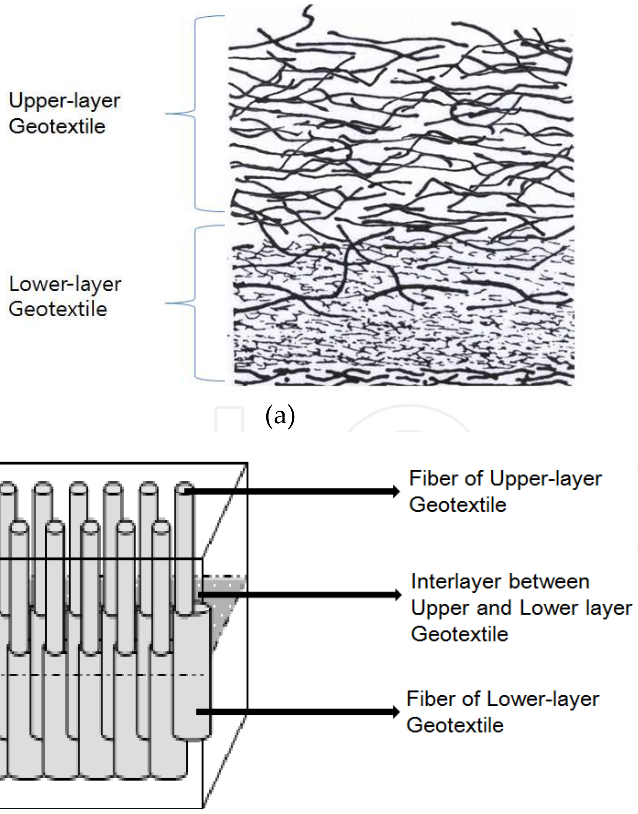
h = head of water on the geotextile, mm

T = the thickness of geotextile, mm

K_1, K_2 = the coefficient of cross-plane permeability of upper- and lower-layer geotextiles, respectively, cm/sec

The coefficient of cross-plane permeability of laminar geotextile composites, K, could be calculated by:

$$K = \frac{T_1 + T_2}{\frac{T_1 \cdot K_2 + T_2 \cdot K_1}{K_1 \cdot K_2}} \tag{2}$$



(a)

(b)

Figure 17. Schematic diagrams of (a) laminar geotextile composites and (b) structural model of tubes with different fiber-packing densities.

Permittivity, Ψ, could be written as

$$\frac{1}{\Psi} = \frac{\Psi_1 + \Psi_2}{\Psi_1 \cdot \Psi_2} \tag{3}$$

where Ψ_1, Ψ_2 = permittivity of the upper/the lower geotextile

If the loss rate of hydraulic pressure, f_i, is considered at the interface between geotextiles, permittivity, Ψ', could be calculated as follows:

$$\frac{1}{\Psi'} = \frac{1}{\Psi_1} + \frac{1}{(1 - f_i) \cdot \Psi_2} \tag{4}$$

For convenience, equation (4) could be rewritten as:

$$f_i = 1 - \frac{1}{\Psi_2 \cdot (\frac{1}{\Psi'} - \frac{1}{\Psi_1})} \tag{5}$$

2.3. Experimental

2.3.1. Sample preparation

To fabricate laminar geotextile composites, fiber-packing densities of geotextiles were discriminated respectively. Six types of fibers were used to manufacture the laminar geotextile composites. The characteristics of these specimens are shown in Table 3.

Specimens	Type of Yarn	Weight (g/m²)	Thickness (mm)
A	Staple fiber	510	4.14
B	"	240	1.88
C	"	390	2.86
D	"	535	3.96
E	Slit-film yarn	700	1.15
F	"	220	0.68

Table 3. Characteristics of specimens for manufacturing laminar geotextile composites.

2.3.2. Manufacturing of laminar geotextile composites

Laminar geotextile composites having different fiber-packing densities were manufactured by needle-punching process. The fiber-packing densities of upper parts were smaller than those of lower parts, and specifications of six laminar geotextile composites are represented in Table 4.

Geotextile Composite	A–B	A–C	A/E	A–F	D/A	D/C
Thickness (mm)	6.02	7.00	5.29	4.82	8.10	6.82
Weight (g/m²)	750	800	1,210	730	1,050	830

Table 4. Specifications of laminar geotextile composites.

2.3.3. Water permeability test

The hydraulic conductivity of laminar geotextile composites was determined in terms of permittivity under the constant head method and falling head method in accordance with ASTM D 4491 test method. The permeability coefficient was determined by multiplication of permittivity and thickness of geotextile. (*Fluet Jr, J. E., 1985; ASTM D 35 Committee, 2015*)

2.4. Results and discussion

2.4.1. Hydraulic permeability

Table 5 shows the values of permittivity and coefficients of cross-plane permeability for six laminar geotextile composites by the cross-plane permeability test and theoretical values obtained by equations (2) and (3). Figure 18 shows the inverse of permittivity and coefficients of cross-plane permeability. To interpret permeable phenomena, it is more convenient to determine the water permeability by using the permittivity than the coefficient of cross-plane permeability. Therefore, theoretical values of water permeability of laminar geotextile composites are larger than those of experimental values. It was considered that this was due to the effects of loss rate of hydraulic pressure as a result of changes of porous areas at the inner interface of geotextile composites.

Laminar Geotextile Composite	**Permeability Coefficient (cm/sec)**				**Permittivity (sec⁻¹)**			
	Upper Layer	Lower Layer	Composite	Eq. (2)	Upper Layer	Lower Layer	Composite	Eq. (3)
A/B	4.951	2.364	3.576	3.757	1.173	1.258	0.578	0.607
A/C	4.441	2.125	2.828	3.039	1.086	0.743	0.411	0.441
A/E	4.914	0.023	0.096	0.105	1.193	0.020	0.018	0.020
E/A	0.023	4.914	0.091	0.106	0.020	1.193	0.017	0.020
A/F	5.033	0.029	0.185	0.199	1.193	0.042	0.038	0.041
D/A	3.487	3.956	3.513	3.712	0.881	0.956	0.434	0.458
D/C	4.427	2.042	2.812	2.972	1.118	0.714	0.412	0.436
C/D	2.042	4.427	2.860	2.972	0.714	1.118	0.419	0.436

Table 5. Permeability coefficient and permittivity of laminar geotextile composites.

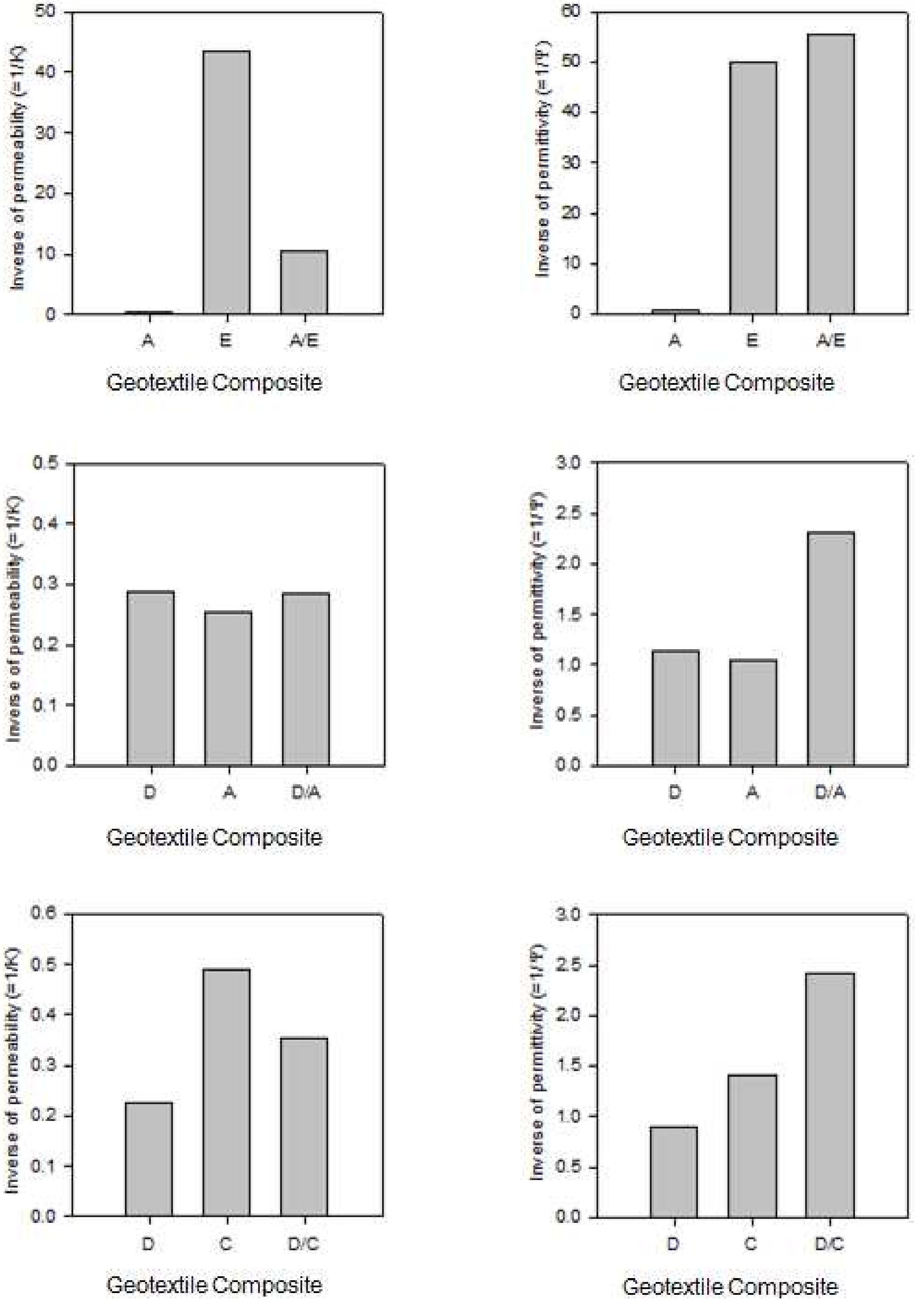


Figure 18. Inverse values of normal permeability and permittivity for several samples of nonwoven geotextiles.

2.4.2. *Modeling by inlet forms*

The inlet forms of inner interface of laminar geotextile composites to be related to the loss rate of hydraulic pressure are shown in Figure 19. In case of various porous areas of laminar geotextile composites, the permittivity and loss rates of hydraulic pressure are represented in Table 6. The lower the coefficient values of cross-plane permeability and permittivity, the larger the loss rate of hydraulic pressure. This was why the inlet forms of inner interface of laminar geotextile composites were bell mouth or soft tube structures.

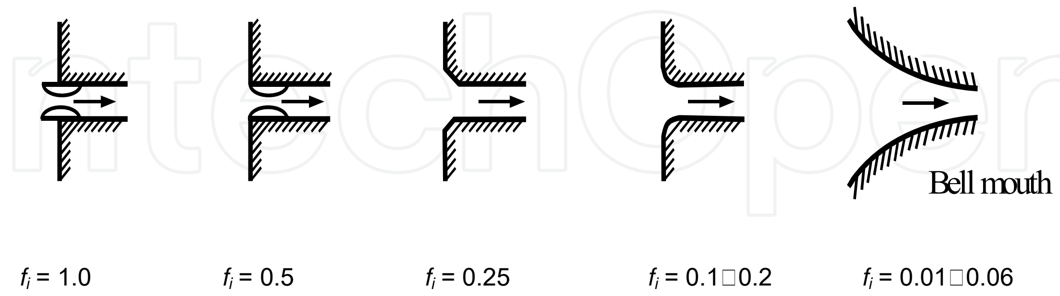


Figure 19. Inlet forms of inner interface of laminar geotextile composites.

Laminar Geotextile Composite		**Permittivity (sec^{-1})**		**Loss Rate of Hydraulic Pressure (f_i)**
Upper Layer	Lower Layer	Composite		
A–B	1.173	1.258	0.578	0.095
A–C	1.086	0.743	0.411	0.111
A–E	1.193	0.020	0.018	0.087
E–A	0.020	1.193	0.017	0.144
A–F	1.193	0.042	0.038	0.066
D–A	0.881	0.956	0.434	0.105
D–C	1.118	0.714	0.412	0.085
C–D	0.714	1.118	0.419	0.091

Table 6. Loss rate of hydraulic pressure of laminar geotextile composites.

2.5. Conclusion

For laminar geotextile composites having different fiber-packing densities, water permeability was decreased with the smaller fiber-packing densities and this was due to the more bulky and less compacted structure of fibers. It was reasonable to apply the permittivity to interpret the water permeability of laminar geotextile composites instead of the coefficient of cross-plane permeability. The experimental values of water permeability exhibited the smaller values than theoretical values due to the loss rate of hydraulic pressure and inlet forms of inner interface. From these results, it was known that the hybrid structure of geotextiles to perform the smart drainage function could be manufactured by the variation of the fiber-packing density.

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