ABSTRACT

FILIZ, SELCUK. Evaluating the Potential Use of Highloft Nonwoven Fabrics for Rain Gutter Applications. (Under the direction of Dr. Behnam Pourdeyhimi and Dr. William Oxenham)

The behavior of fluid flow is an important criterion for nonwoven fabric design and in their applications such as filtration, insulation, geotextiles, geomembranes etc. Highloft nonwoven fabrics are thick, highly porous and bulky, unlike other nonwoven materials. As a result of their structure, these fabrics exhibit both transplanar and in-plane flow capability.

This study is exploring the potential application and utilization of highloft fabrics in rain gutters instead of “costly” alternatives such as gutter guards, screens etc. For this study, a new testing device was developed to examine the volumetric flow rate of water through, and volumetric flow efficiency, of different types of highloft fabrics under different conditions. The testing device was named “Rain Machine” since its purpose was to simulate rainfall effect on a particular size of roof and rain gutter. Also by making a minor modification to the NCRC GATS Absorbency Test System, the drainage time and conditions of the fabrics were examined.

In this study, the experimental work is carried out by focusing on the macrostructure of the highloft nonwovens rather than the microstructure. In addition to
this, two different kinds of foam material were utilized to determine whether there is any improvement of the volumetric flow rate or not.

It was visually found that no microorganism activity occurred by the end of the three-week continuous testing, but structural changes such as loss of loft was significant.

A statistical approach to experimental design and analysis of these research findings was necessary to draw meaningful conclusions from the data obtained. ANOVA statistical method was used to analyze the experimental data and multiple comparisons carried out using Tukey’s pairwise comparison method.

From these analyses, the flow rates for the unsaturated fabrics were found to be less than that of saturated. However, using different kinds of foam materials did not affect the flow rate significantly. The data for black foam material, which had 20 pores per inch, showed a practical difference, but no statistically significant difference due to gravitational forces which caused the fabric to clog the drain spout and made flow of water harder. The data for yellow foam material, which had 90 pores per inch, showed that its water flow rate was the lowest, however, results were not significantly different than that of black foam material.
EVALUATING THE POTENTIAL USE OF HIGHLOFT NONWOVEN FABRICS FOR RAIN GUTTER APPLICATIONS

by

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in partial fulfillment of the requirements for the Degree of Master of Science

DEPARTMENT OF TEXTILE & APPAREL, TECHNOLOGY & MANAGEMENT

RALEIGH

2003

APPROVED BY:

Co-Chairman of Advisory Committee  Co-Chairman of Advisory Committee
Dedicated to

My father, mother and sister in Turkey

My wife Tara Filiz and her family
BIOGRAPHY

The author, Selcuk Filiz was born in Istanbul, Turkey on September 12, 1975. After attending three different high schools, he graduated from Akasya High School in Istanbul in May, 1993. He received his Bachelor of Science degree in Textile Engineering from University of Uludag, Bursa, Turkey in July 1999. Following his graduation, he joined the Turkish Navy and completed his military service in July, 2001.
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INTRODUCTION

Rain gutters are an important part of every house and most buildings and serve to collect rain water runoff from roofs and discharge it at selected locations usually through downspouts. Not only do gutters prevent runoff from the roof’s surface falling directly onto the surrounding lawn or garden causing pitting or trenching of the lawn or garden but also the downspouts direct the water away from the buildings’ foundations decreasing the risk of water seepage and damage to cellars from normal or heavy rainfalls.

Especially in Southern United States, due to the proximity of many homes and buildings to trees and to the shedding of particles from many roofing materials, these gutters may become clogged with many particles such as dead leaves, pine needles, twigs, pollens and roofing shingle particles etc. These may interfere with free flow of rain water runoff along the gutters and into and down the down spouts. This can cause the rain water to flow over the edge of the gutters, pitting or trenching of the lawn, and during periods of freezing weather causes the accumulated water to freeze creating further obstruction to rain fall runoff.

If the gutters or downspouts become clogged with leaves and other material blocking passage of rain water, freezing may burst portions of the gutter system requiring repair or even worse replacement of it. Gutters must therefore, be routinely cleaned to remove the debris. This is a time consuming, dirty job and for most homes can be a dangerous chore for the homeowner and requires them to hire professional gutter cleaners to do the required cleaning and maintenance.

According to the National Safety Council, Accident Facts, falls are the number one cause of accidental death and disabling injuries at home every year. During last year,
6500 accidental deaths were caused by falls at home, 1.9 million disabling and about 20-25 million non-disabling injuries occurred among the nation.

Many devices, such as slotted or perforated metal sheets, screens of wire or other material have been used to cover the open top of rain gutters to filter out debris and prevent them from entering the gutter, but none has proved successful. Mostly, small pieces of debris and even the long pine needles are allowed to enter the gutter and accumulate thus clogging the gutter drain, stopping the flow of water.

The objective of this study is to find a solution to these previously mentioned problems by using highloft nonwoven fabrics as a filler or gutter pack systems to prevent clogging caused by debris. Highloft fabrics perform as a “very permeable barrier”, and it is expected that transfer the rain water to the downspouts the same way screen or guard. Thus, the gutter will remain clean
2. **LITERATURE REVIEW**

2.1. **FLUID FLOW THROUGH POROUS STRUCTURES**

When considering flow through porous media, the pressure gradient across the boundaries drives the fluid through it. The nature of the flow depends on:

1. Fluid properties (viscosity $\mu$, density $\rho$)
2. Applied pressure gradient
3. Internal pore structure
4. Flow condition (single/multiphase)

It is possible to study pressure drop between the entrance and exit of a porous medium to characterize the flow. The volumetric flow rate through a porous medium is related to pressure drop in a creeping flow. Permeability is a characteristic of a porous network of which it conducts fluid through.

Many theories have been developed to describe different flow patterns through porous media. These models have been described by many authors [1,2]. However, not all of them are applicable to highloft nonwovens. Since highloft nonwoven fabrics are a form of layered thin nonwovens, a simple model cannot describe the flow of fluid through them.

We can define a porous medium as a fibrous network consisting of interconnected empty spaces. This network has a dimension known as the porosity of the fibrous material. Simply, porosity is the percentage of the particular material that is empty space.
In 1856, Darcy carried out an experiment on a porous bed of sand through which water was percolated in the vertical direction to observe the theory of laminar flow through porous media. This steady state unidirectional flow can only be applied to systems for which slow laminar flow is found [3]. Darcy has observed that the volumetric flow rate was directly proportional to the cross sectional area of the bed A, to the pressure drop $\Delta P$ across the bed, and inversely proportional to the length of the bed L.

$$Q = \frac{KA \Delta P}{L} \quad \text{or} \quad K = \frac{QL}{A \Delta P} \quad (2.1)$$

where,

$Q$ = volumetric flow rate
$K$ = proportionality constant $L^3 T/M$ (length$^3$ time/mass)
$A$ = area normal to the flow
$\Delta P$ = pressure drop
$L$ = length

The volumetric flow rate $Q$ is inversely proportional to the viscosity of the fluid $\mu$. Therefore, it is possible to express the equation 2.1 utilizing permeability coefficient ($k$) in the form:

$$k = \frac{Q \mu L}{A \Delta P} \quad (2.2)$$
since \( k = \mu K \).

However, Darcy’s law is based on the following assumptions:

1. Interaction between fluid and the porous medium does not exist.
2. The fluid is homogeneous or single phase.
3. Flow rate is within the laminar flow regime.

2.1.1 CAPILLARY MODEL THEORY

Capillaries are not always the sole force that drives fluid into a porous medium. Absorption along with wicking can occur. Often these two terms are used interchangeably.

Wicking is liquid uptake by the capillaries formed by fibers (in case of highloft nonwoven materials) whereas absorption is the liquid uptake into the fiber themselves. Usually, polyester materials are processed with a hydrophilic finish allowing liquid uptake only by wicking whereas naturally absorbent materials (such as cotton) do this both by wicking and absorption.

There are several different theories used to describe the capillary model. These include straight capillary, parallel, serial, and branching models.

The simplest capillary model is the one that represents a porous medium by a bundle of straight, parallel capillaries of uniform diameter [4]. In this type of model, all capillaries are assumed to be parallel one another, thus there can be no flow orthogonal to the capillaries. This means that permeability can only be obtained in one direction. According to Purcell [5], parallel capillary model has a major flaw in it since it assumes
that all pores go from one face of the porous medium through to the other face of the material. Also [6], this model assumes that all pore spaces is lined up serially, thus capillaries of different pore diameter are connected. This assumption requires that each particle of fluid enters at one side of porous medium, travels through very tortuous pore channels and then exits at only one pinhole at the other surface.

Dupuit-Forcheimer [5] defines an average pore velocity that has become a commonly accepted hypothesis for the connection of pore velocity and filter velocity:

\[ v = \frac{V}{n} \]  

(2.3)

where,

\( v \) = filter velocity  
\( V \) = effective velocity (pore velocity)  
\( n \) = porosity

Following equation 2.3, the total volumetric flow rate \( V \) through a capillary can be expressed by:

\[ V = \frac{g i d^2}{32 v} \]  

(2.4)

where,

\( I = \Delta P/L \) (hydraulic gradient)
\( v = \text{kinematic viscosity} \)
\( g = \text{gravitational constant} \)

When we take a look at Darcy’s law, it is:

\[
V = Ki \tag{2.5}
\]

If we take equation 2.3 into account, we can express permeability coefficient \( K \) as:

\[
K = \frac{gd^2n}{32v} \tag{2.6}
\]

where,

\( K = \text{permeability constant} \)
\( g = \text{gravitational constant} \)
\( n = \text{porosity} \)
\( v = \text{kinematic viscosity} \)

An expression for permeability coefficient \( K \) can be obtained by inserting turtuosity factor \( T \) and replacing \( d \) by \( dm \) (mean pore diameter) [7]:

\[
K = \frac{gdm^2n}{32vt^2} \tag{2.7}
\]
Other than equation 2.7, the equations expressed above neglects the fact that the fluid flow path may branch and later join together.

### 2.1.2 Hydraulic Radius Theory

This model is based on the assumption that porous media is composed of interconnected channels that connects two sides of the material. The assumptions basic to the hydraulic theories have been discussed by Carman [8] and Klyachko.

1. Fluid moves through a batch of capillaries
2. The porosity is not too high (<0.5)
3. Diffusion phenomena are absent
4. Continuous pores of uniform sizes
5. Pores are distributed at random
6. None of the pores are sealed off

Carman and Kozeny [9,10] had proposed an earlier model. They assumed that a channel through a porous media has a complicated cross sectional shape but on the average providing a constant cross section area. By assuming that, they have provided the channel diameter \( D_H \) governs the flow rate and can be expressed as:

\[
D_H = \frac{4 \times \text{void volume of porous medium}}{\text{surface area of channels in porous medium}}
\]  

(2.8)

This theory is modified by Hagen-Poiseulle [11] to include not only channels of various cross sections but also of definite lengths. For a laminar flow inside a non circular pore of hydraulic diameter \( D_H \), the average interstitial pore velocity \( \langle V_p \rangle \) can be formulated:
\[ \langle V_p \rangle = \frac{\Delta P D_H^2}{L_e 16 \mu K_0} \]  \hspace{1cm} (2.9)

where,

\[ \langle V_p \rangle = \text{average pore interstitial velocity} \]
\[ L_e = \text{average path length of flow} \]
\[ K_0 = \text{shape factor} \]
\[ \Delta P = \text{pressure drop} \]
\[ \mu = \text{viscosity} \]

If we assume pores governing the structure are circular, by normalizing the average interstitial pore velocity, \( K \) (permeability coefficient) can be obtained:

\[ K = \frac{\varepsilon D_H^2}{16 K_0 \left[ \frac{L_e}{L} \right]^2} \]  \hspace{1cm} (2.10)

Here, hydraulic diameter \( D_H \) is expressed as:

\[ D_H = \frac{4 \varepsilon}{S_0 (l - \varepsilon)} \]  \hspace{1cm} (2.11)

Carman and Kozeny derived the modified the modified relationship between flow rate and pressure drop:
\[ Q = \frac{\varepsilon^3}{\mu K_o S_o^2 (1-\varepsilon)^2 \left( \frac{L_e}{L} \right)^2} \frac{A \Delta P}{L} \]  

(2.12)

where,

\[ \left[ \frac{L_e}{L} \right] = \text{turtuosity factor (T)} \]

\[ K' = K_o T \text{ (Kozeny constant)} \]

\[ \varepsilon = \text{porosity} \]

\[ S_o = \text{specific surface} \]

\[ A = \text{cross sectional area of medium} \]

\[ \Delta P = \text{pressure drop} \]

Basically, the hydraulic radius theory relates the permeability of the material to the porosity of the material and the fiber diameter [12]. Carman and Kozeny equation has been very useful in determining the surface area of some powders particularly with spherical shape.

### 2.1.3 THE DRAG THEORY MODEL

Since hydraulic radius theory fails at high porosities (>0.5) of porous medium, the drag theory was described by Emersleben [13]. In some of the literature, this theory is named as the drag forces model as well. In this model, the fluid is assumed to exert drag
forces on the solid (such as grains, fibers, etc.) [14] or to the walls of the pores treated as obstacles in opposition to straight flow of a viscous fluid [15].

The drag of the fluid on each portion of the walls is considered to be equal to the resistance of the porous medium to flow (according to Darcy’s law, this is equal to viscosity divided by permeability, $\mu/K$).

It is to be expected that this model gives reasonable results for highly porous media such as highloft nonwoven fabrics.

There are a couple of drag theories that are applicable to textile materials. Afifty and Mohamed [16] modified the theory initiated by Spielman and Coren and applied it to needle punch nonwoven fabrics. They have predicted the pressure drop by assuming that a needle punch nonwoven fabric geometry is composed of two parts. These fabrics are considered to have fibers oriented perpendicular to the fabric plane (needling sites) and fibers oriented parallel to the fabric plane.

![Figure 1 The needle punch fabric and its predicted model (15)](image)

If we represent the volume fraction of fibers by $\alpha_1$ and $\alpha_2$, the total fiber volume can be expressed as:
\[ \alpha = \alpha_1 + \alpha_2 \]  \hspace{1cm} (2.13)

F, the total drag force, can be estimated by measuring the drag force per unit length of individual fibers in the fabric.

\[ F_1 = F_{D1} \left( \frac{\alpha_1}{\pi a^2} \right) \quad \text{and} \quad F_2 = F_{D2} \left( \frac{\alpha_2}{\pi a^2} \right) \]  \hspace{1cm} (2.14)

where,

- \( F_1 \) = drag force per unit volume of the fabric (perpendicular)
- \( F_2 \) = drag force per unit volume of the fabric (parallel)
- \( \alpha_1 \) = volume fraction of perpendicular fibers to the plane of fabric
- \( \alpha_2 \) = volume fraction of parallel fibers to the plane of fabric
- \( F_{D1} \) = drag force per unit length of fabric (perpendicular)
- \( F_{D2} \) = drag force per unit length of fabric (parallel)
- \( a \) = fiber radius

Then, the total drag force \( F \) is:

\[ F = F_1 + F_2 \]  \hspace{1cm} (2.15)

The other drag theories that will be presented depend on the geometrical shapes of the obstacles. In case of cylindrical fibers, permeability \( K \) perpendicular to the plane of fabric was expressed by Gourc et.al [17].
where \( D_f \) represents the fiber diameter, \( C_D \) drag coefficient and \( R_e \) Reynolds number.

Another approach is to take obstacles as spheres. For any uniform granular porous medium that is made of spherical particles, another equation can be derived for permeability.

\[
K = \frac{3 \pi g D_f^2}{4 v (1-n)} \frac{1}{C_D R_e} \tag{2.17}
\]

For thin nonwoven fabrics, workers has searched the behavior of flow to derive a relationship between \( R_e \), Reynolds number, friction factor \( \lambda \) and \( C_D \) drag coefficient. In laminar flow regime, \( R_e \) and \( \lambda \) can be expressed as:

\[
R_e = \frac{V D_f}{v (1-n)} \tag{2.18}
\]

and,

\[
\lambda = \frac{2 g i D_f}{V^2} \frac{n^3}{(1-n)} \tag{2.19}
\]
According to Rollin et al. [18], fluid flow through a bundle of tubes was similar to that of bundle of fibers. He modified and applied theory and derived following formula.

\[
C_D = \frac{A}{Re}
\] (2.20)

where \( A \) is a constant related with the ratio of pore diameter to the fiber diameter. He reported \( A \) values from 6 to 10 for thick needle punched nonwovens whereas other workers found 35 for several heat bonded nonwovens. These values were found by using \( Re \) values up to 25.

**Figure 2** Drag coefficient around a cylinder and a bundle of tubes (14)

It can be seen that there is a linear relationship between \( C_D \) and \( Re \) for Reynolds number having values less than 1. Thus, the flow is laminar (creeping flow). For Reynolds numbers larger than 1, \( Re>1 \), the curve becomes non linear. The reason being is that it is believed that a separation occurs in the boundary layer on the cylinder surface.
thus forming a vacuum, which increases the drag coefficient. Also, when the flow rate is increased, the separation point moves towards the rear of cylinder causing a sudden decrease of $C_D$. For a bundle of in-line tubes (fibers), the presence of adjacent fibers affected the behavior of flow since the distance between fibers was decreased. This decrease caused an increase in flow rate resulting higher Reynolds number ($R_e$).

### 2.1.4 Porosity

Porosity can be defined as the ratio of the total void volume to the volume of the bulk material.

$$\Phi = \frac{V_p}{V_B}$$  \hspace{1cm} (2.21)

where $\Phi$ is porosity, $V_p$ total void volume, and $V_B$ bulk volume. Solid fraction of the material occupies a portion of the bulk volume, we can write it as:

$$1 - \Phi = \frac{V_s}{V_B}$$  \hspace{1cm} (2.22)

where $V_s$ is the total volume of solid fraction.

The measurement of porosity can be achieved by many methods such as direct method, optical methods, density methods, gas expansion, electrical resistance, TRI UpKin instrument and PMI’s capillary flow porometer.

In direct method, the bulk volume of a piece of fabric or porous material is measured. Then, the piece is compacted until the void volume is zero. The new volume of
the fabric is measured and the difference is taken between the new and the previous
volume, which gives the void volume. This method is only good for soft (compressible)
structures.

Another way to determine the porosity is to examine the section of the material
under a microscope. It is possible to take photograph of the section and then measure the
area of pores with a planimeter. Difficulties will be encountered since it is not always
possible to make sections of a porous medium easily, especially layered structures such
as highloft nonwovens.

In case of the density of the material forming porous medium is known ($\rho_G$),
porosity can be calculated as:

$$P = 1 - \frac{\rho_B}{\rho_G} \quad (2.23)$$

where $\rho_B$ is bulk density.

Gas expansion method is based on direct measurement of the volume of gas (or
air) contained in void volume. This method is popular since it is fast, accurate and leaves
the sample undisturbed which allows the other tests’ performing immediately after the
application of the method.

The electrical resistance of the porous medium can be found utilizing two parallel
plates charged with batteries. The electrical capacitance change gives an idea about the
pore geometry and volume.
PMI’s Automated Capillary Flow Porometer determines the flow and pressure that indicates the bubble point, which is the pressure at which the largest pores are emptied of fluid, and then continues to increase the pressure and measure the flow of air until all the pores are emptied. The underlying fundamental physical property that allows for this type of testing is capillary action. Capillary action is the attractive force by which a fluid is held in a pore of a solid. The fluid will remain in the pore until it 1) evaporates, or 2) is forced out by air (or other gas) under pressure. This technique utilizes the second of these premises. A sample is fully wetted by a liquid and then a flow of air (or other fluid) is established through the sample until the bubble point and pore size determinations are complete. The basic premise for this testing technique is a simple relationship: the smaller the pore, the greater the pressure needed to overcome the capillary action and push the fluid out of the pore. Also, the size of a pore is determined by the smallest constriction of the pore. The smallest diameter of the pore determines the pressure needed to empty that pore of fluid.

TRI UpKin is a developed instrument to measure the kinetics of rapid, transplanar liquid uptake with a time resolution in the millisecond range, which is well above the capabilities of other existing instruments. Device brings test sample in contact with the test liquid. Capillary pressure pulls the test liquid into the samples’ pores. A precision capacitance sensor measures the position of the moving liquid front in the sample every millisecond.

The total porosity can be defined as the ratio of the void volume to the total volume whereas effective porosity is the ratio of the total “interconnected” pores to the total volume.
Many researchers have found empirical relationships between porosity and permeability but almost all of them contained factors, which should be kept constant in order to be applicable. There is no correlation between permeability and porosity since two totally different porous structures having the same porosity can have different permeabilities.

Also, compression of porous materials results with a decrease of total volume and void volume, which might change porosity. According to Giroud [19], this can be expressed as following:

\[
\frac{T_1}{T_2} = \frac{P_1 + d_f}{P_2 + d_f}
\]

where,

\begin{align*}
P_1 &= \text{average pore space between filaments before compression} \\
P_2 &= \text{average pore space between filaments after compression} \\
T_1 &= \text{thickness before compression} \\
T_2 &= \text{thickness after compression} \\
d_f &= \text{diameter of filaments}
\end{align*}

2.1.5 TURUOSITY

Clarenburg and Piekaar [18] believed that capillaries can be characterized as the ratio of the true flow path length of fluid and the straight line distance between the point fluid enters and exits the porous medium.

They have derived the following formula:
\[ \Delta P = \frac{11.4 \mu L U}{\varepsilon} \frac{N_p}{L_m^2} \left[ \frac{L_e}{L} \right]^2 \]  \hspace{1cm} (2.25)

where,

- \( L_m \) = mean fiber diameter
- \( L_e \) = the effective channel length
- \( U \) = superficial velocity
- \( \Delta P \) = pressure drop
- \( \mu \) = fluid viscosity
- \( L \) = filter thickness
- \( \varepsilon \) = porosity
- \[ \left[ \frac{L_e}{L} \right] \] = turtuosity factor

Turtuosity factor can be given as:

\[
\left[ \frac{L_e}{L} \right]^2 = 1 + \left( 0.855 \left( \frac{\sqrt{1.865}}{\varepsilon} \right) - 1.024 \right)^2 \cdot 0.389 \cdot \frac{L_m^2}{N_p \pi d^2} \]  \hspace{1cm} (2.26)

where \( N_p \) is the number of pores on surface area \( L_m^2 \) and can be given by:

\[
N_p = \frac{N(N - 1)}{\pi} - \frac{N}{2} \]  \hspace{1cm} (2.27)
where \( \bar{d} \) is the mean fiber diameter and \( N \) is the number of fibers in a section with \( L_m^2 \) surface and \( 2 \bar{d} \) thickness. \( N \) can be expressed as:

\[
N = \frac{8}{\pi} (1 - \varepsilon) \frac{\bar{d} L_m^2}{d^2}
\]

(2.28)

### 2.1.6 VOLUME AVERAGED FLOW THROUGH POROUS STRUCTURES

Most of the porous structures have highly complex internal geometry that cannot be modeled easily. It is recommended for such geometries’ flow behavior to be analyzed by utilizing volume averaged flow equation.

In this model, it is assumed that matter is a continuous medium that fills its space completely and any kinematics or thermodynamic variables can be assigned to any point of this medium.

Whitaker et al. [20] has developed theories that are applicable to highly complex internal geometries. Figure 3 shows a macroscopic system (A) where \( V \) is the averaging volume and \( L \) macroscopic length. Also, figure 3 shows a solid-fluid system (B) where \( L_\sigma \) is a characteristic length of the solid phase and \( L_\beta \) is the characteristic length of fluid phase. B phase indicates the fluid (water) whereas \( \sigma \) indicates fiber (solid) phase.

This model has an assumption based on the idea that \( r_0 \) (radius of averaging volume) should also be larger than \( L_\beta \) to obtain reasonable and smooth results. In addition to that \( r_0 \) should be between \( \varepsilon \leq r_0 \leq L \).
Figure 3 Fluid-Solid System for Average Flow Equation (21)
2.1.7 **PERMEABILITY**

Permeability can be defined as the fluid conductivity or the ease of fluid flow through a porous structure. Most of the literature provides Darcy as the unit of permeability as:

\[
1 \text{ darcy} = \frac{1\text{ (cm}^3/\text{sec})}{1\text{ (cm}^2)} \cdot \frac{1\text{ (cp)}}{1\text{ (atm/sec)}} \quad (2.29)
\]

This means, for a porous structure of one Darcy permeability, a pressure difference of one atmosphere will create a flow rate of 1 cubic centimeter per second of a fluid having one centipoises viscosity through a cube having sides of one centimeter in length.

According to Darcy’s law, permeability is defined as:

\[
Q = \frac{K A \Delta P}{\mu L}
\]

for one direction and under laminar flow conditions where,

\[
P = P' + \rho g z \quad (2.30)
\]

where \(P'\) is the hydrostatic pressure, \(\rho\) is fluid density and \(g\) is the gravitational constant.
For layered porous media such as highlof t nonwoven fabrics, it is possible to average the permeability of each layer and provide an average permeability for the whole system for flow normal to the layers (transplanar flow).

In most cases, the passage of each water particle through each layer is successful in transplanar flow is continuous whereas the coefficient of permeability of each layer is supposedly different.

Carman describes the average permeability coefficient ($k_{\perp}$) normal to the layers of multiplayer nonwoven fabric as:

$$k_{\perp} = \frac{L_T}{\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} + \frac{L_4}{K_4} + \ldots + \frac{L_n}{K_n}}$$

(2.31)

The flow perpendicular to multiple layers of nonwoven fabric is presented in figure 4.
Figure 4 Flow Perpendicular to Thin Multiple Layers of Nonwoven Fabrics (14)
2.2 PATENT LITERATURE

2.2.1 Downspout Strainer Device

Many systems and devices have been used to prevent leaves, twigs, pine needles, pollens or roofing materials entering in rain gutters and thus downspouts.

Bugbird U.S. patent no. 3,121,684 [22] claims a downspout strainer device placed into the upper end of a downspout by the use of a long pole having a hook at its upper end that engages the wire loop of the device.

![Figure 5 Downspout Strainer Device (22)](image)

The strainer allows rain water to pass through it while preventing the debris entering the downspout however; debris still enters the gutter and clogs it in time. This device also requires periodical removal and cleaning out of the accumulated material caught by the device. During heavier rainfalls such as in fall season, the strainer can catch enough leaves during a single rainfall to clog entry to the downspout.
Many devices have been developed to prevent foreign materials from entering the rain gutters and downspouts. For example, gutter guards made of wire mesh should be unrolled before attachment to the gutters since these are present in rolled form. Also, the wire mesh can be deformed during manufacture, shipment and even during attachment. Most of the time, these wire meshes deform and gutters are still exposed to debris.

2.2.2 Hinged Gutter Guard

Clarkson U.S patent no. 4,351,134 [23] claims an improved wire mesh and presents a hinged gutter guard device in the form of an elongated perforated cover plate made of a relatively rigid material having hinge straps. Hinge straps are positioned within longitudinal slots and are adapted to be secured to a roof beneath the lower course of shingles.

![Hinged Gutter Guard](image)

Figure 6 Hinged Gutter Guard beneath the lower course of shingles (23)

The straps can be shifted within their slots to ensure proper attachment. However, shingle debris can still pass through perforations and the gutters still must be cleaned. Further, especially in heavy rainfalls, the force of the rain water off the roof can cause part of the
water skid of the gutter guard and fall directly on the lawn below causing pitting or trenching. In time, the stress variation caused by normal use and raising-lowering of the gutter guard weakens or tear shingles, thus necessitating replacing or repair of the shingles.

2.2.3 Rain Gutter with Filter

Another patent, U.S patent no. 4,841,686 [24] claims a filter attachment that fits over the gutter trench. The filter attachment is clamped with a pad of fibrous material, fiberglass, underneath it. The screen has 0.25 to 0.5 inch square openings. These openings can trap smaller particles but in time the surface of the screen clogs thus needs to be cleaned out. The cleaning process is time consuming and difficult for most of the time.

![Figure 7 Rain Gutter Assembly with a filter underneath the trench (24)](image)

2.2.4 Open Through Filler

U.S. patent no. 3,855,132 [25] discloses a fitted porous solid polyurethane foam material that serves as a barrier to leaves, dirt etc. Here, there is a space between foam material and the bottom of the gutter that allows for free flow of water below the porous
section while blocking the debris. The percentage void volume is critical since higher void volume increases the water transfer capacity. In this particular patent, the polyurethane foam has 95% void volume with an average of 10 pores per linear inch.

![Porous Polyurethane Foam Material fitted in a gutter (25)](image)

Many of the devices developed to protect rain gutters have not focused on the overall cost for any parties.

### 2.2.5 Nonwoven Fiber Screen For Rain Gutters

U.S patent no. 5,848,857 [26] provides and inexpensive, easy to manufacture, easy to install rain gutter shield which filters out not only large but also small foreign material permitting only rain water and other easily washed away materials to pass into the downspout. The gutter shield here has an elongated layerless screen of porous nonwoven polymeric fiber material. The porous nonwoven fiber material is a $\frac{1}{8}''$ to $\frac{1}{2}''$ thick mat of silicon carbide-polyamide fiber/flint fiber. These types of nonwovens are known to be scotch bright in the market. It is possible to purchase these in roll form and cut into various lengths to utilize them in a rain gutter. Also, clean & finish roll from 3M company provides silicon carbide/nylon/aluminum oxide type of material known as bear-
tex nonwoven material. The rain gutter shield can be attached to the gutter at the time of mounting or be attached to already mounted rain gutters. The main filtering function is provided by the porous nonwoven polymeric fiber itself. The material is claimed to be weather resistant, flexible enough to be handled, sturdy enough to avoid sagging and stretching without the need for a backing layer. Also, it quickly lets rain water pass through it while filtering the fine solid materials.

When we have take a look at the previous patents, it is possible for us to see a trend going towards the minimizing the size of the solid particles being filtered.

2.2.6 Rain Gutter Shield With Nylon-Polyester Nonwoven Fabric

U.S patent no. 6,134,843 [27] takes this one step further and provides a rain gutter shield that can be used with any type of existing rain gutters on most of any roof design. It is claimed that they provide a gutter shield that is economical to manufacture and install and also not adversely affected by heat or cold. The gutter shield has matting and a covering. The matting is an elongated three dimensional matting that includes plural shapes of rows, the basis of the shapes defining a first plane and the apexes of the shapes defining a second plane. The matting extends outwards from the bases. The covering is an elongated
water porous fabric that has an upper and lower surface. The upper surface is smooth enough to prevent debris from being retained by the fabric material and enables debris being blown off by ambient winds. The lower surface of the fabric is bonded to the matting. One longitudinal edge of the fabric extends outwards for the mounting device to the building and the other edge of the fabric extends for attachment to the outer lip of the gutter. This positions the shield over the opening of the gutter effectively. The plural shapes mentioned above are cones made of nylon that has carbon black to resist the detrimental effects of UV light. The cones are arranged in transverse and longitudinal rows. The fabric mentioned is a porous nylon-polyester nonwoven fabric such that when the rain or snow is gone, the debris will naturally dry and be blown off by winds. The nonwoven fabric is heat bonded to the matting. Fabric extends outward in the first plane, in both transverse directions to the length of the gutter. A portion of the fabric extends to the outer lip of the gutter to prevent debris entering the device.

Some prior gutter guards include gutter screens made of woven metal wire that prevents debris from entering the gutter. [28] Metal wire screens are expensive to
manufacture and install compared to nonmetal screens like plastic or nylon screens. Metal screens can also be awkward to remove to do the cleaning of the gutter. In addition to this, if the metal wire does not have a large enough gauge to prevent the debris, the weight of water running off the roof onto the screen or the weight of the debris that lands on the screen forms valleys on the screen. These valleys then collect debris and interfere with the water collection. Thus, this requires cleaning later on.

According to Southern Building Code Congress International, Inc. (SBCCI) [29], guttering systems consist of gutter attached to fascia boards and then connect to downpipes. These in turn, carry the water from the gutter to ground level. Utilizing the correct type of gutter shield will not only minimize the amount of debris entering the gutter but also will prevent the soakaways that the downpipes lead. The soakaways get clogged as well as gutters and usually to repair this damage they have to be redug and repiped. Sometimes pipework can be cleared by hand operated devices or by pressure devices but it is time consuming and can be expensive. Also, downpipe needs to be removed and then replaced afterwards. [30]
2.3 COMMERCIAL APPLICATIONS OF PATENT LITERATURE

There are also several commercial products designed to protect gutters from clogging, but none of these have been published in the literature.

2.3.1 Flow Free Gutter Protection System

*Flow free* gutter protection system is one of these products that provides a 0.75 inch thick nylon mesh material designed to fit in five inch K type gutters. This device fits over the hanging brackets of the gutters and one side extends to the bottom of the gutter to prevent its collapse into the gutter. But, this system is precut and fits only to 5 inch K type of gutters while many homeowners have other types of gutters. In this particular type, the nylon mesh traps pine needles, shingle material etc and should be cleaned to avoid blocking of the flow of rain water.

2.3.2 Gutter Helmet®

*Gutter Helmet®* is a commercial product for gutter protection. This device covers most of the gutter with a bullnose shaped protrusion proximate the outer edge of the gutter. The design is based on utilizing surface tension of water thus channeling the water down the bullnose into the gutter while leaves and other debris falls down.

![Commercial Gutter Helmet](27)
Most of the commercial gutter helmets are affixed to the edge of the roof by screws that lead to leaks through the roof. Unless the bullnose is completely wetted, gutter helmets are not efficient and water drips directly onto the lawn causing soil erosion and water in the buildings’ basement. In winters, the dripping water causes icicles to form and can fall becoming a safety hazard. Also, dirt mildew builds up on the bullnose preventing water flow into the gutter and necessitates routine scrubbing and cleaning of the system and in some installations gutter helmets are known to buckle from the heat of the sun. At the time of cleaning, the device needs to be removed from the gutter also, which makes cleaning harder.

2.3.3 Gutter Protech™

The Gutter Protech™ gutter protection system also uses surface tension and liquid adhesion of rainwater to direct it into the gutter trench through two rows of alternating angled slots over mini-bullnoses.

![Gutter Protech™ gutter protection system](image)

**Figure 12** The Gutter Protech™ gutter protection system (27)

As in similar designs, until the bullnoses sufficiently gets wet, they do not work properly and dirt build up on them must be routinely cleaned to ensure flow into the gutters.
2.3.4 Waterfall™

Waterfall™ plastic gutter guard system is one of the final commercial products present in the market. The system also uses the principle of water adhesion and includes two sets of parallel channels each having drain holes. Rain water flows from the roof onto the device into the upper channel and into the gutter trench. The second lower channel collects the remaining runoff and directs it into the gutter.

![Image of Waterfall Plastic Gutter Guard System](image)

Figure 13 Waterfall Plastic Gutter Guard System (27)

The classical problem with gutter guards occurs here once again, the debris accumulation. Parallel channels need to be cleaned out periodically. Since this is a rigid PVC gutter system, it cracks in cold weather degrading its performance and requiring replacement. Further, the device does not include end caps so birds gain entry into the gutter and build nests. Another issue with this particular commercial product is that it tends to separate from beneath shingles and be blown off the gutters.

None of the systems above appear to be effective in keeping all debris out of gutter systems. Eventually, debris builds up either on the surface of the devices or within the gutter drenches or downspouts.
3. APPROACH

3.1. Heavy Rainfall Climatology for North Carolina State

The National Weather Service Office (NWSO) defines heavy rainfall as greater than 0.30 inches of rain in one hour or 0.03 inches in 6 minutes [31].

In this study, the hourly rate of our heavy rainfall must be considered when developing the test apparatus. The following figure of yearly rainfall events (figure 14) shows an average of 29 heavy rain events per year. These correspond to the most active thunderstorm periods in North Carolina.

![HEAVY RAIN EVENTS 1961-1995](image)

*Figure 14 Heavy Rain Events in North Carolina (yearly) (31)*

Also, figure 15 of the heavy rain events by the hour shows that the most consistent times of heavy rainfall occurred in the early morning hours around 1:00 am to 5:00 am.
Figure 15 Heavy Rain Events in North Carolina (hourly) (31)

Monthly heavy rainfall events peak in September but the most continuous period is from April to June corresponding to the greater number of severe storms in the spring. There is however, a period of rainfall events in September as well. Figure 16 indicates that the month with the most heavy rainfall (1.50+ inches) events is June.

Figure 16 Heavy Rain Events in North Carolina (monthly) (31)
The final analysis of North Carolina severe weather statistics show that April is the peak tornado and hail month, June is the peak wind event month and September is the peak rainfall month. Figure 17 sums all the severe weather reports and shows that April to be the month with the greatest number of severe events. Also, the severe weather season is shown to begin in April and continue into June while traditional severe weather season runs March thru May [32].

![ALL SEVERE WEATHER 1961-1995](image)

Figure 17 Final Analysis of North Carolina Severe Weather (31)

Tornadoes were found to occur with a frequency of 10 each year and are a significant threat to North Carolina. The majority of these tornadoes are weak, but the occurrence of strong and violent storms is always a possibility and cannot be discounted.

The hourly distribution of severe events occurs between 3:00 pm and 7:00 pm which is concurrent with the traditional severe weather time period.
Of interest is also the patterns relating to Wake County, NC and collect data. According to the State Climate Office of North Carolina at NC State University, there occurred 36 flood events as a result of heavy rainfall reported in Wake County between 01/01/1950 and 06/30/2002 [33]. Some of the events are presented in table 1 below.

Table 1 Some of Flood Events occurred in Wake County (33)

<table>
<thead>
<tr>
<th>Event</th>
<th>Begin Date</th>
<th>End Date</th>
<th>Rainfall intensity</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash flood</td>
<td>31 March 2002, 06:45 pm</td>
<td>31 March 2002, 07:30 pm</td>
<td>1.25 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>24 June 1995, 16:05 EST</td>
<td>24 June 1995, 17:30 EST</td>
<td>1.25 inches</td>
<td>N. Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>06 Sept. 1996, 12:30 am</td>
<td>06 Sept. 1996, 11:00 am</td>
<td>9 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>24 July 1997, 06:30 am</td>
<td>24 July 1997, 08:00 am</td>
<td>2-4 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Stream flood</td>
<td>23 Jan 1998, 12:00 pm</td>
<td>23 Jan 1998, 03:00 pm</td>
<td>3-4 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>09 March 1998, 01:50 am</td>
<td>09 March 1998, 03:30 am</td>
<td>1-1.5 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>19 March 1998, 04:00 am</td>
<td>19 March 1998, 06:50 am</td>
<td>3-4 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Stream flood</td>
<td>16 August 1998, 08:15 pm</td>
<td>16 August 1998, 10:15 pm</td>
<td>2-3 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>05 Sept. 1999, 01:00 pm</td>
<td>05 Sept. 1999, 06:00 pm</td>
<td>6-8 inches</td>
<td>Raleigh</td>
</tr>
<tr>
<td>Flash flood</td>
<td>03 Sept. 2000, 06:10 pm</td>
<td>03 Sept. 2000, 08:00 pm</td>
<td>2 inches</td>
<td>Raleigh</td>
</tr>
</tbody>
</table>
From the data presented above, the average rainfall of all events is calculated to be between 1.53 inches per hour and 1.81 inches per hour.

3.2 Test Apparatus Design Considerations

Since the average heavy rainfall varies between 1.53 inches per hour and 1.81 inches per hour, for calculation convenience, this number is chosen to be 2 inches per hour.

The reason the heavy rainfall amount is considered is because our highloft nonwoven fabric to be used in rain gutter applications should be able to transfer the rain water coming down the roof to the downspout of the gutter without causing an undesired overflow.

In addition to the hourly heavy rainfall, the total catchment area of a roof is very important because it affects the amount of water flow that is directed to a rain gutter system by the roof.

For this purpose, a specific area of a simulated roof is considered as well as a rain gutter when designing the testing device that is named “Rain Machine”.

For a roof part, having 156 inches (≈ 4 meters) of length and 30 inches (≈ 0.8 meters) of width, the area of the roof part can be calculated as:

\[ A_{\text{roof}} = 156 \text{ in} \times 30 \text{ in} = 4680 \text{ in}^2 \]

Within one hour, the amount of rain water \( (V_{\text{root}}) \) that this area of a roof part catches (assuming rainfall intensity is 2 inches per hour) is:
\[ V_{\text{roof}} = 4680 \text{ in}^2 \times 2 \text{ (in/hour)} = 9360 \text{ in}^3 = 153.3 \text{ liters} \]

At the same time, since rain falls on roof and gutter, the amount of water that is caught by the gutter \( V_{\text{gutter}} \) should also be included in calculations. We consider a gutter having 40 inches of length and 5 inches of width attached to the simulated roof. Thus,

\[ V_{\text{gutter}} = 40 \text{ in} \times 5 \text{ in} \times 2 \text{ (in/hour)} = 400 \text{ in}^3 = 6.55 \text{ liters} \]

Thus, the total volume of water that is caught by roof and gutter within one hour should be summed up.

\[ V_{\text{Total}} = V_{\text{roof}} + V_{\text{gutter}} = 153.3 \text{ liters} + 6.55 \text{ liters} = 159.85 \text{ liters} \approx 160 \text{ liters/hour} \]

The "Rain Machine" design is discussed in detail in the following chapter. This testing device basically utilizes a submersible pump that creates a rainfall effect on a piece of roof and gutter. While designing the apparatus, since amount of water in a specific testing time is critical, the pump capacity had to be taken into account as well.

According to the data presented above, the pump should be able to simulate a rainfall of 160 liters per hour. Thus, pump capacity can be calculated as:
\[ \text{Pump Capacity (liters/min)} = \frac{160 \text{ liters}}{60 \text{ min}} = 2.66 \]

For this purpose, a ¾ hp submersible pump was utilized since its capacity range matched the best among the other pumps present.
4. EXPERIMENTAL METHODS

4.1 General Information about Highloft Nonwoven Fabrics

4.1.1 Definition of Highloft

There are not any widely accepted definitions describing a highloft nonwoven. A couple of definitions may be relevant.

Holliday [34] defined a highloft as;

“Nonwovens that are more than 1/8 inches in thickness and contain much more air or voids than fiber”.

Another definition is due to Baigas [35];

“A low density fiber network structure characterized by a high ratio of thickness to weight per unit area. The fibers can be continuous or discontinuous, bonded or unbonded. Highloft battings have no more than 10% solids, by volume, and are greater than 3 mm (0.13 inch) in thickness”.

4.1.2 Historical Overview of Highloft Nonwovens

Primeval men took hair from animal skins and fibers from plants to produce the first highloft low density mats to provide cushioning and protection from the cold weather and ground [36].

In the early 1900s, cotton and wool battings continued to be the major products in the commercial highloft nonwovens. These batts or filling materials were usually unbonded fibrous webs that were processed on card or garnett machines. A portion of the production was stitched with an open pattern to hold it together without compressing the loose and bulky fibers.
In 1950s and 1960s, companies producing cotton battings began using rayon and acetate in their highloft materials. These products were used for filling primarily in bed coverings, pillows, automotive and other padding products.

During the 1960s, polyester fibers were designed for filling applications where crimp, fiber cross-sections and finishes were engineered to enhance end use properties of fiberfill. Spray bonding of battings with acrylic binders was developed where it bonded the fibers at their cross over points, thereby preventing their entangling and maintaining their loft even during washing. During this period, the term “Fiberfill” became the dominant label for polyester highlofts.

The energy crisis of the 1970s stimulated the introduction of sub denier and micro denier fiber products, which offered good thermal properties. Thermally bonded highloft appeared on the scene with the development of lower melting fibers. Thermal bonding began making significant headway in this market during the late 1970s and early 1980s. Thermal bonding is still one of the most popular bonding methods of highloft nonwoven fabrics since it is energy efficient and environment friendly.

4.1.3 Highloft Nonwoven Manufacturing

Highloft nonwoven fabrics have been produced exclusively on garneted/cross lapped/thermally bonded lines. Thus, manufacturing of these products has been classified in dry nonwovens class. Since samples tested in this study were provided by Leggett & Platt, their production line was included as manufacturing technology of highlofts which utilized garneted/cross lapped/thermally bonded lines.

A typical line configuration is shown on figure 13 on the following page.
Fiber Preparation is the first element of good nonwoven manufacturing. Blendline utilizes a series of electronically controlled weigh pans, which distributes the appropriate blend of unique fiber types onto a moving apron. A blending line typically consists of two to ten blending feeders. The blending feeder weighs the amount of fiber dumped on the common conveyor. The conveyor then feeds the blending picker, which is normally a simple machine of one or two rolls that opens the fiber clumps, a small amount. From blending picker the fibers are conveyed by air to another feeder. This picker feeder feeds the opening picker (fine openers). The opening picker’s job is to open the fibers as much as possible for feeding to the card. The fibers are now preopened and blended [37].

Web Forming is usually done by carding or garneting. Carding is the process of opening, disentangling or separating and straightening individual fibers, parallelizing, blending and cleaning or extracting foreign matter and delivering the opened mass of fibers for further processing by using carding machines [38].
Garnett was designed primarily for reclaiming fiber from trimming waste and old rugs that had previously been processed through a rag picker. Because of this, they were clothed with rugged metallic clothing and the main cylinder was large so high surface speeds could be achieved. In addition, the workers and stripper provided excellent opening and fiber blending. Garnettes usually feed a cross-lapper.
### Table 2 Carding and Garneting comparison (37)

<table>
<thead>
<tr>
<th>CARD</th>
<th>GARNETT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Originally to process quality yarn</td>
<td>Originally to process waste</td>
</tr>
<tr>
<td>Has workers and strippers</td>
<td>Has workers and strippers</td>
</tr>
<tr>
<td>Usually no Fancy Roll</td>
<td>Usually has Fancy Roll</td>
</tr>
<tr>
<td>Process virgin fiber</td>
<td>Process virgin fiber and/or waste</td>
</tr>
<tr>
<td>Usually cast iron construction</td>
<td>Usually cast iron construction</td>
</tr>
<tr>
<td>Sometimes stationary card plates</td>
<td>Usually never stationary plates</td>
</tr>
</tbody>
</table>

Garnettes generally have higher loft in the finished product due to the action of the fancy Roll. Carded webs tend to be more linear because they do not have the turbulent action of the fancy roll [38].

Card systems incorporate a *cross lapper* to build up weight, loft and cross directional strength. The cross lapper folds the web on a floor apron running perpendicularly to the machine direction of the card and cross lapper. Web weights vary from 1 oz/yd² to 50 oz/yd². Sometimes cross lappers leave lap marks or diagonal streaks where two of the webs join on the floor apron. With a properly timed lapper and card in good operating condition, the lap marks are extremely difficult to see. Usually, there are two kinds of cross lappers; the vertical (camel back) cross lapper and horizontal cross lapper [39].

The vertical cross lapper consists of feeding belts 2 bringing the carded web 1 and of a couple of reciprocating belts 3. The reciprocating belts 3 lay the carded web or garneted web into folds on the output belt 4. The area mass density of the resulting layer depends on the feeding velocity and area weight of the web, on the width of layer, and on velocity of output belt. The fiber orientation is a function of velocities of both the layering and output belts [39].
Web Drafting is a means of simultaneously increasing web throughput, decreasing web weight, and altering fiber orientation. In the production of samples, for the purpose of balancing the orientation of fibers in the x-y plane, multi-roll drafters were utilized.

After being drafted, highlofts are thermally bonded. In thermal bonding, heat energy is used to activate an adhesive (for this study, the sheath of bicomponent fibers), which in turn flows to fiber intersections and interlocks the fibers upon cooling, thus layer-to-layer consolidation is achieved. Thermal bonding is achieved as a result of sequence of three events; heating, flowing, and cooling. Some nonwovens are now being produced with core-spun fibers in which the inner portion of the fiber is a high melting core and the outer sheath is a low melting polymer. Bicomponent fibers consisting of a half high and half low melting component are also being used to manufacture thermally bonded nonwovens. The use of bicomponent fibers permits bonding to take place only at the fiber cross over points and highlofts having softness, flexibility and loftiness can be produced if through air bonded.
The web to be bonded moves on a permeable support screen over a flat bed. Above the flat bed is a plenum into which heated air (using either electric or gas fired heaters) at selected temperature is blown in. Below the flat bed are vacuum units that suck the heated air from the plenum above, through the passing fabric over the flat bed, and after reheating the air is circulated back into the heating zone. For a given basis weight, the web needs a certain dwell time to reach the desired thermal equilibrium. Thus, the length of the flat bed, the temperature of the heated air and the throughput speed need to be optimized. Alternatively, the web to be bonded is carried by a permeable screen around a perforated drum enclosed in a chamber. The upper part of the chamber serves as a plenum into which heated air can be sucked in through the fabric. Suction boxes located inside the drum aid the air suction. The sucked in air is then reheated and circulated back to the heating zone. Through air bonding is the method of choice for highloft structures where bonding through the web is desired to be homogenous [41].
After bonding, highloft nonwovens enter a cooling/compression zone that usually consists of two opposing porous aprons. The distance between these aprons is adjustable and determines the final thickness of the product. Highloft products remain at whichever thickness they are set while being cooled.

If the product is in roll form, the highloft product is rolled up using a simple two-roll surface winder. If the product is in panel form, these panels are typically doffed and stacked by hand. Packages are then vacuumed and shipped.
4.2 MATERIALS

4.2.1 Fabric Materials

4.2.1.1 Fabric Samples used in Volumetric Flow Rate Tests

In measuring Volumetric Flow Rate, 3 different types of highloft samples were precut and chosen. The samples were evaluated according to their thickness and areal mass density. The characteristics of each sample type are shown in Table 3.

<table>
<thead>
<tr>
<th>I.D of sample</th>
<th>Fabric Dim. (inch)</th>
<th>Fabric Dim. (cm)</th>
<th>Fabric Layers</th>
<th>A.M.D. (g/m²)</th>
<th>Fiber Denier</th>
<th>Fiber density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>40 x 4 x 4</td>
<td>101.6 x 10.2 x 10.2</td>
<td>24</td>
<td>1221</td>
<td>14.79</td>
<td>1.38</td>
</tr>
<tr>
<td>Type 2</td>
<td>40 x 4 x 4</td>
<td>101.6 x 10.2 x 10.2</td>
<td>45</td>
<td>2289</td>
<td>15.88</td>
<td>1.38</td>
</tr>
<tr>
<td>Type 3</td>
<td>40 x 4 x 5</td>
<td>101.6 x 10.2 x 12.7</td>
<td>44</td>
<td>2746</td>
<td>15.34</td>
<td>1.38</td>
</tr>
</tbody>
</table>

In Table 3, A.M.D stands for Areal Mass Density of the samples.

Samples were produced from 100% polyester fibers with;

- 85% 15 denier PET
- 15% sheath/core Co-Pet binder fibers

According to Table 3, I.D of sample indicates the specific numbering system used to characterize the sample. According to that, I.D numbers indicate the following;

- Type 1: 4 inches thick sample and one square foot of the sample weighs 4 ounces. (1221 g/m²)
- Type 2: Sample that is 4 inches thick and one square foot of the sample weighs 7.5 ounces. (2289 g/m²)
- Type 3: Sample that is 5 inches thick and one square foot of the sample weighs 9 ounces. (2746 g/m²)

Since these samples were made by using drafted cross lappers, the majority of the fibers are oriented in x-y plane, with many being roughly at 45° or 135° to either the machine direction or cross direction.

One lap of a crosslapper is one complete cycle. Each lap forms two layers in the sample. If we multiply number of laps by the number of cross lappers on the production line, we can get the number of layers in the samples. For example, the normal set up on the line would produce 24 layers for 4 inches thick, 4 oz/ft² product and thus 45 layers for 4 inches thick, 7.5 oz/ft² product.

The fluid medium used in this study was city water supplied from a laboratory faucet.

**Weight of Samples**

The weights of samples were measured by OHAUS ES 50L (50 x 0.02 kg) type of scale and were recorded in Table 4.

**Thickness of Samples**

Sample thickness was determined using Compression Tester Thickness Machine (Kawabata’s Evaluation System-3) and were recorded in Table 4.
Table 4 Measured characteristics of samples

<table>
<thead>
<tr>
<th>I.D of sample</th>
<th>Fabric Dim. (cm) length x width x height</th>
<th>Sample weight (g)</th>
<th>Sample volume (cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Sample Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Fiber Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>101.6 x 10.2 x 10.2</td>
<td>125.99</td>
<td>10487.7</td>
<td>0.012</td>
<td>1.38</td>
</tr>
<tr>
<td>Type 2</td>
<td>101.6 x 10.2 x 10.2</td>
<td>236.24</td>
<td>10487.7</td>
<td>0.023</td>
<td>1.38</td>
</tr>
<tr>
<td>Type 3</td>
<td>101.6 x 10.2 x 12.7</td>
<td>283.49</td>
<td>13109.7</td>
<td>0.022</td>
<td>1.38</td>
</tr>
</tbody>
</table>

4.2.1.2 Fabric samples used in Water Drainage Tests

Fabric samples used in drainage tests were of the same type as used in volumetric flow rate tests. Sample lengths and widths were the same but the thickness (type 1 and type 2 had 4 inches of thickness; type 3 had 5 inches). For each type of fabric, two samples were precut and weighed. Table 5 shows fabric sample weight used in drainage tests.

Table 5 Sample characteristics used in Drainage Tests

<table>
<thead>
<tr>
<th>Weight of sample (grams)</th>
<th>Length (in)</th>
<th>Width (in)</th>
<th>Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.04</td>
<td>1.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5.4</td>
<td>1.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Type 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.68</td>
<td>1.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>10.55</td>
<td>1.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Type 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.82</td>
<td>1.5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>9.66</td>
<td>1.5</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Drainage tests were done using these samples with/without foam materials of having same base area of fabric samples thus covering the bottom surfaces of the fabrics.
4.2.2 Foam Materials

There are two kinds of foam materials utilized in the tests.

- 1/8 inch thick, 90 pores per inch (yellow colored)
- 1/8 inch thick, 20 pores per inch (black colored)

4.3 MEASUREMENT OF VOLUMETRIC FLOW RATE AND EFFICIENCY

4.3.1 Test Apparatus

Most of the testing devices measure absorbency/deabsorbency etc. only for thin nonwoven fabrics and the physical structure of these testing devices do not allow highloft nonwoven fabrics to be tested. Thus, a new testing device is developed and utilized to measure the volumetric flow rate and efficiency of highloft nonwoven fabrics.

The testing device is named “Rain Machine” since its purpose is to simulate rainfall effect on a particular size of roof and gutter.

While designing Rain Machine, IRONCAD 3.02 software was used. By applying this software for design, it was possible to create machine parts and assemble them in a 3D visual screen effectively and in a short period of time.

On the following page, figure 23 illustrates the rain machine designed by IRONCAD 3.02 software.
The Rain machine consists of electrical and mechanical components. These will be individually explained in the following section.

4.3.1.1 Electrical components

The rainfall effect was created by water being pumped from a submersible sump pump manufactured by Sta-Rite (model D 175110T). An extension cable connected to a switch supplied sump pump power that has a power capacity of ¾ hp. Also, pump was put in an open top water tank and pump’s discharge is connected to piping.
4.3.1.2 Mechanical components

The Rain machine has the following mechanical components.

- Support frame
- Chamber
- Piping
- Open top water tank
- Flowmeter
- Guttering
- Flow control valve

The support frame was made from ¾ inch plywood and white pine boards.

The chamber was supported by support frame and made from ¼ inch thick clear acrylic plastic.

The piping was assembled from ½ inch PVC pipes.

The water tank was a 100-gallon galvanized steel open top tank.

The spray nozzles are square pattern full cone spray nozzles rated at 0.85 gal/min@20 psi with a spray angle of 65 degrees.

The flowmeter is called “Acrylic Tube Flowmeter” with a flow range of 0.5-5.0 gpm (gallons per minute).

The guttering is made from commercial grade PVC gutter and fittings and silicone sealant was used to seal the end caps.
The flow control valve is a ½ inch pipe PVC shut off valve with socket glue connections.

After the pump is started, water is recirculated following sequence.

- Sump pump pumps the water to piping.
- By adjusting the valve, the desired flow rate is obtained.
- Following valve, the water passes through the flowmeter and at that point, it is possible to read the flow rate by checking the scale of flowmeter.
- After passing flowmeter, water reaches to a hose of which one end is attached to flowmeter and the other to spray nozzles pipe.
- Water is transferred to spray nozzles and is sprayed to the utilized roof part exactly covering its entire surface since the spray nozzles are full square pattern.
- From the simulated roof, sprayed water flows to utilized gutter and its downpipe.
- From downpipe, water is returned back into open top water tank and completes its circulation.

On the following page, the water flow sequence is illustrated with some digital pictures taken while the Rain Machine is running.
Figure 24 Rain Machine parts- (from left to right) general appearance, submersible pump, flowmeter, and connection hose from flowmeter to spray nozzles
Figure 25 Rain Machine parts- (from left to right) spray nozzles (not running), individual nozzle, spray nozzles (working), and water flowing to the rain gutter from simulated roof
4.3.2 Test Procedure

The measurement of volumetric flow rate and efficiency is done by using the Rain Machine. In these tests, the drying behavior of the fabrics was not tested since it was measured by another device called the Gravimetric Absorbency Testing Device (GATS).

The testing procedure was as follows;

- The Rain Machine is run, however flow control valve was closed, thus water was prevented from flowing.
- The specific precut highloft sample is placed inside the gutter.
- The stainless steel bucket is placed under the downpipe for the collection of water.
- The flow control valve is opened until the desired flow is obtained.
- The flowmeter is read for accuracy.
- As soon as the valve is opened, a stop watch is started and test is continued for 2 minutes. (The reason testing time was limited to 2 minutes was because of the bucket size).
- Water penetrates into the samples and after a short period of time, there happens to be a continuous flow of water through the downpipe.
- The water is collected into the bucket for 2 minutes. Then the machine is stopped immediately and bucket is taken away and weighed on a balance.
- The amount of water inside the bucket can be found by simply subtracting the bucket weight (3.02 kg) from gross weight of the bucket.
- Later on, the data is recorded.
- Each time before repeating the tests, the samples and bucket were dried.
There were 4 trials for each testing. The first trials were followed by 3 additional trials. First trials were done to determine the unsaturated flow behavior of the fabric. After the first 2 minutes, the samples got saturated and the remaining 3 trials were done to determine the saturated behavior of samples after saturation since, most of the time, fabrics are supposed to transfer the rain water in saturated condition.

Testing parameters included different discharge rates of water, different types of highloft fabric, and different types of foam material used underneath these fabrics.

The tests parameters are:

- **Discharge Rate**
  - 4.73 liters/min (1.25 gallons/min)
  - 5.68 liters/min (1.50 gallons/min)
  - 6.625 liters/min (1.75 gallons/min)
  - 7.57-18.93 liters/min (2 to 5 gallons/min) (used to determine the overflow)

- **Type of Highloft Fabric**
  - Type 1 (4 inches thickness, 4 oz/ft²) (1221 g/m²)
  - Type 2 (4 inches thickness, 7.5 oz/ft²) (2289 g/m²)
  - Type 3 (5 inches thickness, 9 oz/ft²) (2746 g/m²)

- **Type of Foam Material**
  - 1/8 inch thick, 90 pores per inch (yellow colored)
  - 1/8 inch thick, 20 pores per inch (black colored)
Overflow rate was measured visually by utilizing the flow rates larger than 6.625 liters/min (1.75 gpm) since there was no overflow for flows lower than 6.625 liters/min. This was not a practical data for real life situations (roofs are always bigger than 0.325 m²) thus, this claim was interpreted by applying it to realistic roof dimensions in the following chapter (results and discussions).

The overflow test conditions had exactly the same test parameters as the volumetric flow rate tests other than discharge rates. Here, discharge rates were between 7.57-18.93 liters/min (2-5 gallons/min) and the tests were done by increasing the flow rate as 0.5 gallons per minute increments.

Also, tests were done without fabrics or foam materials to find out maximum volumetric flow range and efficiency.

Volumetric flow rate is calculated by;

\[
\text{Vol. Flow Rate (liters/min)} = \frac{\text{Volume of water (liters)}}{\text{time (min)}}
\]

and efficiency by;

\[
\text{Efficiency} = \frac{\text{Measured flow rate (liters/min)}}{\text{Theoretical flow rate (liters/min)}} \times 100
\]
4.4 Measurement of Overflow

4.4.1 Test Apparatus

Measurement of overflow is done by using Rain Machine.

4.4.2 Test Procedure

First, Rain Machine was run in the absence of highloft samples and foam materials. The discharge rates differed from 7.57-18.93 liters/min (2-5 gpm) and machine was run for 10 minutes using a stop watch on each of 0.5 gpm increments. No overflow was observed during any of the tests without fabrics or foam materials.

Then, testing procedure above was applied to highloft samples both with the absence and existence of 2 different types of foam materials, and results were recorded. In each scenario, overflow was observed. No bucket was used since at higher discharge rates, the bucket got full before the overflow began. Thus, overflow measurement was done visually without using a bucket. Overflow time was determined to be the time when the first water droplet dropped down from the gutter.

The test results from measurement of overflow are provided in the following chapter.

4.5 Measurement of Water Drainage

4.5.1 Test Apparatus

Measurement of water drainage was conducted simply modifying GATS device. GATS device measures the wicking and/or absorbency/deabsorbency of porous materials. Thus, device can output data of absorption/deabsorption versus time graphics.
GATS consists of a liquid reservoir that is connected to a platform via a plastic tube. Plastic tube is connected to the bottom of the absorbency test plate and delivers the water to the samples. Water reservoir is on top of a balance that is connected to a computer, thus providing test data. The circular piece of fabric is placed on the absorbency test plate and test is initiated.

However, for drainage tests, GATS device had to be modified. For absorbency tests, as the water in the reservoir drops, the value on the balance also drops and this is recorded by the computer as the amount of water absorbed by the material per unit time. This feature of GATS was utilized for drainage testing simply by removing the water reservoir away from the balance, resting a very light rectangular box with a valve, placing the precut fabric samples with/without inside the foam box, filling it with a particular
amount of water and letting it drain by opening the valve thus obtaining drainage versus time graphs.

![Diagram of Modified GATS system with labels for Foam box, Valve, Balance, Hose, and Water collection]

**Figure 27 Modified GATS**

The drainage system had to be very light since maximum capacity of GATS balance is 620 grams. This is the reason why foam material was chosen.

### 4.5.2 Test Procedure

Drainage box was 98 grams and fabric samples’ weights varied between 5-10 grams depending on the areal mass density. Also, foam materials’ weights varied between 1-2 grams. The foam box weighed 105-110 grams when placed on the balance when including fabric samples and foam materials. Considering the maximum balance capacity is 620 grams, 450 milliliters of water was found to be suitable to be put inside
foam box and saturate the samples. After putting 450 milliliters of water inside foam box, each sample saturated for ten minutes, then valve was opened to initiate the tests. After tests were over, data was recorded.
5. RESULTS AND DISCUSSION

5.1 Volumetric Flow Rate and Efficiency

5.1.1 Effect of Discharge Rate

In this chapter, the results of the tests will be discussed by providing both the data obtained from tests and statistical analysis to draw reasonable conclusions.

As mentioned earlier, each test had 4 runs, first observations always being lower than the rest of the 3 observations. The reason for that is samples get saturated in the first place while holding most of the sprayed water inside them and transferring little water within the first 2 minutes. Then, after saturation, water is transferred according to the structural characteristics of the samples without being stored inside the pores, because samples got already saturated within the first 2 minutes. So, the three following observations have higher values, which is reasonable.

Because of this situation, it is necessary to classify the test results as saturated and unsaturated. Also, when we take a look at rainy weather conditions, we see that rain starts slowly and maintains an average fall down for the majority of the time and then stops. This is why tests were done on a continuous manner.

As expected, when the charge rate increases, flow through the highloft nonwoven samples increases as a result of more volume of water is sprayed over the samples per unit time.

For the purpose of comparing results with a control group, Rain Machine was run without any type of samples or foam materials to find out the maximum volumetric flow rate and efficiency. Also, theoretical flow (assuming no loss of water) was considered so
that in case of water loss, it could be calculated. Table 6 illustrates the results obtained by running Rain Machine without any samples or foam materials. Three different discharge rates were used 4.73-liters/min., 5.68-liters/min, and 6.63-liters/min.

Table 6  Control flow without any type of highloft or foam material

<table>
<thead>
<tr>
<th>Water discharge (liters/min)</th>
<th>Amount of water transfer (liters)</th>
<th>Average</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.73</td>
<td>4.11 4.44 4.42 4.48</td>
<td>4.36</td>
<td>0.17</td>
</tr>
<tr>
<td>5.68</td>
<td>5.11 5.29 5.31 5.30</td>
<td>5.25</td>
<td>0.10</td>
</tr>
<tr>
<td>6.63</td>
<td>5.87 6.23 6.37 6.34</td>
<td>6.20</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Also, Table 7 shows the theoretical flow, which assumes no water loss.

Table 7 Theoretical flow

<table>
<thead>
<tr>
<th>Water flow (liters/min)</th>
<th>Amount of water transfer (liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.73</td>
<td>4.73</td>
</tr>
<tr>
<td>5.68</td>
<td>5.68</td>
</tr>
<tr>
<td>6.63</td>
<td>6.63</td>
</tr>
</tbody>
</table>

From the tables above, it can be understood that there is a loss of water in the system. The reason of water loss is that since water comes out of spray nozzles intensely, some of the tiny water particles fly away from the Rain Machine after hitting the simulated roof surface, thus causing not all the sprayed water flow down into gutter.

The amount of water loss is 0.4 liters/min. This data was computed to each testing result obtained and necessary corrections were made while calculating flow rates and efficiencies.
According to results found in table 6 and table 7, table 8 was prepared. Table 8 illustrates the efficiencies of Rain Machine when machine was run empty (without samples or foam materials).

Table 8 Rain Machine Efficiencies without samples or foam materials

<table>
<thead>
<tr>
<th>Water flow (liters/min)</th>
<th>Efficiency (%)</th>
<th>Std error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.73</td>
<td>94.52</td>
<td>0.09</td>
</tr>
<tr>
<td>5.68</td>
<td>93.71</td>
<td>0.05</td>
</tr>
<tr>
<td>6.63</td>
<td>96.27</td>
<td>0.11</td>
</tr>
</tbody>
</table>

As we can see from table 8, Rain Machine works with an efficiency of 96.27% (maximum) and 93.71% (minimum).

5.1.2 Effect of Sample Density

There are three different types of highloft samples used in tests, each having different densities. These samples are 400C400C, 400C750C, and 500C900C having densities of 1221 g/m², 2289 g/m², and 2746 g/m², respectively. No foam material is used in these tests.

While choosing the samples, the structural characteristics were considered to be critical such as density because samples having too low a density would have had too open a structure and would not have acted as a filler for usage in a gutter whereas very dense samples would have obstructed a good flow. Table 9, Table 10 and Table 11 shows the test results of average flow rates (both unsaturated and saturated conditions) for the three different types of samples under three discharge rates.
Table 9 Flow Rate of different samples each having different densities at 4.73 liters/min

<table>
<thead>
<tr>
<th>Water Discharge (liters/min)</th>
<th>Fabric Type</th>
<th>Flow Rate (liters/min) (Unsat)</th>
<th>Flow Rate (liters/min) (Sat)</th>
<th>Std.Err. (Unsat)</th>
<th>Std.Err. (Sat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.73</td>
<td>Type 1</td>
<td>4.10</td>
<td>4.39</td>
<td>0.30</td>
<td>0.06</td>
</tr>
<tr>
<td>4.73</td>
<td>Type 2</td>
<td>4.27</td>
<td>4.42</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>4.73</td>
<td>Type 3</td>
<td>4.20</td>
<td>4.38</td>
<td>0.19</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 10 Flow Rate of different samples each having different densities at 5.68 liters/min

<table>
<thead>
<tr>
<th>Water Discharge (liters/min)</th>
<th>Fabric Type</th>
<th>Flow Rate (liters/min) (Unsat)</th>
<th>Flow Rate (liters/min) (Sat)</th>
<th>Std.Err. (Unsat)</th>
<th>Std.Err. (Sat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.68</td>
<td>Type 1</td>
<td>4.96</td>
<td>5.33</td>
<td>0.37</td>
<td>0.03</td>
</tr>
<tr>
<td>5.68</td>
<td>Type 2</td>
<td>4.85</td>
<td>5.30</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td>5.68</td>
<td>Type 3</td>
<td>4.74</td>
<td>5.28</td>
<td>0.55</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 11 Flow Rate of different samples each having different densities at 6.63 liters/min

<table>
<thead>
<tr>
<th>Water Discharge (liters/min)</th>
<th>Fabric Type</th>
<th>Flow Rate (liters/min) (Unsat)</th>
<th>Flow Rate (liters/min) (Sat)</th>
<th>Std.Err. (Unsat)</th>
<th>Std.Err. (Sat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.63</td>
<td>Type 1</td>
<td>5.61</td>
<td>6.02</td>
<td>0.41</td>
<td>0.02</td>
</tr>
<tr>
<td>6.63</td>
<td>Type 2</td>
<td>5.74</td>
<td>6.21</td>
<td>0.47</td>
<td>0.01</td>
</tr>
<tr>
<td>6.63</td>
<td>Type 3</td>
<td>5.61</td>
<td>6.24</td>
<td>0.63</td>
<td>0.02</td>
</tr>
</tbody>
</table>

In tables 9, 10 and 11; type 1, 2 and 3 indicates 400C400C, 400C750C, and 500C900C, respectively. Normally, it is expected that type 1 sample should give the highest flow rate since it has the more open structure than the other types. When we look at the above tables, this is true for table 9 but not for the others. In table 9, type 2 sample has the best flow rate whereas on table 10 and table 11, the best flow rates are produced by type 1 and type 2 samples, respectively. However, when we take a look at the overall results, it is possible to see that, there is no significant difference among the flow rates of samples (this will statistically be proved in the following section also), which is quiet
interesting. One normally should expect a significant difference in the performance but this is not the case here. The reason for that is because; the flow is limited by the diameter of the downpipe, which is a parameter of flow rate in rain gutter applications.

Figure 28, figure 29 and figure 30 shows the flow rates according to different densities of fabric samples.
Figure 28 Fabric Type vs. Flow Rate at 4.73 liters/min discharge

Figure 29 Fabric Type vs. Flow Rate at 5.68 liters/min discharge
It is possible to see that the samples follow a similar behavior in terms of water transfer from the above figures as well. It is believed that these fabric samples should have different permeabilities and penetration rates with type 1 having the best permeability whereas type 2 and three having similar permabilities and penetration rates. The permeability and penetration rates were not studied in this study since they require sensitive and precise measuring methods and testing devices. Rain machine is not capable of measuring these characteristics.

As mentioned earlier, the samples have similar volumetric flow rates and thus efficiencies. The other approach to explain this situation might be related with the behavior of saturated fabrics under continuous flow. Once fabric pores are saturated with water, assuming samples have very similar or same pore size distribution and mean pore size and turtuosity, this is possible. But again, this is just an approach.

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Flow Rate (liters / min / 0.325 m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>open gutter</td>
<td>3</td>
</tr>
<tr>
<td>type 1</td>
<td>4</td>
</tr>
<tr>
<td>type 2</td>
<td>5</td>
</tr>
<tr>
<td>type 3</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 30 Fabric Type vs. Flow Rate at 6.63 liters/min discharge
While testing the samples in the gutter, gravitational force affects the samples also and pulls down the samples while draining the water into water tank. Thus, it might be very possible that this is another factor affecting and limiting the performance of the fabric samples.

The efficiencies of the samples were also considered. When we take a look at the efficiencies, we see the same trend as volumetric flow rates, which is reasonable. Figure 31, figure 32, and figure 33 illustrate the volumetric flow efficiencies of the samples under three discharge rates.
Figure 31 Vol. Flow Efficiency of Type 1 sample at different discharge rates

Figure 32 Vol. Flow Efficiency of Type 2 sample at different discharge rates
From the figures 31, 32 and 33, type 2 and type 3 samples behave similar to each other. When we look at their characteristics, we see that their numbers of layers are almost the same (type 2 has 45 and type 3 has 44 layers). Their thicknesses are different, type 2 is 4 inches and type 3 is 5 inches. One may expect different flow behavior but since 5 inch sample was not totally inside the gutter, only 4 inches of the fabric was in contact with the flow of water, thus behavior was similar to that of type 2.

On the overall, samples had volumetric flow efficiencies between 90-94% depending on the conditions. The results match with the expected performance of the samples, which are all lower than the Rain Machine Efficiency when no samples or foam materials were used.
5.1.3 Effect of Foam Material Type

There are two different kinds of foam material used in the tests.

- Yellow Foam – 1/8 inch thick, 90 pores per inch
- Black Foam – 1/8 inch thick, 20 pores per inch

Figure 34 shows both yellow and black foams under a highloft sample.

Figure 34 Yellow foam material (left) and Black foam material (right) under a highloft

Foam materials used in tests are very light materials and their density is less than water, thus they float on water. When utilized under a highloft sample inside a gutter system, it is expected that foams apply a push up force to the fabrics and ease the flow of water inside the gutter. Foam materials ease the flow from the fabric to the gutter, because they have highly porous structure. Also, foam materials allow drainage.
According to test results, in some cases, foam materials performed well and increased flow rates compared to tests where only fabric samples were used with no foam. However, this is not true for all cases and for each foam material.

Tables 12 shows the results obtained from all of the tests.

Table 12: Overall Test Data for Vol. Flow Rate

<table>
<thead>
<tr>
<th>Water Discharge</th>
<th>Fabric Type</th>
<th>Flow Rate (liters/min)</th>
<th>Flow Rate (liters/min)</th>
<th>Std.Err.Un</th>
<th>Std.Err.Sat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unsaturated (Unsat)</td>
<td>Saturated (sat)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.73 liters/min</td>
<td>Type 1</td>
<td>4.10</td>
<td>4.39</td>
<td>0.30</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>4.27</td>
<td>4.42</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Type 3</td>
<td>4.20</td>
<td>4.38</td>
<td>0.19</td>
<td>0.02</td>
</tr>
<tr>
<td>5.68 liters/min</td>
<td>Type 1</td>
<td>4.96</td>
<td>5.33</td>
<td>0.37</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>4.85</td>
<td>5.30</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Type 3</td>
<td>4.74</td>
<td>5.28</td>
<td>0.55</td>
<td>0.10</td>
</tr>
<tr>
<td>6.63 liters/min</td>
<td>Type 1</td>
<td>5.61</td>
<td>6.02</td>
<td>0.41</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>5.74</td>
<td>6.21</td>
<td>0.47</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Type 3</td>
<td>5.61</td>
<td>6.24</td>
<td>0.63</td>
<td>0.02</td>
</tr>
</tbody>
</table>

No Foam Material

Yellow foam (90 ppi)

| 4.73 liters/min | Type 1      | 4.02                   | 4.41                   | 0.40       | 0.03       |
|                 | Type 2      | 3.81                   | 4.44                   | 0.63       | 0.01       |
|                 | Type 3      | 3.87                   | 4.45                   | 0.59       | 0.02       |
| 5.68 liters/min | Type 1      | 4.74                   | 5.20                   | 0.46       | 0.02       |
|                 | Type 2      | 4.55                   | 5.27                   | 0.72       | 0.03       |
|                 | Type 3      | 4.77                   | 5.30                   | 0.54       | 0.01       |
| 6.63 liters/min | Type 1      | 5.51                   | 6.11                   | 0.60       | 0.05       |
|                 | Type 2      | 5.58                   | 6.13                   | 0.55       | 0.04       |
|                 | Type 3      | 5.67                   | 6.34                   | 0.68       | 0.01       |

Black foam (20 ppi)

| 4.73 liters/min | Type 1      | 4.22                   | 4.40                   | 0.18       | 0.03       |
|                 | Type 2      | 4.18                   | 4.43                   | 0.25       | 0.02       |
|                 | Type 3      | 4.04                   | 4.44                   | 0.41       | 0.01       |
| 5.68 liters/min | Type 1      | 4.92                   | 5.28                   | 0.36       | 0.01       |
|                 | Type 2      | 4.89                   | 5.28                   | 0.40       | 0.01       |
|                 | Type 3      | 4.86                   | 5.30                   | 0.45       | 0.01       |
| 6.63 liters/min | Type 1      | 5.90                   | 6.32                   | 0.42       | 0.02       |
|                 | Type 2      | 5.77                   | 6.28                   | 0.52       | 0.02       |
|                 | Type 3      | 5.80                   | 6.17                   | 0.37       | 0.03       |
When compared, it can be seen that the first observations (flow rates-unsaturated) in table 12 are smaller than the first observations for all discharge rates in table 9,10 and 11. This means for the first observations, yellow and black foams have smaller volumetric flow rates than the tests where only fabric samples were utilized. The reason for that is related with what happens in the first 2 minutes. Most of the water is captured inside the pores of the fabric, thus saturated the fabric and foam materials did not have enough water flowing under them to apply a push up force to the sample. Thus, foam materials acted like a barrier or another layer added up to the fabric thus decreasing the flow rate during that time.

Interestingly, most of the saturated flow rates for both foam materials in table 12 are larger than no foam data. This is because the fabrics were already saturated and started to transfer the water instead of capturing it. This lead to water accumulation under the foam materials and a push up force was generated by them thus easing the flow of water and increased water flow efficiencies.

Figures on the following pages illustrate the volumetric flow efficiencies of foam materials and also it is possible to see and compare them with the test results where no foam materials used (without foam).
Highloft Type 1
(0.012 g/cm³)

Figure 35 Type 1 (under the presence of different foams) vs. Vol. Flow Efficiency at 4.73 liters/min

Figure 36 Highloft Type 1 (under the presence of different foams) vs. Vol. Flow Efficiency at 5.68 liters/min
Figure 37 Highloft Type 1 (under the presence of different foams) vs. Vol. Flow Efficiency at 6.63 liters/min
Highloft Type 2 (0.023 g/cm³)

Open gutter No foam Yellow (90 ppi) Black (20 ppi)

Volumetric Flow Efficiency (%)

Unsaturated

Saturated

Discharge rate: 4.73 liters / min

Discharge rate: 5.68 liters / min

Figure 38 Highloft Type 2 (under the presence of different foams) vs. Vol. Flow Efficiency at 4.73 liters/min

Figure 39 Highloft Type 2 (under the presence of different foams) vs. Vol. Flow Efficiency at 5.68 liters/min
Figure 40 Highloft Type 2 (under the presence of different foams) vs. Vol. Flow Efficiency at 6.63 liters/min
Highloft Type 3
(0.022 g/cm³)

Figure 41 Highloft Type 3 (under the presence of different foams) vs. Vol. Flow Efficiency at 4.73 liters/min

Highloft Type 3
(0.022 g/cm³)

Figure 42 Highloft Type 3 (under the presence of different foams) vs. Vol. Flow Efficiency at 5.68 liters/min
Figure 43 Highloft Type 3 (under the presence of different foams) vs. Vol. Flow Efficiency at 6.63 liters/min
It is not possible to evaluate the behavior of the foam materials in the figures on the previous pages since in some figures one foam material has better flow rates than the other one whereas the same foam material has worse in the other one. Thus, further analysis is needed and provided in the following section (statistical analysis).

5.2 Overflow Behavior

5.2.1 Discharge Rate

Volumetric flow rate tests were limited by the spray nozzles’ capacity as previously mentioned. Thus, discharge rates were between 4.73-6.63 liters/min for the tests. Even if the flow control valve was opened all the way, the maximum flow through the nozzles was 6.63 liters/min. At these values of discharge rate, no overflow was observed when a fabric sample was utilized with/without a foam material. These values were not reasonable because, the particular roof size (0.325 m²) used in the testing is much more smaller than a real roof size thus, a typical roof will feed much more rainwater into the gutter. Consequently, there was a need to increase the discharge rate to observe overflow. Since spray nozzles were limiting the discharge rate, an attempt was made by simply removing the spray nozzles away from the machine. This was successful in increasing the discharge rates to 17.04 liters/min. Beginning from 7.57 liters/min (2 gallons per minute), discharge rates were increased by 1.89 liters/min (0.5 gallons per minute) intervals up to 17.04 liters/min (4.5 gallons per minute-maximum discharge rate obtained) and data was recorded as soon as overflow began.

Overflow time was considered to be the time as soon as the first water droplet fell down from the top surface of the gutter and was recorded using a stopwatch.
There were three trials for each testing and all of the samples were dried out before each trial. It is necessary to express discharge rates in terms of rainfall intensity. Thus, a generalization can be made easier for real lifetime applications.

For example, for 0.325 m$^2$ roof size, 4.73 liters/min of discharge rate indicates an average of 34.2 inches/hour of rainfall.

\[
4.73 \text{ dm}^3/\text{min} = (0.325 \text{ m}^2) \times r_i = (32.5 \text{ dm}^2) \times r_i
\]

\[
r_i = \left(\frac{4.73}{32.5}\right) \frac{\text{dm}}{\text{min}} = 0.146 \times \frac{\text{dm}}{\text{min}} = 1.46 \frac{\text{cm}}{\text{min}} = 0.57 \frac{\text{in}}{\text{min}} = 34.2 \frac{\text{in}}{\text{hour}}
\]

where $r_i$ indicates the rainfall intensity. The rainfall intensity above is an unrealistic value. However, when we consider a roof size that is 32.5 m$^2$ (one hundred times bigger than the test roof), then, this value makes perfect sense. In this case, if it rains 0.34 in/hour on a 32.5 m$^2$ roof, then this particular roof will feed the same amount of water volume to the gutter. Table 13 shows the related rainfall intensities for test roof and their interpretation for a typical roof size.

**Table 13 Simulated Rainfall Intensity by using different discharge rates**

<table>
<thead>
<tr>
<th>Discharge Rate (liters/min)</th>
<th>Rainfall Intensity Chart (in/hour)</th>
<th>North Carolina Rainfall Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roof size (0.325 m$^2$)</td>
<td>Relative roof size (32.5 m$^2$)</td>
</tr>
<tr>
<td>4.73</td>
<td>34.20</td>
<td>0.34</td>
</tr>
<tr>
<td>5.68</td>
<td>41.07</td>
<td>0.41</td>
</tr>
<tr>
<td>6.63</td>
<td>47.94</td>
<td>0.48</td>
</tr>
<tr>
<td>7.57</td>
<td>54.73</td>
<td>0.55</td>
</tr>
<tr>
<td>9.46</td>
<td>68.40</td>
<td>0.68</td>
</tr>
<tr>
<td>11.36</td>
<td>82.14</td>
<td>0.82</td>
</tr>
<tr>
<td>13.25</td>
<td>95.80</td>
<td>0.96</td>
</tr>
<tr>
<td>15.14</td>
<td>109.47</td>
<td>1.09</td>
</tr>
<tr>
<td>17.04</td>
<td>123.21</td>
<td>1.23</td>
</tr>
</tbody>
</table>
Tables 14, 15 and 16 illustrate the observations obtained after each type of tests. Overflow conditions were tested by using the same samples and foam materials used in volumetric flow rate tests. Table 14 indicates tests that were done only using fabric samples whereas table 15 and 16 indicates the tests with yellow foam and black foam materials in addition to fabric samples, respectively. Here are the results:

Table 14 Overflow conditions (only fabric samples were used)

<table>
<thead>
<tr>
<th>Discharge rate (liters/min)</th>
<th>Overflow Rate (liters/min)</th>
<th>Average Time for Overflow of three types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
</tr>
<tr>
<td></td>
<td>400C400C</td>
<td>400C750C</td>
</tr>
<tr>
<td>7.57-9.46</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>9.46-11.36</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>11.36-13.25</td>
<td>A</td>
<td>O (12.30-12.87)</td>
</tr>
<tr>
<td>15.14-17.04</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Table 15 Overflow conditions (yellow foam material was used)

<table>
<thead>
<tr>
<th>Discharge rate (liters/min)</th>
<th>Overflow Rate (liters/min)</th>
<th>Average Time for Overflow of three types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
</tr>
<tr>
<td></td>
<td>400C400C</td>
<td>400C750C</td>
</tr>
<tr>
<td>7.57-9.46</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>9.46-11.36</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>11.36-13.25</td>
<td>O (12.30)</td>
<td>O (12.30)</td>
</tr>
<tr>
<td>13.25-15.14</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>15.14-17.04</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>
Table 16 Overflow conditions (black foam material was used)

<table>
<thead>
<tr>
<th>FOAM TYPE (BLACK)</th>
<th>Overflow Rate (liters/min)</th>
<th>Average Time for Overflow of three types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
</tr>
<tr>
<td>Discharge rate</td>
<td>400C400C</td>
<td>400C750C</td>
</tr>
<tr>
<td>(liters/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.57-9.46</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>9.46-11.36</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>11.36-13.25</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>15.14-17.04</td>
<td>O (15.14)</td>
<td>O (15.14)</td>
</tr>
</tbody>
</table>

In above tables, the following letters stand for:

- N: None
- A: Almost
- O: Overflow

In above tables, also critical overflow value ranges were given since overflow rates’ average were taken. It is possible for the researcher to claim that black foam had better overflow rates as can be seen from table 15 compared to yellow foam or where only fabric samples were used. Is there any significance, this will be discussed in the following section.

These overflow rates were obtained only for the present testing conditions where 0.325 m² roof, 40 inches of gutter and only one downpipe, which has a smaller radius than most commercial downpipes, were utilized. Thus, a generalization needs to be made to be applicable to a realistic roof size and gutter.

If we consider a roof size of 32.5 m², then it is possible for us to get more reasonable results from tables 14-15-16. For example, for table 14, when type 1 fabric
was used, we had overflow rate of 13.25-13.63 liters/min, for 0.325 m² roof. Thus, for a
32.5 m² roof, this will be 0.96-1.09 in/hour.

5.2.2 Effect of Fabric Density and Foam Material Type

Highloft type 1 is the most porous fabric whereas type 3 is the densest. Normally,
it is expected better results from type 1 fabric compared to other ones. According to test
results, there was not a significant difference in terms of overflow behavior.

Tests where black foam was utilized under the fabric samples had higher overflow
rates than tests with yellow foam. Also, highloft type 1 tends to have better overflow
rates than other types. This will be discussed further in statistical analysis section.

Figures 44, 45 and 46 illustrate overflow comparisons of the samples with/without
foam materials.

---

**Figure 44 Overflow rate vs. type of sample (no foam was used)**

![Overflow Comparison Chart](chart.png)

Overflow when (no foam was used)

- **Type 1**: 13.44 liters/min, 0.97 in/h
- **Type 2**: 12.59 liters/min, 0.91 in/h
- **Type 3**: 12.3 liters/min, 0.89 in/h
Figure 45 Overflow rate vs. type of sample (yellow foam was used)

Figure 46 Overflow rate vs. type of sample (black foam was used)
5.3 Drainage Behavior

Effect of Fabric Density and Foam Material Type

Drainage capacities of the samples were calculated as follows;

\[ \text{Drainage Capacity (grams)} = W_i - W_f \]

where;

\(W_i\): Initial weight of the water inside the drainage box at the beginning of the test
\(W_f\): Final weight of the water inside the drainage box at the beginning of the test

<table>
<thead>
<tr>
<th>Type</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Foam</td>
<td>311.7</td>
<td>160.5</td>
<td>253.3</td>
</tr>
<tr>
<td>Yellow (90 ppi)</td>
<td>294.5</td>
<td>185.2</td>
<td>253.3</td>
</tr>
<tr>
<td>Black (20 ppi)</td>
<td>278.9</td>
<td>185.9</td>
<td>197.6</td>
</tr>
</tbody>
</table>

Type 1 sample had the maximum drainage capacity where no foam was used and type 2 sample had the minimum drainage capacity where no foam was used. This is due to the sample porosity. Type 2 is less porous than sample 1, thus holding more water at the end of test compared to sample 1. For the same volume of type and 2, type 1 has 24 layers whereas type 2 has 44. Thus, type 2 is more packed. In terms of permeability, type 2 is less permeable than type 1. Also, mean pore size of type 2 sample should be lower than type 1. The larger pores would allow more drainage compared to smaller pores. This could be the other reason why type 1
had better drainage. Type 3 has 44 layers but its thickness was 5 inches thus, it was less packed than type 2. This could be the reason why type 3 had the medium drainage capacity. These were summarized in the following figures.

Figure 47 Drainage Capacity (grams) and Specific Drainage Capacity (g/g) of samples with/without foam materials

**Drainage Capacity vs. Type of Fabric/Foam**

<table>
<thead>
<tr>
<th>Type of Fabric</th>
<th>Drainage Capacity (Wi-Wf) (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>(0.012 g/cm³)</td>
</tr>
<tr>
<td>Type 2</td>
<td>(0.022 g/cm³)</td>
</tr>
<tr>
<td>Type 3</td>
<td>(0.023 g/cm³)</td>
</tr>
</tbody>
</table>

**Specific Drainage Capacity (g/g) vs. Type of fabric/foam**

<table>
<thead>
<tr>
<th>Type of Fabric</th>
<th>Specific Drainage Capacity (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>(0.012 g/cm³)</td>
</tr>
<tr>
<td>Type 2</td>
<td>(0.022 g/cm³)</td>
</tr>
<tr>
<td>Type 3</td>
<td>(0.023 g/cm³)</td>
</tr>
</tbody>
</table>
In terms of foam material type effect on drainage, these did not increase the drainage for type 1 sample, whereas both of the foam materials increased it for type 2. For type 3, yellow foam increased the drainage capacity whereas black foam decreased it.

When we take a look at figure 40, yellow foam material’s specific drainage for type 3 and 2 is higher than the ones with no foam for the same categories whereas this is the opposite for type 1 fabric. The effects of foam materials increase as the samples get more packed.

Black foam material only increases the drainage at the densest type of sample, which is type 2. For other types, it did not increase drainage, actually resulted with a decrease in results.

It is also beneficial to look at the drainage times of these scenarios and make conclusions about how they performed in terms of draining time. Figure 48, 49 and 50 summarizes the test results.

**Figure 48 Drainage time for type 1 sample with/without foam materials**
Figure 49 Drainage time for type 2 sample with/without foam materials

Drainage time-type 2

Figure 50 Drainage time for type 3 sample with/without foam materials

Drainage time-type 3
Yellow foam material has the longest drainage time for all of the samples whereas black foam’s drainage time is almost the same as the test results where no foam was used.
5.4 Statistical Analysis

Since volumetric flow rate test results were hard to draw reasonable conclusions, further statistical analysis was needed for this purpose. In some cases, highloft type 1 had the maximum volumetric flow rate whereas in other cases, type 2 and 3 had this. The same comment can be made for foam material behaviors also.

Thus, there was a need to look for whether there was a significant difference among the fabric types or foam materials in terms of volumetric flow rate or not. ANOVA (analysis of variance) model was chosen and applied to test results to determine significance.

Three variables were considered for statistical analysis. These are fabric type, foam material type and discharge rate.

First, ANOVA was applied to test results including the first trials (when saturation of fabrics occurs) and conclusions were made accordingly.

Later on, ANOVA was applied to test results without the first trials (results after fabrics were saturated) where saturation effect was not considered.

For p values to be considered to have statistical difference, they should be smaller than 0.05.

According to first ANOVA results, only discharge rate made a statistical difference (p=0.000) whereas according to second ANOVA results (where saturation effect was not considered) in addition to discharge rate (p=0.000), fabric types also made a statistical difference (p=0.061) at 95% confidence interval. However, practical difference was observed to be very small. Foam materials were observed not to have a statistical difference (p=0.232).
Table 18 illustrates first ANOVA results where saturation effect was considered.

### Table 18 ANOVA TEST RESULTS (saturation effect included)

**FLOW RATE (LITERS/MIN) versus FABRIC TYPE, FOAM, DISCHARGE RATE (LITERS/MIN)**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRIC TYPE</td>
<td>fixed</td>
<td>3</td>
<td>HIGHLOFT TYPE 1</td>
</tr>
<tr>
<td>FOAM</td>
<td>fixed</td>
<td>3</td>
<td>B</td>
</tr>
<tr>
<td>DISCHARGE</td>
<td>fixed</td>
<td>3</td>
<td>4.73</td>
</tr>
</tbody>
</table>

Analysis of Variance for FLOW RATE

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRIC Type</td>
<td>2</td>
<td>0.178</td>
<td>0.089</td>
<td>0.03</td>
<td>0.969</td>
</tr>
<tr>
<td>FOAM</td>
<td>2</td>
<td>4.095</td>
<td>2.047</td>
<td>0.72</td>
<td>0.488</td>
</tr>
<tr>
<td>DISCHARGE</td>
<td>2</td>
<td>187.117</td>
<td>93.558</td>
<td>33.05</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>101</td>
<td>285.895</td>
<td>2.831</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>477.285</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where sum of squares were calculated as:

\[
SS_{Total} = SS_{Fabric} + SS_{Foam} + SS_{Discharge} + \varepsilon + SS_{Saturation}
\]

As can be seen from table 16, only discharge rate’s p value is smaller than 0.05. This means there is no significant difference among fabric types or foam materials.

Table 19 shows second ANOVA results where saturation effect was not considered.
Table 19 ANOVA TEST RESULTS (saturation effect is not included)

FLOW RATE (LITERS/MIN) versus FABRIC TYPE, FOAM, DISCHARGE RATE (LITERS/MIN)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRIC Type</td>
<td>fixed</td>
<td>3</td>
<td>HIGHLOFT TYPE 1</td>
</tr>
<tr>
<td>FOAM</td>
<td>fixed</td>
<td>3</td>
<td>B</td>
</tr>
<tr>
<td>DISCHARGE</td>
<td>fixed</td>
<td>3</td>
<td>4.73</td>
</tr>
</tbody>
</table>

Analysis of Variance for FLOW RATE

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRIC Type</td>
<td>2</td>
<td>0.147</td>
<td>0.073</td>
<td>2.90</td>
<td>0.061</td>
</tr>
<tr>
<td>FOAM</td>
<td>2</td>
<td>0.075</td>
<td>0.038</td>
<td>1.49</td>
<td>0.232</td>
</tr>
<tr>
<td>DISCHARGE</td>
<td>2</td>
<td>171.899</td>
<td>85.949</td>
<td>3396.29</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>74</td>
<td>1.873</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>173.994</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where sum of squares were calculated as:

$$SS_{Total} = SS_{Fabric} + SS_{Foam} + SS_{Discharge} + \epsilon$$

Here, $SS_{Saturation}$ (sum of squares of saturation effect) is not included, thus decreased the SS$_{Total}$ from 477.285 to 173.994 and mean of squares from 2.381 to 0.025 compared to first ANOVA results.

As can be seen from table 18, again, discharge rate’s p value is zero, which is smaller than 0.05, thus having a significant difference. Also, fabric type’s p value is 0.061 (very close to 0.05), which can be considered to have significant difference, almost. Foam materials have a p value of 0.232, which indicates that there is no significant difference among foam materials.
Figure 51 illustrates second ANOVA main effects plot.

It is possible to see the overall results from figure 39 where fabric types were given as type 1, 2 and 3; foam materials were given as B (black foam), N (no foam), and Y (yellow foam).
6. CONCLUSIONS AND RECOMMENDATIONS

Volumetric flow rate, overflow rate and drainage time of highloft nonwoven fabrics have been measured using Rain Machine and G.A.T.S. device. Measured results were used along with ANOVA statistical method to draw conclusions. Variables such as discharge rates, fabric types and foam material types were used as testing parameters. The effects of each of these parameters on volumetric flow rate, overflow rate and drainage time were evaluated.

The volumetric flow rate test results were evaluated according to fabric samples’ saturation situation. For tests including first trials (during saturation of fabrics), only discharge rate had significant effect whereas fabric types and foam materials did not. For tests excluding first trials (after saturation of fabrics), fabric types had significant effect in addition to discharge rate whereas foam materials did not. However, practical difference among fabric types is very small.

The overflow rate test results showed that, as expected, discharge rate had significant effect. No overflow was observed for discharge rates ranging from 9.46-13.25 liters/2min. When no foam material was used, type 1 fabric had the highest overflow rate whereas type 2 and 3 had similar behaviors. The overflow rates were all the same when yellow foam was used. However, when black foam was used, all of the fabrics’ overflow rates increased up resulting with better performance for overflow. This is due to black foams structural characteristics (such as being more porous compared to yellow foam).

The drainage capacity test results showed that type 1 fabric had the highest drainage capacity whereas type 2 had the lowest. This was due to the different porosities of the samples. Type 1 was much more porous than type 2. Type 3 fabric had same
number of layers as type 2, but since it was 5 inches thick, its porosity was more than type 2.

Drainage capacity test results showed that yellow foam material’s capacity for type 2 and 3 was higher than the ones with no foam for the same categories whereas this was the opposite for type 1 fabric.

Black foam material only increased the drainage at the densest type of sample, which was type 2. For other types, it did not increase drainage, actually resulted with a decrease in results

On the overall, it is believed that using samples with LOWER DENSITY and THICKER fibers (higher deniers) will increase the chance of potential usage of highloft nonwovens in rain gutter applications. Lower density provides more openness (more porosity) whereas thicker fibers are necessary to keep the samples durable and stronger.
Recommendations for Future Work

1. The study can be extended to different types of highlofts with a wide variety of densities and thicknesses.

2. More variety of foam materials with different pore sizes and thicknesses can be used and evaluated in future work.

3. More precise flowmeter (a digital flowmeter) within the same flow reading range can be installed for more accurate testing results.

4. Spray nozzles with higher capacity might be installed to Rain Machine.

5. Rain Machine can be equipped with an electronic weigh balance with an interface to a computer for obtaining better testing results.

6. Effects of cold weather, mold and mildew, ultraviolet light, pollen, pine needles etc on the fabrics can be searched.

7. The study of various samples with different fiber orientation, porosity, permeability, number of layers etc. is recommended.

8. In time, fabrics might loose their loft. Effects of compression on structural properties of fabrics on flow rate and drainage can be searched.

9. Different alternatives of highlofts can be utilized instead of highloft fabrics (for ex. Thick and porous foam materials)

10. The chamber of Rain Machine can be a more closed system to minimize water loss.

11. Another flow control valve can be installed on Rain Machine (on downpipe) to make drainage tests also (thus no need to use other testing devices).
REFERENCES

10. Carman, P.C., Soil Science, 52, 1, (1941)
13. Emersleben, O., Phys. Z. 26, 601 (1925)
16. Afifty, E., Mohamed, H., Efficient Use of Fibrous Structures in Filtration, Environmental Protection Technology Series, EPA-600/2-76-204 (1940)
31. National Oceanic and Atmospheric Administration, 1994-1995: Strom Data. 36-37; No 1-12, National Climatic Data Center, Asheville, NC
32. Hart, J. A., SVR PLOT version 1.00: SELS Severe Weather Archive Display Program, NSSFC, December, 1992
33. Flood Events Report in Wake County, State Climate Office of North Carolina at NC State University
35. Baigas, J., High Loft Nonwovens, Nonwoven Fabrics Forum, Clemson University, August 14-17, 1995
38. Wagner, J. R., Nonwoven Fabrics, p. 12, 1982


APPENDIX I

Conversion Factors

\[
1 \frac{oz}{ft^2} = 28.349523 \, \frac{g}{m^2} = 305.15 \, \frac{g}{m^2}
\]

1 inch = 2.54 cm

\[
1 \frac{gallons}{minute} = 3.785 \, \frac{liters}{min}
\]
APPENDIX II

VOLUMETRIC FLOW RATE GRAPHS
Discharge rate: 9.46 liters / 2min

Flow Rate (liters / 2min / 0.325 m²)

Discharge rate: 11.36 liters / 2min
Highloft Type 1

Flow Rate (liters / 2min / 0.326 m²)

- Without foam
- Yellow foam
- Black foam

Discharge rate: 13.25 liters / 2min

Unsaturated
Saturated
Highloft Type 2

<table>
<thead>
<tr>
<th></th>
<th>Without foam</th>
<th>Yellow foam</th>
<th>Black foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (liters / 2 min / 0.325 m²)</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Unsaturated Discharge rate</td>
<td>9.46 liters / 2 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Without foam</th>
<th>Yellow foam</th>
<th>Black foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (liters / 2 min / 0.325 m²)</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Unsaturated Discharge rate</td>
<td>11.36 liters / 2 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Highloft Type 2

Discharge rate: 13.25 liters / 2min

- Without foam
- Yellow foam
- Black foam

Flow Rate (liters / 2min / 0.325 m²)

- Unsaturated
- Saturated

Highloft Type 2
Highloft Type 3

Without foam | Yellow foam | Black foam
---|---|---
Flow Rate (liters / 2min / 0.325 m²)
6
7
8
9
10

Discharge rate : 9.46 liters / 2min

Unsaturated
Saturated

Discharge rate : 11.36 liters / 2min

Unsaturated
Saturated
Discharge rate: 13.25 liters / 2min

Flow Rate (liters / 2min / 0.325 m²)

- Without foam
- Yellow foam
- Black foam

Highloft Type 3
<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Flow Rate (liters / 2min / 0.325 m²)</th>
<th>Unsaturated</th>
<th>Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type 2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type 3</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discharge rate: 9.46 liters / 2min
Black foam used

Discharge rate: 11.36 liters / 2min
Black foam used
<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Flow Rate (liters / 2min / 0.325 m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>type 1</td>
<td>10</td>
</tr>
<tr>
<td>type 2</td>
<td>11</td>
</tr>
<tr>
<td>type 3</td>
<td>12</td>
</tr>
</tbody>
</table>

Discharge rate: 13.25 liters / 2min
Black foam used
## Fabric Type

<table>
<thead>
<tr>
<th>Flow Rate (liters / 2min / 0.325 m²)</th>
<th>Fabric Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>type 1</td>
</tr>
<tr>
<td>8</td>
<td>type 2</td>
</tr>
<tr>
<td>9</td>
<td>type 3</td>
</tr>
</tbody>
</table>

**Discharge rate**: 9.46 liters / 2min

No foam used

<table>
<thead>
<tr>
<th>Flow Rate (liters / 2min / 0.325 m²)</th>
<th>Fabric Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>type 1</td>
</tr>
<tr>
<td>9</td>
<td>type 2</td>
</tr>
<tr>
<td>10</td>
<td>type 3</td>
</tr>
<tr>
<td>11</td>
<td>type 1</td>
</tr>
<tr>
<td>12</td>
<td>type 2</td>
</tr>
</tbody>
</table>

**Discharge rate**: 11.36 liters / 2min

No foam used
Fabric Type

<table>
<thead>
<tr>
<th></th>
<th>type 1</th>
<th>type 2</th>
<th>type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (liters / 2min / 0.325 m²)</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

Discharge rate: 13.25 liters / 2min
No foam used

Unsaturated
Saturated

Fabric Type

Flow Rate (liters / 2min / 0.325 m²)
<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (liters / 2min / 0.325 m²)</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Unsaturated</td>
<td>●</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Saturated</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Discharge rate: 9.46 liters / 2min
Yellow foam used

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (liters / 2min / 0.325 m²)</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Unsaturated</td>
<td>●</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Saturated</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Discharge rate: 11.36 liters / 2min
Yellow foam used
Discharge rate: 13.25 liters / 2min
Yellow foam used

![Graph showing flow rates for different fabric types.](image-url)
APPENDIX III

VOLUMETRIC FLOW EFFICIENCY GRAPHS
Highloft Type 1

Volumetric Flow Efficiency (%)

70 75 80 85 90 95 100

Unsaturated
Saturated

Discharge rate: 9.46 liters / 2min

Without foam  Yellow foam  Black foam

Highloft Type 1

Discharge rate: 11.36 liters / 2min

Without foam  Yellow foam  Black foam

Highloft Type 1
Highloft Type 1

Without foam  Yellow foam  Black foam

Volumetric Flow Efficiency (%)

70  75  80  85  90  95  100

Unsaturated
Saturated

Discharge rate: 13.25 liters / 2min

Highloft Type 1

70  75  80  85  90  95  100

Without foam  Yellow foam  Black foam
Highloft Type 2

Discharge rate: 9.46 liters / 2min
Discharge rate: 11.36 liters / 2min

Volumetric Flow Efficiency (%)

- Unsaturated
- Saturated

Without foam | Yellow foam | Black foam

Discharge rate: 9.46 liters / 2min
Discharge rate: 11.36 liters / 2min
Highloft Type 2

Volumetric Flow Efficiency (%)

Discharge rate: 13.25 liters / 2min

- Unsaturated
- Saturated

Without foam  Yellow foam  Black foam

Highloft Type 2
Highloft Type 3

Volumetric Flow Efficiency (%)

Discharge rate: 9.46 liters / 2min

- Unsaturated
- Saturated

Discharge rate: 11.36 liters / 2min

- Unsaturated
- Saturated

Without foam | Yellow foam | Black foam
---|---|---
Volumetric Flow Efficiency (%)
65
70
75
80
85
90
95
100
Highloft Type 3

Without foam Yellow foam Black foam

Discharge rate: 13.25 liters / 2min

Volumetric Flow Efficiency (%)

- Unsaturated
- Saturated

Discharge rate: 13.25 liters / 2min
Discharge Rate (liters/2 min)
9.46 11.36 13.25

Volumetric Flow Efficiency (%)
75 80 85 90 95 100

Black foam used

- Unsaturated
- Saturated

Unsaturated and Saturated points are marked on the graph.
Discharge Rate (liters/2 min)

<table>
<thead>
<tr>
<th></th>
<th>9.46</th>
<th>11.36</th>
<th>13.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>No foam used</td>
<td>70</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Unsaturated</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Saturated</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Volumetric Flow Efficiency (%)
Discharge Rate (liters/2 min)

<table>
<thead>
<tr>
<th></th>
<th>9.46</th>
<th>11.36</th>
<th>13.25</th>
</tr>
</thead>
</table>
| Volumetric Flow Efficiency (%)  
| Unsaturated | 65   | 80    | 90    |
| Saturated   | 70   | 85    | 95    |

Yellow foam used

Discharge Rate (liters/2 min)
Discharge Rate (liters/2 min)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.46</td>
<td>11.36</td>
</tr>
<tr>
<td></td>
<td>13.25</td>
<td></td>
</tr>
</tbody>
</table>

Volumetric Flow Efficiency (%)

- 65
- 70
- 75
- 80
- 85
- 90
- 95
- 100

Yellow foam used

- Unsaturated
- Saturated

Unsaturated

Saturated
APPENDIX IV

ANOVA TEST RESULTS
ANOVA: FLOW RATE versus FABRIC TYPE, FOAM, FLOW

Factor | Type | Levels | Values
---|---|---|---
FABRIC | fixed | 3 | HIGHLOFT TYPE 1 HIGHLOFT TYPE 2 HIGHLOFT TYPE 3
FOAM | fixed | 3 | B N Y
FLOW (GPM) | fixed | 3 | 1.25 1.50 1.75

Analysis of Variance for FLOW RATE

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FABRIC</td>
<td>2</td>
<td>0.178</td>
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<td>4.095</td>
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<td>0.488</td>
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<tr>
<td>FLOW (GPM)</td>
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<td>187.117</td>
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<td>Total</td>
<td>107</td>
<td>477.285</td>
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</tbody>
</table>

Only Discharge Rate makes a Statistical Difference.

One-way ANOVA: FLOW RATE versus FOAM

Analysis of Variance for FLOW RATE

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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<tbody>
<tr>
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<td>4.09</td>
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<td>0.636</td>
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<tr>
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<td>473.19</td>
<td>4.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>477.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Individual 95% CIs For Mean
Based on Pooled StDev

| Level | N  | Mean | StDev |----------+---------+---------+---------+---------|
|-------|----|------|-------|---------+---------+---------+---------+---------|
| B     | 36 | 9.897| 1.938 | (----------*----------)
| N     | 36 | 9.791| 1.910 | (----------*----------)
| Y     | 36 | 9.441| 2.473 | (----------*----------)

Pooled StDev = 2.123

9.00 9.60 10.20 10.80

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0193
Critical value = 3.36

Intervals for (column level mean) - (row level mean)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>-1.082</td>
<td>1.295</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.733</td>
<td>-0.839</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.645</td>
<td>1.538</td>
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</tr>
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</table>
One-way ANOVA: FLOW RATE versus FOAM

Analysis of Variance for FLOW RATE

<table>
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<th>MS</th>
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<th>P</th>
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</thead>
<tbody>
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<td>2</td>
<td>4.09</td>
<td>2.05</td>
<td>0.45</td>
<td>0.636</td>
</tr>
<tr>
<td>Error</td>
<td>105</td>
<td>473.19</td>
<td>4.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>477.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Individual 95% CIs For Mean Based on Pooled StDev

| Level | N  | Mean | StDev | -----+---------+---------+---------+--|
|-------|----|------|-------|------|---------+---------+---------+--|
| B     | 36 | 9.897| 1.938 | (-----------*-----------) |
| N     | 36 | 9.791| 1.910 | (-----------*-----------) |
| Y     | 36 | 9.441| 2.473 | (-----------*-----------) |

Pooled StDev = 2.123

9.00  9.60  10.20  10.80

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0193

Critical value = 3.36

Intervals for (column level mean) - (row level mean)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>-1.082</td>
<td>1.295</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>-0.733</td>
<td>-0.839</td>
<td>1.645</td>
</tr>
</tbody>
</table>

Boxplots of FLOW RATE by FOAM

(means are indicated by solid circles)
Dotplots of FLOWRATE by FOAM

(group means are indicated by lines)
### One-way ANOVA: FLOW RATE versus FLOW

Analysis of Variance for FLOW RATE

<table>
<thead>
<tr>
<th>Source</th>
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<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW (GP)</td>
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<td>33.85</td>
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<td>477.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>Individual 95% CIs For Mean Based on Pooled StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>36</td>
<td>8.151</td>
<td>1.365</td>
<td>(----*---)</td>
</tr>
<tr>
<td>1.50</td>
<td>36</td>
<td>9.609</td>
<td>1.727</td>
<td>(----*----)</td>
</tr>
<tr>
<td>1.75</td>
<td>36</td>
<td>11.370</td>
<td>1.856</td>
<td>(----*---)</td>
</tr>
</tbody>
</table>

Pooled StDev = 1.662

| 8.4 | 9.6 | 10.8 |

Tukey's pairwise comparisons

- Family error rate = 0.0500
- Individual error rate = 0.0193
- Critical value = 3.36

Intervals for (column level mean) - (row level mean)

<table>
<thead>
<tr>
<th>Level</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>-2.389</td>
<td>-0.527</td>
</tr>
<tr>
<td>1.75</td>
<td>-4.150</td>
<td>-2.692</td>
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<tr>
<td></td>
<td>-2.289</td>
<td>-0.830</td>
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</tbody>
</table>
Descriptive Statistics: FLOW RATE by FLOW

<table>
<thead>
<tr>
<th>Variable</th>
<th>FLOW (GPM)</th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>TrMean</th>
<th>StDev</th>
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</thead>
<tbody>
<tr>
<td>FLOW RATE</td>
<td>1.25</td>
<td>36</td>
<td>8.151</td>
<td>8.820</td>
<td>8.357</td>
<td>1.365</td>
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<tr>
<td></td>
<td>1.50</td>
<td>36</td>
<td>9.609</td>
<td>10.540</td>
<td>9.791</td>
<td>1.727</td>
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<tr>
<td></td>
<td>1.75</td>
<td>36</td>
<td>11.370</td>
<td>12.380</td>
<td>11.538</td>
<td>1.856</td>
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</tbody>
</table>

Variable FLOW (GPM) SE Mean Minimum Maximum Q1 Q3
FLOW RATE 1.25 0.227 3.880 8.960 7.865 8.880
1.50 0.288 4.780 10.840 8.300 10.615
1.75 0.309 7.280 12.700 10.030 12.522

Executing from file: C:\Program Files\MTBWIN\MACROS\Describe.MAC

Descriptive Statistics Graph: FLOW RATE by FLOW

Descriptive Statistics Graph: FLOW RATE by FLOW

Descriptive Statistics Graph: FLOW RATE by FLOW

Descriptive Statistics

Variable: FLOW RATE (L)
FLOW (GPM): 1.75

Anderson-Darling Normality Test
A-Squared: 5.506
P-Value: 0.000

Mean 11.3700
StDev 1.8558
Variance 3.44382
Skewness -1.31828
Kurtosis 1.24E-02
N 36

Minimum 7.2800
1st Quartile 10.0300
Median 12.3800
3rd Quartile 12.5225
Maximum 12.7000

95% Confidence Interval for Mu
10.7421 11.9979
95% Confidence Interval for Sigma
1.5052 2.4207
95% Confidence Interval for Median
12.0641 12.4306

95% Confidence Interval for Mu
95% Confidence Interval for Median
### Descriptive Statistics

**Variable: FLOW RATE (L)**

**FLOW (GPM): 1.50**

Anderson-Darling Normality Test

- A-Squared: 5.922
- P-Value: 0.000

- Mean: 9.60889
- StdDev: 1.72739
- Variance: 2.98367
- Skewness: -1.44065
- Kurtosis: 0.625818
- N: 36

- Minimum: 4.7800
- 1st Quartile: 8.3000
- Median: 10.5400
- 3rd Quartile: 10.6150
- Maximum: 10.8400

95% Confidence Interval for Mu:
- Lower: 9.0244
- Upper: 10.3841

95% Confidence Interval for Sigma:
- Lower: 8.3000
- Upper: 10.5800

95% Confidence Interval for Median:
- Lower: 8.8244
- Upper: 10.3841

### Descriptive Statistics

**Variable: FLOW RATE (L)**

**FLOW (GPM): 1.25**

Anderson-Darling Normality Test

- A-Squared: 5.935
- P-Value: 0.000

- Mean: 8.15056
- StdDev: 1.36485
- Variance: 1.86283
- Skewness: -2.02541
- Kurtosis: 3.30029
- N: 36

- Minimum: 3.88000
- 1st Quartile: 7.86500
- Median: 8.82000
- 3rd Quartile: 8.88000
- Maximum: 9.96000

95% Confidence Interval for Mu:
- Lower: 7.68876
- Upper: 8.61236

95% Confidence Interval for Sigma:
- Lower: 1.10701
- Upper: 1.78037

95% Confidence Interval for Median:
- Lower: 8.71471
- Upper: 8.84529
One-way ANOVA: FLOW RATE versus FABRIC TYPE

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>Fabric</td>
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<td>0.18</td>
<td>0.09</td>
<td>0.02</td>
<td>0.981</td>
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<tr>
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<td>105</td>
<td>477.11</td>
<td>4.54</td>
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<td></td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>477.29</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHLOFT</td>
<td>36</td>
<td>9.766</td>
<td>1.930</td>
<td>-1.119</td>
<td>1.268</td>
<td>-1.099</td>
<td>1.214</td>
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<tr>
<td>HIGHLOFT</td>
<td>36</td>
<td>9.692</td>
<td>2.194</td>
<td>-1.099</td>
<td>1.214</td>
<td>-1.079</td>
<td>1.288</td>
</tr>
<tr>
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<td>36</td>
<td>9.672</td>
<td>2.257</td>
<td>-1.079</td>
<td>1.288</td>
<td>-1.060</td>
<td>1.314</td>
</tr>
</tbody>
</table>

Pooled StDev = 2.132

Tukey’s pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.0193

Critical value = 3.36

Intervals for (column level mean) - (row level mean)

<table>
<thead>
<tr>
<th></th>
<th>HIGHLOFT</th>
<th>HIGHLOFT</th>
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<tbody>
<tr>
<td>HIGHLOFT</td>
<td>-1.119</td>
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<tr>
<td>HIGHLOFT</td>
<td>-1.099</td>
<td>-1.174</td>
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<tr>
<td></td>
<td>1.288</td>
<td>1.214</td>
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</tbody>
</table>
Boxplots of FLOW RATE by FABRIC TYPE
(means are indicated by solid circles)

Dotplots of FLOW RATE by FABRIC TYPE
(group means are indicated by lines)
Results for: Worksheet 5

**Paired T-Test and CI: FLOW RATE _1, FLOW RATE _2**

Paired T for FLOW RATE (LITER)_1 - FLOW RATE (LITER)_2

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW RATE</td>
<td>27</td>
<td>7.054</td>
<td>1.377</td>
<td>0.265</td>
</tr>
<tr>
<td>FLOW RATE</td>
<td>27</td>
<td>10.531</td>
<td>1.488</td>
<td>0.286</td>
</tr>
<tr>
<td>Difference</td>
<td>27</td>
<td>-3.478</td>
<td>1.203</td>
<td>0.232</td>
</tr>
</tbody>
</table>

95% CI for mean difference: (-3.954, -3.002)

T-Test of mean difference = 0 (vs not = 0): T-Value = -15.02  P-Value = 0.000

Boxplot of Differences
(with Ho and 95% t-confidence interval for the mean)
Dotplot of Differences
(with Ho and 95% t-confidence interval for the mean)

Boxplot FLOW RATE (LITERS/2MIN)) * Sub Sample
Two-Sample T-Test and CI: FLOW RATE_1, FLOW RATE_2

Two-sample T for FLOW RATE (LITER)_1 vs FLOW RATE (LITER)_2

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW RATE</td>
<td>27</td>
<td>7.05</td>
<td>1.38</td>
<td>0.27</td>
</tr>
<tr>
<td>FLOW RATE</td>
<td>27</td>
<td>10.53</td>
<td>1.49</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Difference = mu FLOW RATE (LITER)_1 - mu FLOW RATE (LITER)_2
Estimate for difference: -3.478
95% CI for difference: (-4.261, -2.694)
T-Test of difference = 0 (vs not =): T-Value = -8.91  P-Value = 0.000  DF = 51

Boxplots of FLOW RATE and FLOWRATE
(means are indicated by solid circles)
REVISED DATA without OBSERVATION 1

ANOVA: FLOW RATE versus FABRIC TYPE, FOAM, FLOW

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
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<tbody>
<tr>
<td>FABRIC</td>
<td>fixed</td>
<td>3</td>
<td>HIGHLOFT TYPE 1, HIGHLOFT TYPE 2, HIGHLOFT TYPE 3</td>
</tr>
<tr>
<td>FOAM</td>
<td>fixed</td>
<td>3</td>
<td>B, N, Y</td>
</tr>
<tr>
<td>FLOW</td>
<td>fixed</td>
<td>3</td>
<td>1.25, 1.50, 1.75</td>
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</tbody>
</table>

Analysis of Variance for FLOW RATE

<table>
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<tr>
<th>Source</th>
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<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
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<tr>
<td>FABRIC</td>
<td>2</td>
<td>0.147</td>
<td>0.073</td>
<td>2.90</td>
<td>0.061</td>
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<tr>
<td>FOAM</td>
<td>2</td>
<td>0.075</td>
<td>0.038</td>
<td>1.49</td>
<td>0.232</td>
</tr>
<tr>
<td>FLOW</td>
<td>2</td>
<td>171.899</td>
<td>85.949</td>
<td>3396.29</td>
<td>0.000</td>
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<tr>
<td>Error</td>
<td>74</td>
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<td>Total</td>
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</table>

Main Effects Plot - Data Means for FLOW RATE (liters/2min)
Descriptive Statistics: FLOW RATE by FABRIC TYPE

<table>
<thead>
<tr>
<th>Variable</th>
<th>FABRIC T</th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>TrMean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW RATE</td>
<td>HIGHLOFT</td>
<td>27</td>
<td>10.539</td>
<td>10.540</td>
<td>10.532</td>
<td>1.467</td>
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<td>10.606</td>
<td>10.580</td>
<td>10.599</td>
<td>1.484</td>
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<tr>
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<td></td>
<td></td>
<td>10.641</td>
<td>10.600</td>
<td>10.636</td>
<td>1.527</td>
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<table>
<thead>
<tr>
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<th>FABRIC T</th>
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<th>Minimum</th>
<th>Maximum</th>
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<th>Q3</th>
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<td>0.294</td>
<td>8.720</td>
<td>12.680</td>
<td>8.900</td>
<td>12.420</td>
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</table>

Descriptive Statistics Graph: FLOW RATE by FABRIC TYPE

Descriptive Statistics Graph: FLOW RATE by FABRIC TYPE

Descriptive Statistics Graph: FLOW RATE by FABRIC TYPE

Descriptive Statistics

Variable: FLOW RATE (L)
FABRIC TYPE: HIGHLOFT TYPE 3

Anderson-Darling Normality Test
A-Squared: 1.506
P-Value: 0.001

Mean: 10.6411
StDev: 1.5273
Variance: 2.33263
Skewness: 7.04E-02
Kurtosis: -1.54773
N: 27
Minimum: 8.7200
1st Quartile: 8.9000
Median: 10.6000
3rd Quartile: 12.4200
Maximum: 12.6800

95% Confidence Interval for Mu
10.0369 - 11.2453

95% Confidence Interval for Sigma
1.2028 - 2.0931

95% Confidence Interval for Median
8.9582 - 12.2053
Descriptive Statistics

Variable: FLOW RATE (L)
FABRIC TYPE: HIGHLOFT TYPE 2

Anderson-Darling Normality Test
A-Squared: 1.562
P-Value: 0.000

Mean 10.6059
StDev 1.4840
Variance 2.20225
Skewness 6.35E-02
Kurtosis -1.54126
N 27

Minimum 8.7800
1st Quartile 8.8800
Median 10.5800
3rd Quartile 12.3800
Maximum 12.6000

95% Confidence Interval for Mu
10.0189 11.1930

95% Confidence Interval for Sigma
1.1687 2.0337

95% Confidence Interval for Median
8.9388 12.1327

Descriptive Statistics

Variable: FLOW RATE (L)
FABRIC TYPE: HIGHLOFT TYPE 1

Anderson-Darling Normality Test
A-Squared: 1.183
P-Value: 0.004

Mean 10.5385
StDev 1.4668
Variance 2.15154
Skewness 4.33E-02
Kurtosis -1.45951
N 27

Minimum 8.5400
1st Quartile 8.8800
Median 10.5400
3rd Quartile 12.0200
Maximum 12.7000

95% Confidence Interval for Mu
9.9583 11.1188

95% Confidence Interval for Sigma
1.1551 2.0102

95% Confidence Interval for Median
8.9582 11.9800