EVALUATION OF EROSION AND SEDIMENT CONTROL BEST MANAGEMENT PRACTICES: USE OF SILT FENCE TIEBACK SYSTEMS AND ANIONIC POLYACRYLAMIDE ON HIGHWAY CONSTRUCTION SITES

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Justin Scott McDonald

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Date of Graduation

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Justin Scott McDonald, son of Ronald J. McDonald and Debra B. Bradshaw, was born on October 25, 1982, in Mobile, AL. He graduated high school from Mobile Christian School in Mobile, AL in 2000. After graduating, he attended Auburn University in Auburn, AL and graduated with a Bachelor of Civil Engineering degree in December of 2005. In January 2006, he entered the Graduate School at Auburn University to pursue a Master of Science in Civil Engineering. He was married to Kimberly R. Price on June 3, 2006.

THESIS ABSTRACT

EVALUATION OF EROSION AND SEDIMENT CONTROL BEST MANAGEMENT PRACTICES: USE OF SILT FENCE TIEBACK SYSTEMS AND ANIONIC POLYACRYLAMIDE ON HIGHWAY CONSTRUCTION SITES

Justin Scott McDonald

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Every year the construction process exposes millions of acres of earth to the elements of wind, rain, and snow. This greatly increases the potential for erosion; therefore, the need for efficient erosion and sediment control practices is a high priority. In this research, silt fence tieback (a.k.a. "j-hook") systems and anionic polyacrylamide (PAM) were investigated to determine their effectiveness as erosion and sediment control technologies. In the first phase of this research effort, a computational design procedure used to determine the storage capacity of silt fence tieback systems was outlined and a Visual Basic (VBA) coded spreadsheet design tool was developed to assist practitioners in the proper design of silt fence tieback systems. This tool was then used to design a silt fence tieback system on an Alabama Department of Transportation (ALDOT) job site and

the performance was monitored over multiple rainfall events. The results from this phase of the study show that the silt fence tiebacks were very effective at containing transported sediment from their contributing drainage areas and preventing erosion from occurring along the toe of the fence.

In the second phase of the research effort, intermediate-scale experiments were performed to determine the effectiveness of dry granular anionic polyacrylamide (PAM) as an erosion control BMP. Three experimental scenarios were evaluated which included a bare untreated soil (control experiment) and PAM treated soil at application rates of 20 and 40 lb/ac. We also investigated whether PAM, when used as an erosion control BMP, provided sediment control benefits by decreasing the settling time of suspended solids in the surface runoff. The results from this phase of the research show that PAM applied at 40 lb/ac effectively reduced erosion and the settling time of suspended solids in the surface runoff. PAM applied at 20 lb/ac, on the other hand, provided little erosion control benefits but did reduce the settling time of suspended solids in most instances.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Nonpoint source pollution is a very important environmental issue facing our society today. Nonpoint source pollution can be defined as pollution that comes from a diffuse source and is driven by rainfall or snowmelt moving over or through the land. Some sources of nonpoint source pollution include sediment from improperly managed construction sites, oil, grease, and toxic chemicals from urban runoff, bacteria and nutrients from livestock, and faulty septic systems. In many U.S. states, nonpoint source pollution is the leading cause of water quality problems which affect drinking water, recreation, fisheries, and wildlife (U.S. EPA, 1994).

One of the most widely recognized causes of nonpoint source pollution is the sediment load discharged from poorly managed construction sites. The construction process exposes bare earth to the elements of wind, rain, and snow which greatly increase the potential for erosion. If proper nonpoint source pollution abatement methods are not followed, eroded material from construction sites can end up in streams and other water bodies. It is estimated that in the U.S. alone, over 80 million tons of sediment are washed from construction sites into surface water bodies each year (Novotny, 2003). This

process can be devastating to the chemical, physical, and biological integrity of streams, rivers, lakes, and estuaries. Some of the environmental effects of erosion and sedimentation include loss of storage capacity of reservoirs, deterioration of fish spawning areas and habitat for other stream organisms, and increased nutrient loadings within streams (Novotny, 2003). With increasing growth and development throughout the world, the need to develop better methods for preventing erosion and controlling sediment on construction sites is a high priority.

1.2 THE EROSION PROCESS

In order to establish a good understanding of the role that erosion plays in nonpoint source pollution, the basics of the erosion process will be outlined in this section. The erosion process can be defined as the wearing down the earth's surface by the elements of wind, rain, and snow where sediment is detached, transported, and deposited downslope. This is a natural process but is often increased due to the high rate of construction occurring around the world. Factors influencing erosion include climate, topography, soil type, and vegetative cover (Alabama Soil and Water Conservation Committee, 2003a). Therefore, when construction processes expose bare earth by eliminating vegetative cover, soils become much more vulnerable to erosion than in their natural state. The erosion process is then greatly accelerated when a rainfall event occurs. According to the Alabama Soil and Water Conservation Committee, "erosion accelerated by the disturbances of humans, through agricultural and non-agricultural uses of the land, has caused several inches of erosion over the last 100 to 150 years, a comparatively short period" (Alabama Soil and Water Conservation Committee, 2003a).

Though wind and snow induced erosion is an important consideration, water-related erosion from rainfall events is the largest problem in developing areas of Alabama (Alabama Soil and Water Conservation Committee, 2003a). During a rainfall event, erosion is caused by the detachment of soil particles due to the impact of rain droplets and the shear stress of surface runoff. Once the sediment is detached, it is transported downslope by overland flow and deposited into downstream water bodies. This sediment, which will eventually settle out of suspension as the velocity of the water decreases, greatly impairs the natural aquatic habitat of the receiving water bodies. Therefore, the need for good erosion and sediment control alternatives is critical for maintaining the health of the aquatic environment.

1.3 BEST MANAGEMENT PRACTICES (BMPs)

Several types of best management practices (BMPs) are currently being used to minimize environmental damages caused by eroded sediment from construction sites. These BMPs include structural and nonstructural measures and can be classified by two basic categories. The first category of BMPs is used for surface stabilization to prevent the erosion process from occurring and the second category is used for sediment control to minimize the eroded sediment from leaving the construction site. Examples of surface stabilization BMPs listed by the Alabama Soil and Water Conservation Committee (2003a) include: i.) chemical stabilization, ii.) erosion control blankets (ECBs), iii.) groundskeeping, iv.) mulching, v.) permanent seeding, vi.) preservation of vegetation, vii.) retaining walls, viii.) shrub, vine, and groundcover plantings, ix.) sodding, x.) temporary seeding, and xi.) tree planting on disturbed areas. Examples of sediment

control BMPs listed by the Alabama Soil and Water Conservation Committee (2003a) include: i.) block and gravel inlet protection, ii.) brush/fabric barriers, iii.) excavated drop inlet protection, iv.) fabric drop inlet protection, v.) filter strips, vi.) floating turbidity barriers, vii.) rock filter dams, viii) sediment barriers / silt fence systems, ix.) sediment basins, x.) straw bale sediment traps, and xi.) temporary sediment traps. The BMPs listed above can be very effective in controlling nonpoint source pollution if designed and installed correctly and maintained regularly.

In this research two of the abovementioned BMPs were evaluated to determine their effectiveness as erosion and sediment control technologies. The first BMP investigated was the sediment control measure known as a silt fence tieback (a.k.a. "j-hook") system. A silt fence tieback system is created by turning the downslope end of the linear silt fence back into the fill slope and extending the fence up the slope to an elevation higher than the top of the fence at the toe of the slope. This creates temporary detention basins that impound stormwater runoff during a rainfall event allowing suspended sediment to settle out of suspension. These systems were previously studied on an intermediate-scale model by Halverson (2006) and the results showed that a well designed silt fence tieback system can remove up to approximately 90% of the total suspended solids (TSS) transported in the surface runoff.

The second BMP investigated in this research was the use of anionic polyacrylamide (PAM). PAM, which is considered a chemical stabilization BMP, is a negatively charged polymer chain that is applied to the soil surface to maintain the soil structure and prevent erosion. PAM also serves as a binding agent for soil particles that are detached during erosion. The flocculation of fine particles caused by the PAM allows

suspended sediment to settle out of suspension rapidly due to their increased particle size. This process suggests that PAM can not only serve as an erosion control BMP but also as a sediment control alternative if used in conjunction with other sediment control BMPs that impound surface runoff.

1.4 RESEARCH OBJECTIVES

This research was divided into two components to evaluate and test two potential erosion and sediment control BMPs that are used in the highway construction industry. The first component developed a method to quantify the effectiveness of silt fence tieback (a.k.a. "j-hook") systems as a sediment control BMP. The second component focused primarily on the use of anionic PAM as a surface stabilization BMP to prevent erosion on highway construction sites. The effect of PAM as a sediment control BMP was also briefly investigated. The specific objectives of these two components are described in the following sections:

Component 1: Silt Fence Tieback Systems

1. Develop a computational method to determine the storage capacity of a silt fence tieback system.
2. Develop a Visual Basic (VBA) coded spreadsheet design tool for practitioners to use in the construction industry that predicts the volume of stormwater runoff generated from a user specified rainfall event and provides design guidance for a tieback configuration to accommodate the generated stormwater runoff.
3. Use the tool to design a tieback system on a local construction project and evaluate its performance over time during a case study.

Component 2: Anionic Polyacrylamide (PAM)

1. Perform intermediate-scale physical experiments to determine the effectiveness of dry granular PAM applied to a typical 3H:1V slope for erosion control.
2. Determine whether PAM, when used for erosion control, can also provide sediment control benefits by decreasing the settling time of suspended solids in the surface runoff.
3. Provide recommendations for future erosion and/or sediment control testing using PAM.

1.5 ORGANIZATION OF THESIS

This thesis is divided into five chapters which document the efforts taken to complete the objectives of this research. Following this chapter, Chapter 2: Design of Silt Fence Tieback Systems, is a continuation of the work performed by Halverson (2006). This chapter outlines the importance of determining the storage capacity of a silt fence tieback system and summarizes a computational procedure to do so. The chapter also describes the procedures used to develop a Visual Basic (VBA) coded spreadsheet design tool that can be used by practitioners to design silt fence tieback systems to accommodate a user specified rainfall event. Chapter 2 concludes by providing an actual case study where the design tool was used to determine a tieback configuration for an Alabama Department of Transportation (ALDOT) construction site. A linear silt fence system was also installed at this site and the performance of the two systems were compared over four rainfall events. Chapter 3: Literature Review: Use of PAM as an Erosion and Sediment Control BMP, introduces the application of anionic

polyacrylamide (PAM) as an erosion and sediment control alternative. Also discussed in this chapter are the important variables to consider when selecting a PAM product and previous research on PAM as an erosion and sediment control technology. Chapter 4: Intermediate-Scale Erosion Control Experiments Using PAM, outlines the development details of an intermediate-scale experimental model used for evaluating PAM as an erosion and sediment control technology, the experimental design used for the research, the data collection procedure, and the results from the experiments. Chapter 5: Conclusions and Recommendations, provides some insights on the use of PAM as an erosion and sediment control technology and recommendations for future research using PAM.

CHAPTER TWO

DESIGN OF SILT FENCE TIEBACK SYSTEMS

2.1 INTRODUCTION

The pollution of water bodies due to sediment transported from poorly managed construction sites is an important environmental problem. This transported sediment can dramatically alter or even destroy the aquatic habitat of the water bodies in which it is deposited. To address this issue, a common practice in the construction industry is the installation of silt fence systems. Silt fence systems are composed of a geotextile filter fabric that is sometimes supported by wire mesh and is fastened to either wooden or steel posts for structural support. Their primary purpose is to serve as a sediment barrier where sheet flow can be detained allowing sediment to settle out of suspension. These fences are usually installed around the perimeter of a construction site and often serve as the final barrier to capture sediment before leaving the site.

Traditionally, silt fence systems are installed as long, linear sections, but recent research suggests that tying the fence back into the contour at intermittent intervals and creating small detention basins is actually a much more effective design (Barrett et. al., 1995; Robichaud et. al., 2001; Stevens et. al., 2004; Zech et. al., 2006). This silt fence tieback design, commonly referred to as “j-hooks”, can be an effective solution to

controlling nonpoint source pollution on highway construction sites if designed and installed correctly. A silt fence tieback system is created by turning the downslope end of the linear silt fence back into the fill slope and extending the fence up the slope to an elevation higher than the top of the fence at the toe of the slope. This prevents stormwater runoff from passing around the toe of the fence and forces it to flow through the fence at the bottom of the fill slope. These systems should only be used when there is runoff flow both down the fill slope and longitudinally in the direction of the road as shown in Figure 2.1. The figure illustrates a properly designed silt fence tieback system on a highway construction site. Halverson (2006) provided experimental data to describe the efficiency of this design.

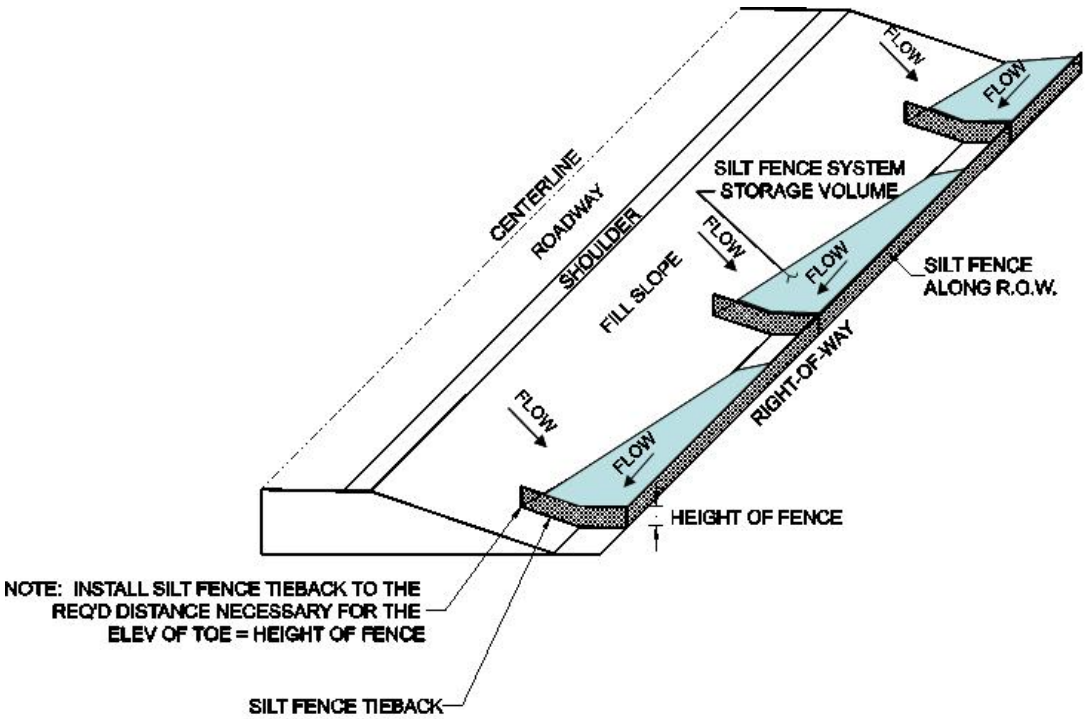


Figure 2.1 Silt Fence Tieback System

In this effort, we will outline an analytical method for determining the storage capacity of a silt fence tieback system and provide design guidance to practitioners in the proper design of a tieback system using a spreadsheet design tool. By using the computational procedures presented in this chapter, practitioners will be able to design silt fence tieback systems that will more effectively reduce sediment and other stormwater pollutant loads leaving highway construction sites.

2.2 STORAGE CAPACITIES OF SILT FENCE TIEBACK SYSTEMS

When designing silt fence tiebacks, one of the most important factors to consider is the storage capacity of the system. This storage capacity is critical in determining an effective tieback design that can accommodate a design rainfall event. Important parameters that determine the storage capacity of a tieback system include the height of the fence above the existing ground (H_1), existing ground width (L_1), existing ground slope (S_1), road fill slope (S_2), ditch slope (S_3), and the linear length of fence between tiebacks (L_{FENCE}). Figure 2.2 shows one typical silt fence tieback section incorporating the parameters that are considered when designing a tieback system. During a rainfall event, the tieback section shown in Figure 2.2 serves as a temporary storage area to detain stormwater runoff. The temporary detention of stormwater runoff allows sediment and other transported pollutants to be retained on site due to particles settling out of suspension. This deposition process will lead to higher quality of water leaving the construction site since it contains less suspended sediment.

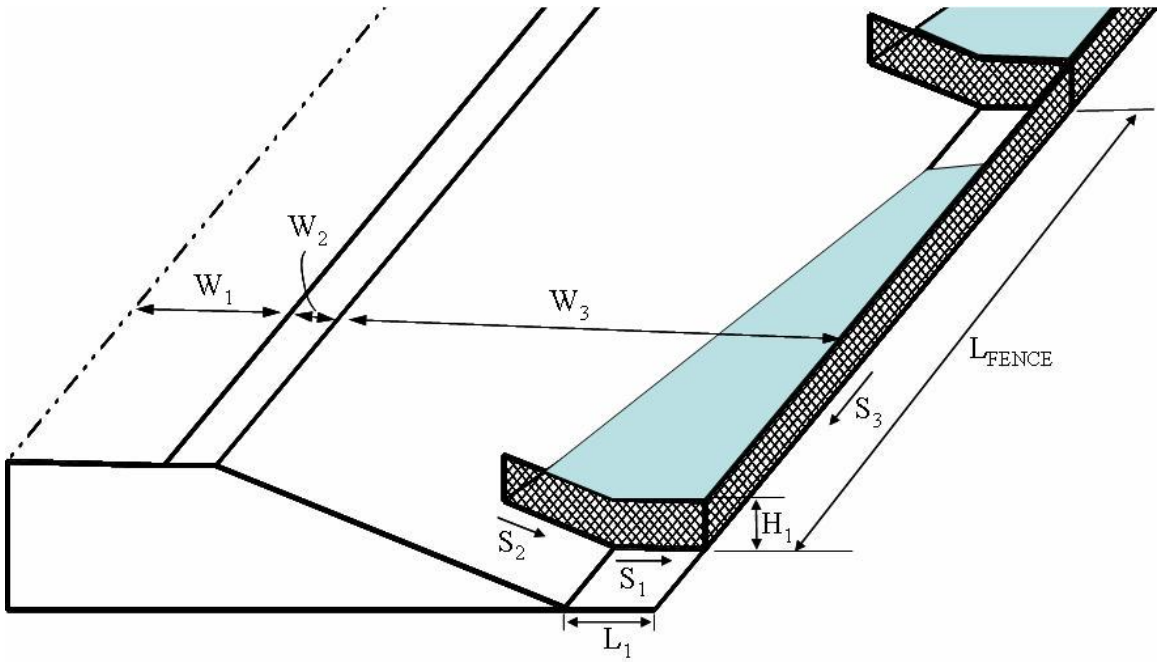


Figure 2.2 Typical Silt Fence Tieback Section.

As illustrated in the figure, the storage capacity of the silt fence is a critical component that needs to be considered while designing an effective system. For a heavy rainfall event where the runoff volume exceeds the storage capacity behind the fence, the tieback system will experience an overtopping condition. This scenario can be result of improper tieback spacing, poor silt fence installation practices, or an unforeseen rainfall event exceeding the design storm. Therefore, the procedure for calculating the storage capacity of silt fence tieback systems is a critical design consideration and will be discussed in the following sections. First, the discussion will focus on the mathematical procedures used to determine the maximum storage capacity required for a specified rainfall event along with the associated tieback spacing for a silt fence tieback system to satisfy the stormwater demand. Next, the discussion will focus on an alternative design procedure developed to determine tieback storage capacities if the designer opts to install and configure the tiebacks more frequently where only a portion of the maximum storage

capacity is utilized. The goal of this research is to develop a comprehensive understanding of the design and performance of a silt fence tieback system.

2.2.1 Maximum Storage Capacity Calculation Procedure

The maximum storage capacity and associated intermittent tieback spacing are critical parameters in the design of effective silt fence tieback systems. An ideal, cost effective system is one that uses the least amount of tiebacks required while still being capable of accommodating the stormwater runoff generated by the design rainfall event. The reasoning behind the ideal system is that it is assumed that the cost and work required for the installation of a silt fence tieback system increases as tieback frequency increases. Figure 2.1, mentioned previously, illustrates a silt fence tieback system configuration where the maximum storage capacity is utilized by each tieback.

To determine the maximum storage capacity for a silt fence tieback, the available storage volume behind the fence was solved analytically. The available storage volume behind the fence was divided into two components consisting of: (1) the fill slope storage volume (V_1), and (2) the existing ground storage volume (V_2) as shown in Figure 2.3. The total available storage volume was then calculated by evaluating the two components separately and combining the results. The origin (0, 0, 0) was set at the existing ground on the downslope end of the silt fence installation as shown in Figure 2.3.

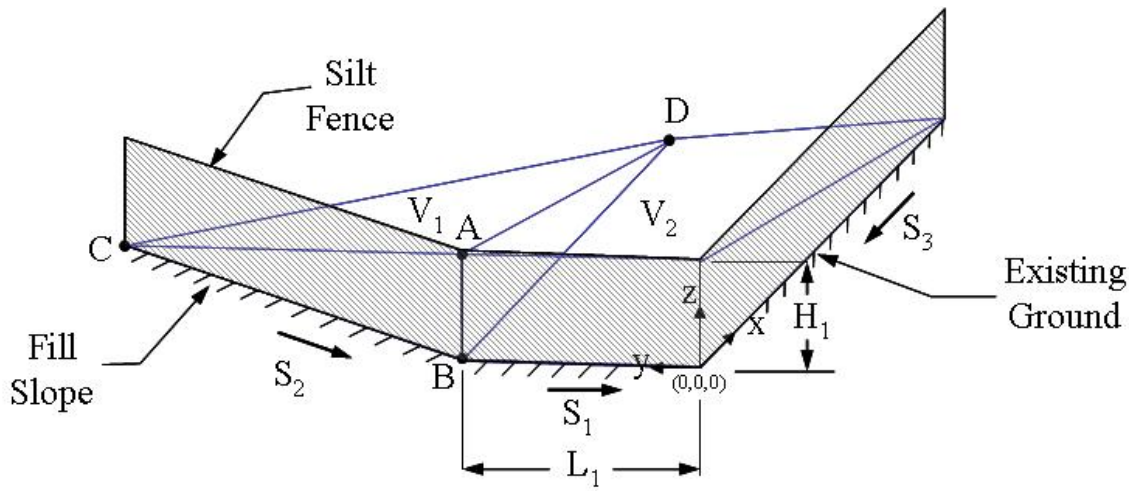


Figure 2.3 Total Storage Volume.

2.2.1.1 Fill Slope Storage Volume (V_1)

The first step in computing the volume stored on the fill slope (V_1) was to determine the equations for the four boundary planes (Planes 1-4) that define V_1. The establishment of the defined coordinate system allowed Planes 1 through 3 to be easily determined. The volume V_1 along with points A, B, C, and D which define Planes 1 through 4 are shown in Figure 2.4.

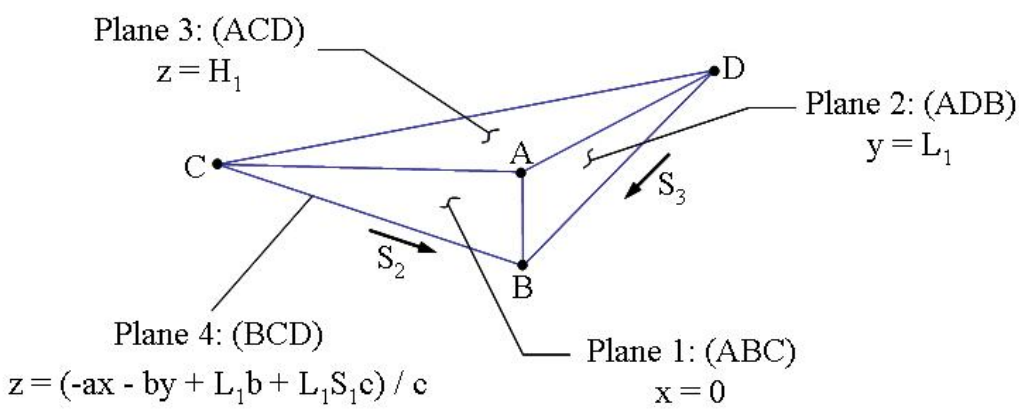


Figure 2.4 Volume Stored on Fill Slope (V_1).

The equations for Planes 1 through 3 are shown below as:

- Plane 1: $x = 0$;
- Plane 2: $y = L_1$;
- Plane 3: $z = H_1$.

The equation for the fourth plane of the system (Plane 4), which represents the fill slope, was not easy to define. The first step in determining the equation for Plane 4 was to determine the coordinates of nodes B, C, and D as shown below:

- $B = (0, L_1, L_1S_1)$;
- $C = (0, (H_1 - L_1S_1) / S_3 + L_1, H_1)$;
- $D = ([(H_1 - L_1S_1) / S_3], L_1, H_1)$.

The normal vector (n) to Plane 4 was then determined from the established points by taking the cross product of vectors $\overrightarrow{BC}$ and $\overrightarrow{BD}$. The equation for the normal vector (n) is shown in equation 2.1 below.

$$n = \overrightarrow{BC} \times \overrightarrow{BD} = ai + bj + ck \tag{2.1}$$

where,

$$a = \left(\frac{H_1 - L_1S_1}{S_2} \right) \left(H_1 - L_1S_1 \right)$$

$$b = \left(\frac{H_1 - L_1S_1}{S_3} \right) \left(H_1 - L_1S_1 \right)$$

$$c = -\left(\frac{H_1 - L_1S_1}{S_3} \right) \left(\frac{H_1 - L_1S_1}{S_2} \right)$$

Using the normal vector (n) and point B, the scalar equation for Plane 4 was determined and is shown in equation 2.2.

$$a(x-0)+b(y-L_1)+c(z-L_1S_1)=0 \tag{2.2}$$

Equation 2.2 was rewritten in terms of elevation (z) and is shown in equation 2.3.

$$z=\frac{-ax-by+L_1b+L_1S_1c}{c} \tag{2.3}$$

With all of the boundary planes defined, the volume V_1 of the tetrahedron shown in Figure 2.4 was computed using triple integration. The limits of integration in the z-direction were defined by Plane 3 ($z = H_1$) and Plane 4 ($z = (-ax - by + L_1b + L_1S_1c) / c$) while the limits of integration for the x and y directions were determined from the projection of the tetrahedron on the x-y plane shown in Figure 2.5.

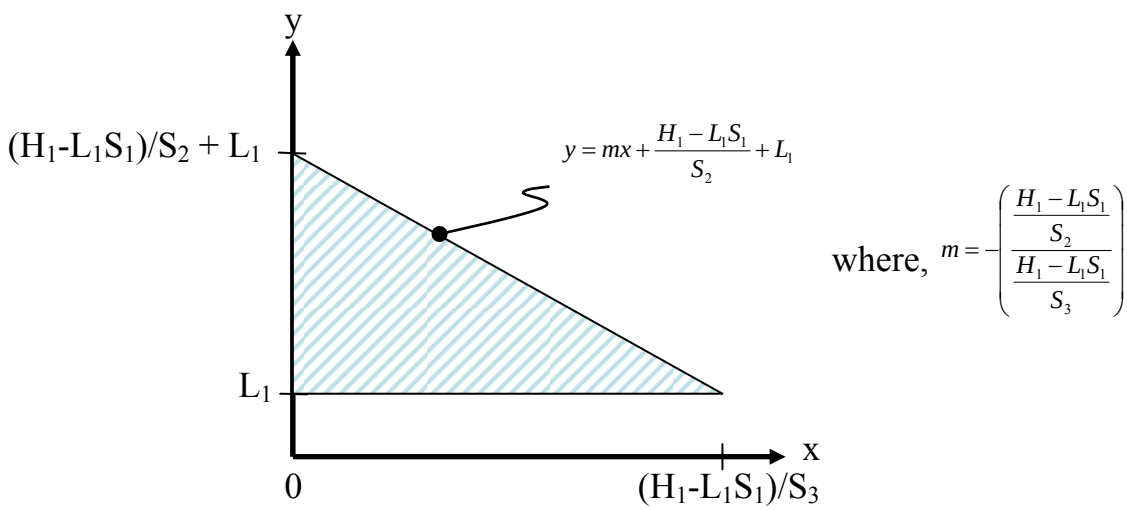


Figure 2.5 Projection of V_1 in the x-y Plane.

As shown in Figure 2.5, the limits of integration in the y-direction were $y = mx + (H_1 - L_1S_1)/S_2 + L_1$ and $y = L_1$. The limits of integration in the x-direction were $x = (H_1 -$

$L_1S_1)/S_3$ and x = 0. The triple integral used to compute V_1 is shown in equation 2.4 and the solution is shown in equation 2.5.

$$V_1 = \int_0^{\frac{H_1 - L_1S_1}{S_3}} \int_{L_1}^{mx + \frac{H_1 - L_1S}{S_2} + L_1} \int_{\frac{-ax - by + L_1b + L_1S_1c}{c}}^{H_1} dzdydx \tag{2.4}$$

$$\begin{aligned} V_1 = & \left(\frac{2am + bm^2}{6c}\right)\left(\frac{H_1 - L_1S_1}{S_3}\right)^3 + \left(\frac{H_1m}{2} + \frac{H_1 - L_1S_1}{S_2}\left(\frac{a + bm}{2c}\right) - \frac{L_1S_1m}{2}\right)\left(\frac{H_1 - L_1S_1}{S_3}\right)^2 \\ & + \left(\frac{H_1 - L_1S_1}{S_2}(H_1 - L_1S_1) + \frac{b}{2c}\left(\frac{H_1 - L_1S_1}{S_2}\right)^2\right)\left(\frac{H_1 - L_1S_1}{S_3}\right) \end{aligned} \tag{2.5}$$

2.2.1.2 Existing Ground Storage Volume

The volume stored on the existing ground (V_2) is shown in Figure 2.6 below.

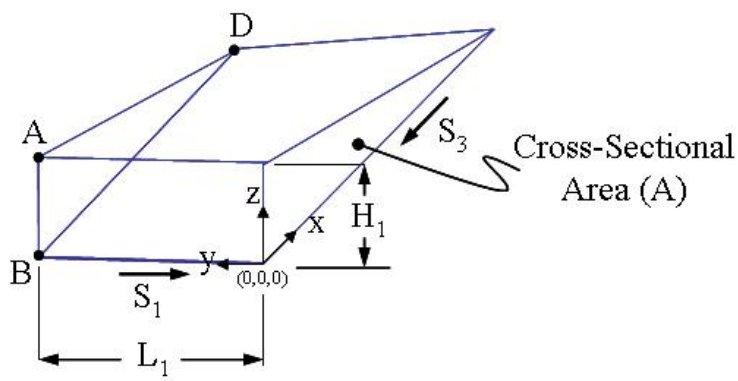


Figure 2.6 Maximum Storage Volume on Existing Ground (V_2).

In order to determine V_2, a relationship of how the cross-sectional area (A) in the x-z plane changes with respect to y was determined. This relationship was easily defined since the cross-section is triangular in shape. Using Figure 2.6 as a reference, an equation for the cross-sectional area (A) with respect to the y-direction was written as the following:

$$A(y) = \frac{1}{2}\left(H_1 - S_1 y\right)\left(\frac{H_1 - S_1 y}{S_3}\right) \tag{2.6}$$

The volume V_2 was then determined by simply integrating equation 2.6 for the entire existing ground length of y = 0 to y = L_1. This integral is shown in equation 2.7 below as:

$$V_2 = \int_0^{L_1} \frac{1}{2}\left(H_1 - S_1 y\right)\left(\frac{H_1 - S_1 y}{S_3}\right) dy \tag{2.7}$$

The solution to the integration of equation 2.7 is shown below in equation 2.8 as:

$$V_2 = \frac{1}{2}\left(\frac{H_1^2 L_1}{S_3} - \frac{H_1 S_1 L_1^2}{S_3} + \frac{S_1^2 L_1^3}{3S_3}\right) \tag{2.8}$$

2.2.1.3 Maximum Storage Capacity (V_T) and Associated Tieback Spacing

The maximum storage capacity of a silt fence tieback was found by combining equation 2.5 and equation 2.8. The expression for the maximum storage capacity (V_T) is shown in equation 2.9.

$$\begin{aligned} V_T = {} & \left(\frac{2am + bm^2}{6c}\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right)^3 + \left(\frac{H_1 m}{2} + \frac{H_1 - L_1 S_1}{S_2}\left(\frac{a + bm}{2c}\right) - \frac{L_1 S_1 m}{2}\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right)^2 \\ & + \left(\frac{H_1 - L_1 S_1}{S_2}\left(H_1 - L_1 S_1\right) + \frac{b}{2c}\left(\frac{H_1 - L_1 S_1}{S_2}\right)^2\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right) + \frac{1}{2}\left(\frac{H_1^2 L_1}{S_3} - \frac{H_1 S_1 L_1^2}{S_3} + \frac{S_1^2 L_1^3}{3S_3}\right) \end{aligned} \tag{2.9}$$

The equation for the tieback spacing that will provide the maximum storage capacity is shown in equation 2.10. This relationship, which was determined from the geometric properties of the total storage volume shown in Figure 2.3, is strictly a function of the height of the silt fence above ground (H_1) and the ditch slope (S_3).

$$L_{FENCE} = \frac{H_1}{S_3} \tag{2.10}$$

By using equations 2.9 and 2.10 during design, practitioners will have a better understanding of the required tieback frequency and the maximum available storage capacity associated with the system on their project site.

2.2.2 Storage Capacities for More Frequent Tieback Configurations

There are instances when a practitioner may decide to use a tieback spacing less than the spacing that provides the maximum storage capacity. Therefore, the equations for the maximum storage capacity outlined in the previous sections were modified to determine the storage capacities of more frequent tieback configurations. There are two possible situations that can occur if a shorter length of linear fence between tiebacks is utilized. The first situation occurs when the linear length of fence between tiebacks is long enough to utilize the entire available storage capacity on the fill slope but only a portion of the available storage capacity on the existing ground. The second situation is where the linear length of fence between tiebacks only uses a portion of both the storage capacity on the fill slope and the existing ground. These two situations are shown in Figure 2.7 and Figure 2.8 and can be described mathematically as:

(1) $\frac{H_1 - L_1 S_1}{S_3} \leq L_{FENCE} < \frac{H_1}{S_3}$, and (2) $L_{FENCE} < \frac{H_1 - L_1 S_1}{S_3}$. The procedure for determining the storage capacities for scenarios (1) and (2) are outlined in the following sections.

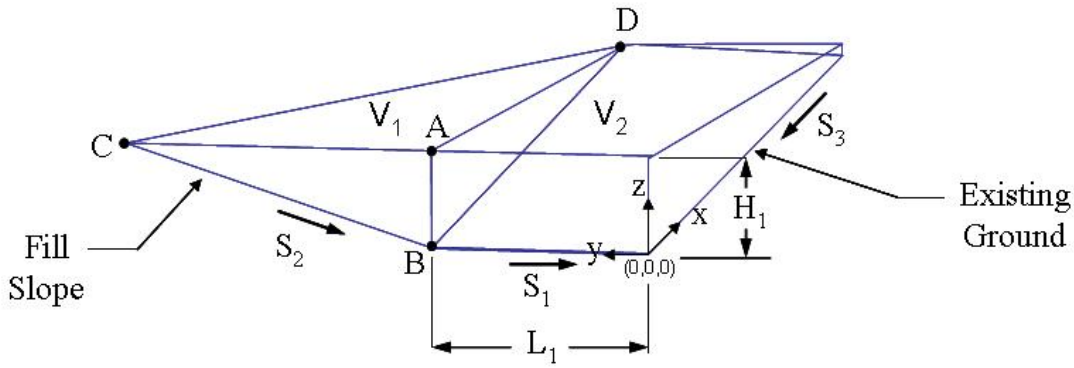


Figure 2.7 Storage Volume for Scenario 1.

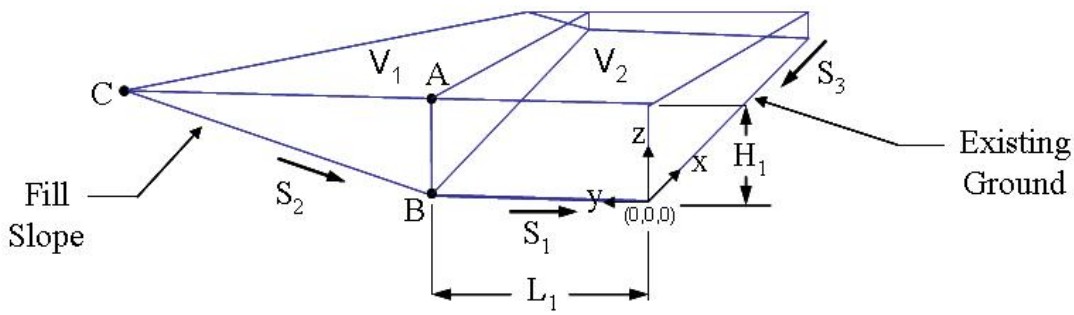


Figure 2.8 Storage Volume for Scenario 2.

2.2.2.1 Computational Procedure for Scenario 1

The volumes V_1 and V_2 for scenario 1, where $\frac{H_1 - L_1 S_1}{S_3} \le L_{FENCE} < \frac{H_1}{S_3}$, were found by modifying the previously defined maximum storage capacity equations. Under the first scenario, the total available storage capacity on the fill slope is still utilized; therefore, the equation for V_1 is exactly the same as shown in equation 2.5. V_2, on the other hand, was found from analyzing Figure 2.6 through Figure 2.10. Figure 2.6 and Figure 2.9 show the maximum and modified V_2 while Figure 2.10 shows a cross-sectional view of the maximum and modified V_2.

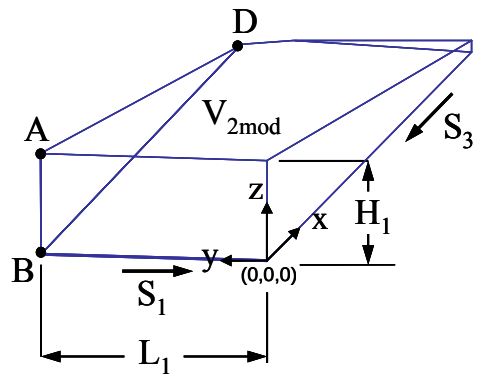


Figure 2.9 Modified Storage Volume on Existing Ground ($V_{2modified}$).

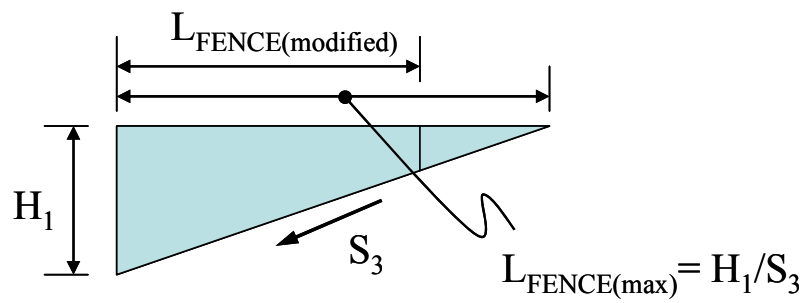


Figure 2.10 Projection of Maximum and Modified Storage Volumes on Existing Ground (V_2).

The modified equation for V_2 was determined using Figure 2.9 as a reference. The integral and solution for the modified V_2 in scenario 1 are shown in equation 2.11 and equation 2.12.

$$V_2 = \int_0^{L_1} \frac{1}{2}\left(H_1 - S_1 y\right)\left(\frac{H_1 - S_1 y}{S_3}\right)dy - \int_0^{xL_1} \frac{1}{2}\left(H_1 - S_1 y - L_{FENCE} S_3\right)\left(\frac{H_1 - S_1 y}{S_3} - L_{FENCE}\right)dy \tag{2.11}$$

$$V_2 = \frac{1}{2}\left(\frac{H_1^2 L_1}{S_3} - \frac{H_1 S_1 L_1^2}{S_3} + \frac{S_1^2 L_1^3}{3S_3}\right) - \frac{1}{2}\left(\begin{array}{l} \frac{H_1^2}{S_3} xL_1 - H_1 \frac{S_1}{S_3} x^2 L_1^2 - 2H_1 L_{FENCE} xL_1 \\ + L_{FENCE} S_1 x^2 L_1^2 + \frac{S_1^2 x^3 L_1^3}{3S_3} + L_{FENCE}^2 xL_1 \end{array}\right) \tag{2.12}$$

where, $$x = \left(\frac{\frac{H_1}{S_3} - L_{FENCE}}{\frac{H_1}{S_3} - \frac{H_1 - L_1 S_1}{S_3}}\right).$$

The total storage capacity for a silt fence tieback section in scenario 1 is shown in equation 2.13.

$$\begin{aligned} V_T = & \left(\frac{2am + bm^2}{6c}\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right)^3 + \left(\frac{H_1 m}{2} + \frac{H_1 - L_1 S_1}{S_2}\left(\frac{a + bm}{2c}\right) - \frac{L_1 S_1 m}{2}\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right)^2 \\ & + \left(\frac{H_1 - L_1 S_1}{S_2}\left(H_1 - L_1 S_1\right) + \frac{b}{2c}\left(\frac{H_1 - L_1 S_1}{S_2}\right)^2\right)\left(\frac{H_1 - L_1 S_1}{S_3}\right) + \frac{1}{2}\left(\frac{H_1^2 L_1}{S_3} - \frac{H_1 S_1 L_1^2}{S_3} + \frac{S_1^2 L_1^3}{3S_3}\right) \\ & - \frac{1}{2}\left(\frac{H_1^2}{S_3} xL_1 - H_1 \frac{S_1}{S_3} x^2 L_1^2 - 2H_1 L_{FENCE} xL_1 + L_{FENCE} S_1 x^2 L_1^2 + \frac{S_1^2 x^3 L_1^3}{3S_3} + L_{FENCE}^2 xL_1\right) \end{aligned} \tag{2.13}$$

2.2.2.2 Computational Procedure for Scenario 2

The equations for V_1 and V_2 in scenario 2, where $L_{FENCE} < \frac{H_1 - L_1 S_1}{S_3}$, are very similar to the equations developed in scenario 1. The equation for V_1 was found by simply changing the upper limit of integration in the x-direction to the length of fence (L_{FENCE}) or tieback spacing of interest. The modified integral and solution for V_1 are shown in equation 2.14 and equation 2.15.

$$V_1 = \int_0^{L_{FENCE}} \int_{L_1}^{mx+\frac{H_1-L_1S_1}{S_2}+L_1} \int_{\frac{-ax-by+L_1b+L_1S_1c}{c}}^{H_1} dzdydx \tag{2.14}$$

$$\begin{aligned} V_1 = & \left(\frac{2am+bm^2}{6c}\right)L_{FENCE}^3 + \left(\frac{H_1m}{2} + \frac{H_1-L_1S_1}{S_2}\left(\frac{a+bm}{2c}\right) - \frac{L_1S_1m}{2}\right)L_{FENCE}^2 \\ & + \left(\frac{H_1-L_1S_1}{S_2}\left(H_1-L_1S_1\right) + \frac{b}{2c}\left(\frac{H_1-L_1S_1}{S_2}\right)^2\right)L_{FENCE} \end{aligned} \tag{2.15}$$

The equation for V2 in scenario 2 was almost identical to the previous scenario except for one small difference. The difference in scenario 2 was that x = 1 in the V_2 equation. The equation for V_2 is shown in equation 2.16.

$$V_2 = \frac{1}{2}\left(2H_1L_{FENCE}L_1 - L_{FENCE}S_1L_1^2 - L_{FENCE}^2S_3L_1\right) \tag{2.16}$$

The total storage capacity for a silt fence tieback section in scenario 2 is shown in equation 2.17

$$\begin{aligned} V_T = & \left(\frac{2am+bm^2}{6c}\right)L_{FENCE}^3 + \left(\frac{H_1m}{2} + \frac{H_1-L_1S_1}{S_2}\left(\frac{a+bm}{2c}\right) - \frac{L_1S_1m}{2}\right)L_{FENCE}^2 \\ & + \left(\frac{H_1-L_1S_1}{S_2}\left(H_1-L_1S_1\right) + \frac{b}{2c}\left(\frac{H_1-L_1S_1}{S_2}\right)^2\right)L_{FENCE} \\ & + \frac{1}{2}\left(2H_1L_{FENCE}L_1 - L_{FENCE}S_1L_1^2 - L_{FENCE}^2S_3L_1\right) \end{aligned} \tag{2.17}$$

2.2.3 Sensitivity Analysis

A sensitivity analysis was performed to determine effects of the existing ground width (L_1), existing ground slope (S_1), road fill slope (S_2), and ditch slope (S_3) on the maximum storage capacity and associated tieback spacing of silt fence tieback systems. To determine the sensitivity of each of the parameters, the parameter of interest was

varied while all of the other parameters remained constant. These results are shown in Figure 2.11 through Figure 2.14 below. The silt fence height (H_1) remained constant for the analysis.

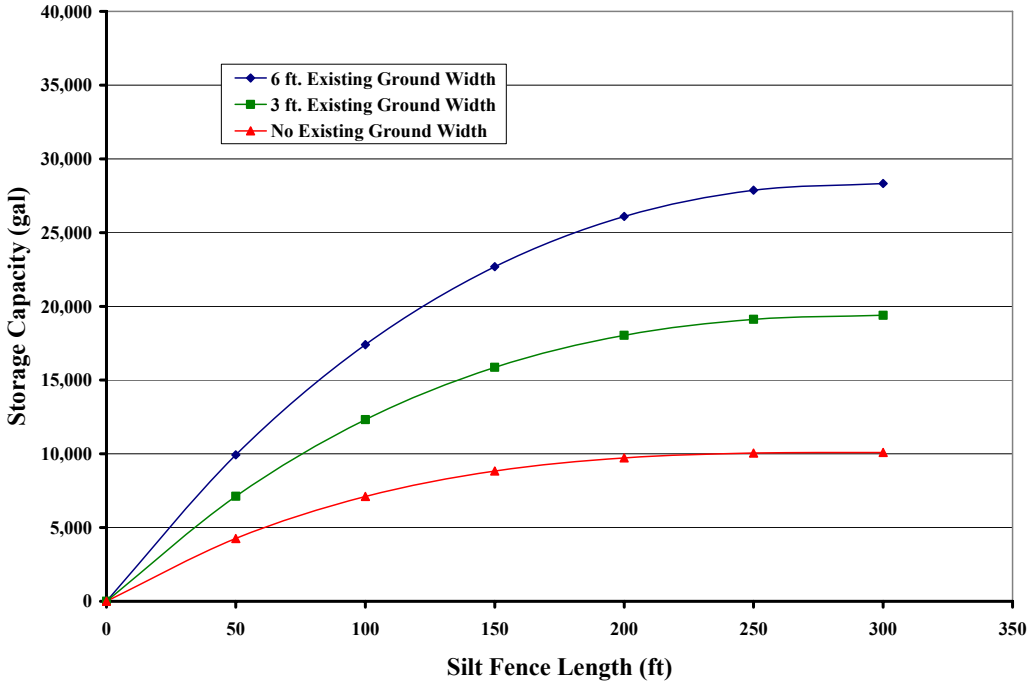


Figure 2.11 Constant S_1, S_2 and S_3; Varying L_1.

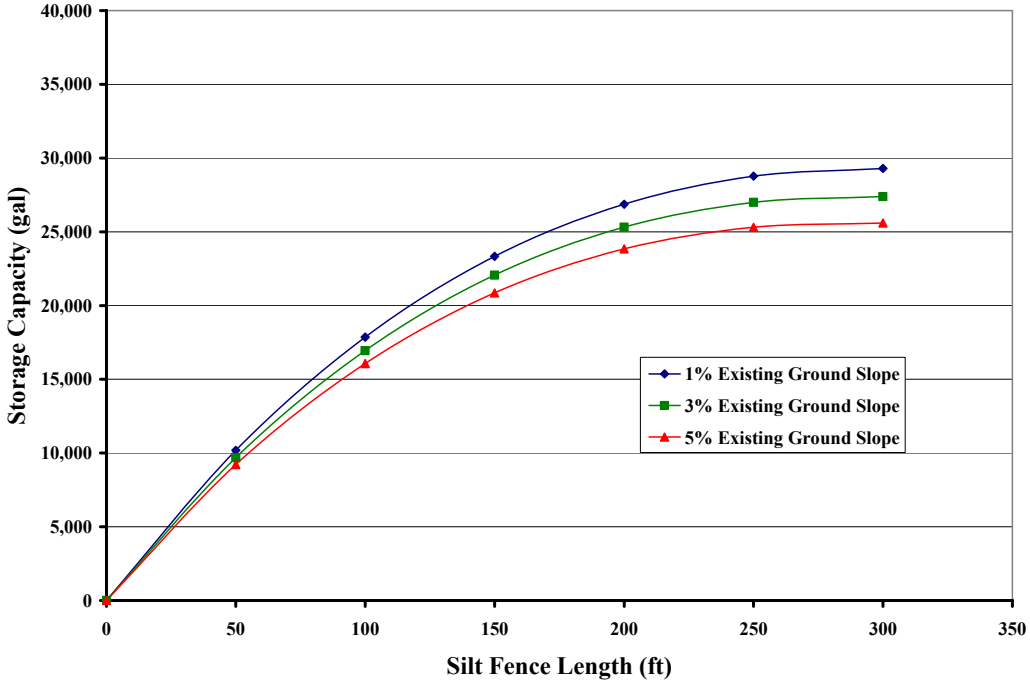


Figure 2.12 Constant L_1, S_2 and S_3; Varying S_1.

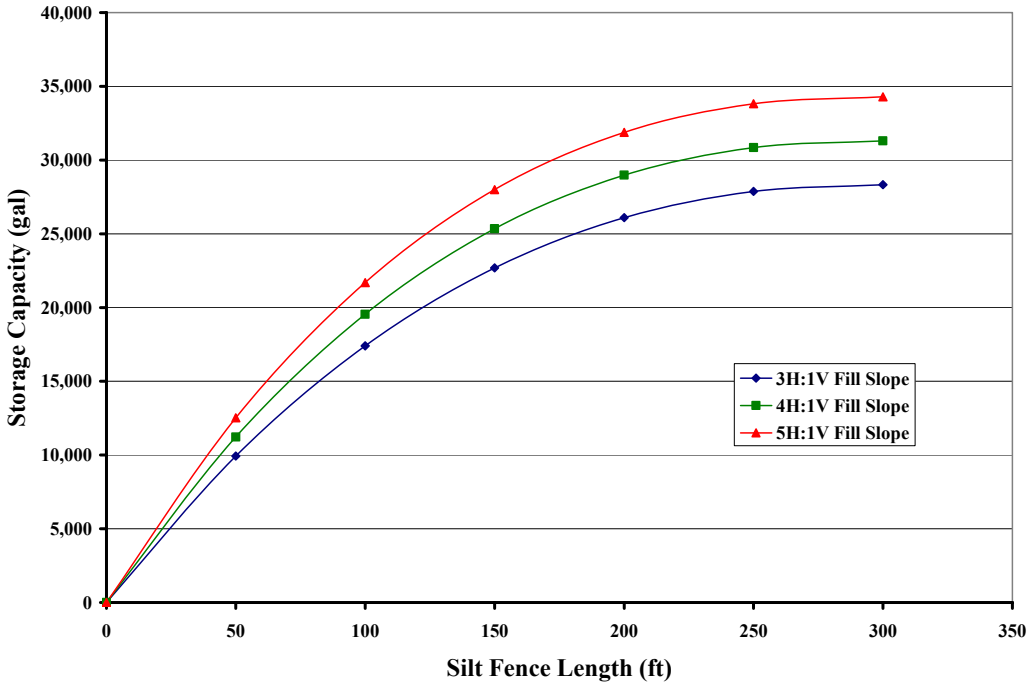


Figure 2.13 Constant L_1, S_1 and S_3; Varying S_2.

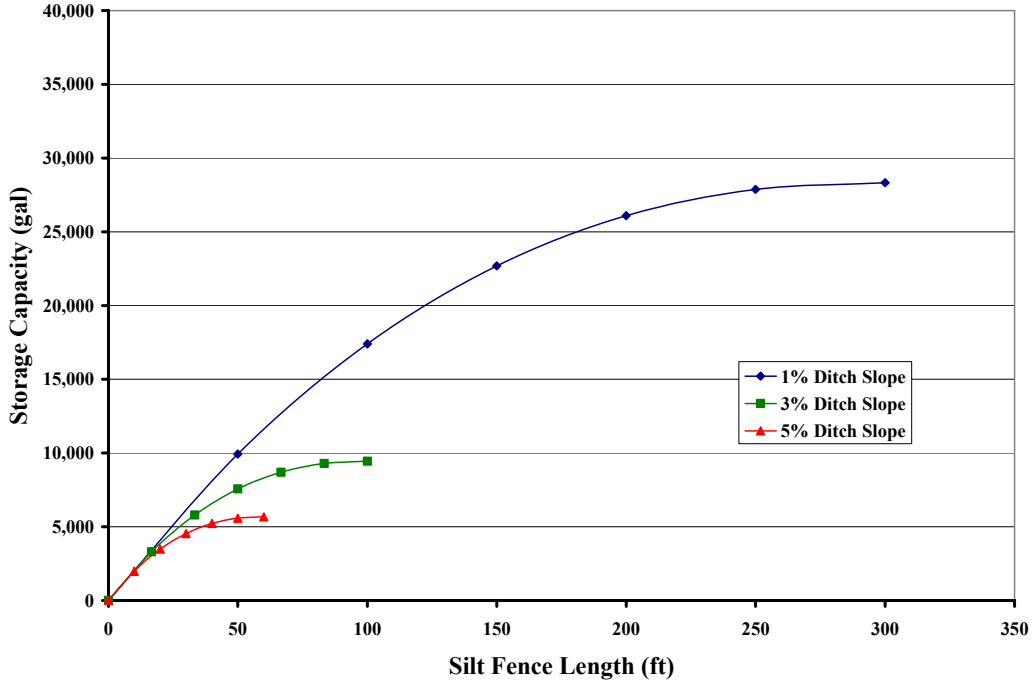


Figure 2.14 Constant L_1, S_1 and S_2; Varying S_3.

As can be seen from Figure 2.11 through Figure 2.14, the most critical parameter affecting the maximum storage capacity and associated silt fence length between tiebacks is the ditch slope (S_3). As the value for S_3 increases, the maximum storage capacity and associated tieback spacing decrease. When any of the other parameters are varied, the maximum storage capacity changes but the silt fence length associated with the maximum storage capacity remains constant. This proves that the silt fence length between tiebacks associated with the maximum storage capacity is purely a function of the height of the silt fence (H_1) and the ditch slope (S_3) as shown in equation 2.10.

2.3 SILT FENCE TIEBACK CONFIGURATION DESIGN TOOL

A Visual Basic (VBA) coded spreadsheet design tool was developed to assist practitioners in the proper design of silt fence tieback systems to be used on highway

construction sites. The tool uses the mathematical concepts outlined previously in this chapter along with the Soil Conservation Service (SCS) Curve Number (CN) method to determine an adequate tieback spacing that will accommodate a user specified rainfall event. The tool is composed of two components which are (1) the stormwater runoff component and (2) the silt fence storage capacity component. The details of these two components are outlined in the following sections along with an actual field example where the design tool was used to determine an appropriate tieback configuration on an Alabama Department of Transportation (ALDOT) job site.

2.3.1 Stormwater Runoff Volume Component

The first component of the silt fence tieback design tool is the stormwater runoff volume component. The stormwater runoff volume is computed in the design tool by multiplying the rainfall excess determined from the SCS Curve Number method by the drainage area of the roadway section. Inputs of this component include a single storm precipitation depth over a 24-hour period, SCS Curve Numbers (CNs) for the roadway, shoulder, and fill slope, the length and width of the roadway, the roadway shoulder width, and the width from the shoulder to the right of way (ROW). The single storm precipitation depth can be determined from the Technical Paper No. 40 Rainfall Frequency Atlas maps while the CNs, which are a function of the area's hydrologic soil group, land use, and impervious area, are shown in Appendix A. The length and width of the roadway, roadway shoulder width, and width from the shoulder to the ROW can be determined from either field measurements or construction plans. The details of how the

design tool computes the stormwater runoff volume by the SCS Curve Number method are outlined in the following paragraphs.

The first step in the computation of the stormwater runoff volume using the SCS CN method is the determination of the total rainfall depth (P) and a weighted CN ($CN_{weighted}$) for the entire roadway section. P is specified in the design tool by the user and $CN_{weighted}$ is computed using the CNs of the roadway, shoulder, and fill slope which are also specified by the user. The computation for $CN_{weighted}$ is shown in equation 2.18.

$$CN_{weighted} = \sum_{i=1}^{n} \frac{CN_i A_i}{A_{watershed}} \tag{2.18}$$

where,

CN_i = Curve Number for each individual section (e.g. roadway, shoulder, fill slope)
A_i = drainage area of each section
$A_{watershed}$ = total drainage area

Once P and $CN_{weighted}$ have been determined for the roadway section, the rainfall excess (Q) is calculated from equation 2.19

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{2.19}$$

where,

Q = rainfall excess (in)
P = total rainfall depth (in)
I_a = initial abstraction (surface storage, interception, and infiltration prior to runoff; assumed to be 0.2S)
S = storage parameter given by equation 2.20

$$S = \frac{1{,}000}{CN_{weighted}} - 10 \tag{2.20}$$

Q is then multiplied by the drainage area of the roadway section to produce the total stormwater volume V_{total} that needs to be accommodated by the silt fence tieback system. The equation for V_{total} is shown in equation 2.21.

$$V_{total} = \frac{Q * A_{watershed}}{12} \tag{2.21}$$

where,

V_{total} = total stormwater runoff volume (ft^3)
Q = accumulated runoff (in)
$A_{watershed}$ = drainage area of the roadway section (ft^2)

2.3.2 Silt Fence Storage Capacity Computation

An adequate silt fence tieback configuration that can handle the total stormwater runoff volume given by equation 2.21 can be determined using the silt fence storage capacity component. The inputs of this component include height of the silt fence above the existing ground (H_1), existing ground width (L_1), existing ground slope (S_1), road fill slope (S_2), and the ditch slope (S_3). These parameters are illustrated in Figure 2.2 shown previously. Using these parameters along with the equations outlined in section 2.2, the storage capacity component can compute the total storage capacity for various tieback configurations at a specific ditch slope. Figure 2.15 shows an example of the results as computed by the storage capacity component.

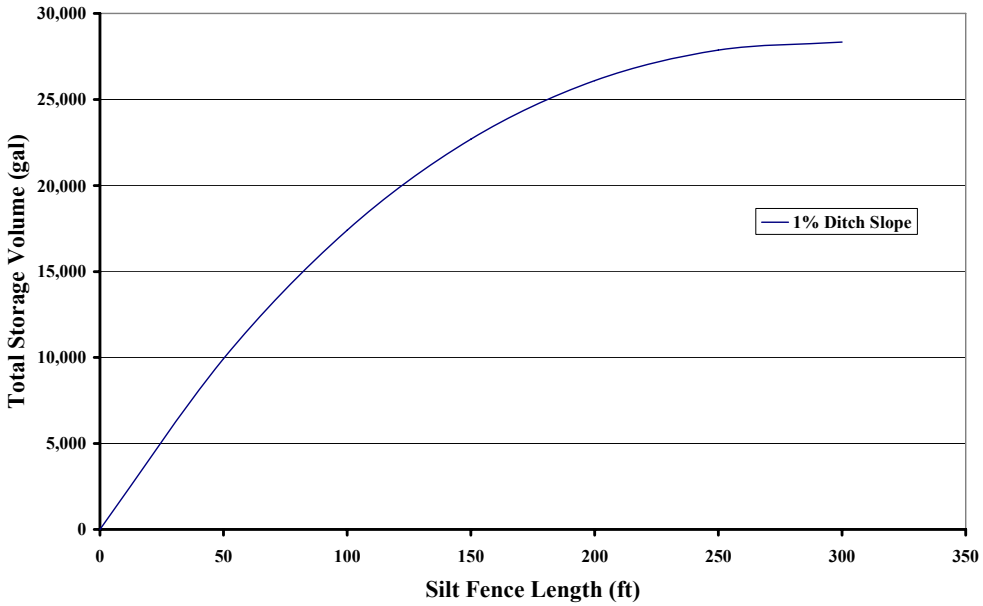


Figure 2.15 Silt Fence Storage Capacity for Various Tieback Configurations.

The data shown in Figure 2.15 illustrates the relationship between the linear length of silt fence between tiebacks and the total storage volume per tieback at a specified ditch slope. As shown in the figure, the total storage volume increases as the silt fence length between tiebacks increases to a certain point. The point at which the curve flattens out corresponds to the maximum storage capacity of the silt fence tieback. In the example output shown in Figure 2.15, the maximum storage capacity is at a silt fence length between tiebacks of 300 feet. This means that any tieback spacing greater than 300 feet will have the same storage capacity as a tieback spacing of 300 feet at a ditch slope of 1%.

Practitioners can use the output of the storage capacity component like the one shown in Figure 2.15 to design to a tieback configuration that can handle the runoff volume generated from equation 2.21. For cost effectiveness and ease of installation, an

ideal system is one that uses the least number of uniformly spaced tiebacks. To meet this criterion, designers should first consider using the tieback spacing given by equation 2.10. If the storage provided by this tieback spacing is not enough, the designer should then consider a more frequent tieback configuration.

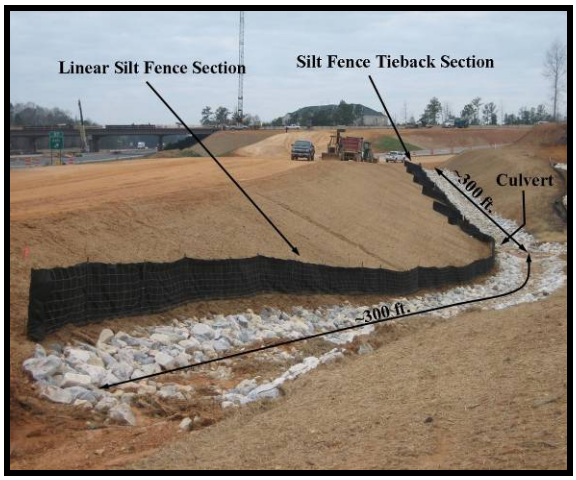
2.3.3 Case Study: Application of the Silt Fence Tieback Design Tool

The silt fence tieback design tool discussed in this chapter was used to design a tieback system for a 2 in. design storm on an ALDOT highway construction site located in Auburn, AL. The field test site was developed to illustrate the proper application of the design tool and test the effectiveness of a silt fence tieback design versus a traditional linear silt fence system. The field test site was monitored over several rainfall events and the performance results were documented.

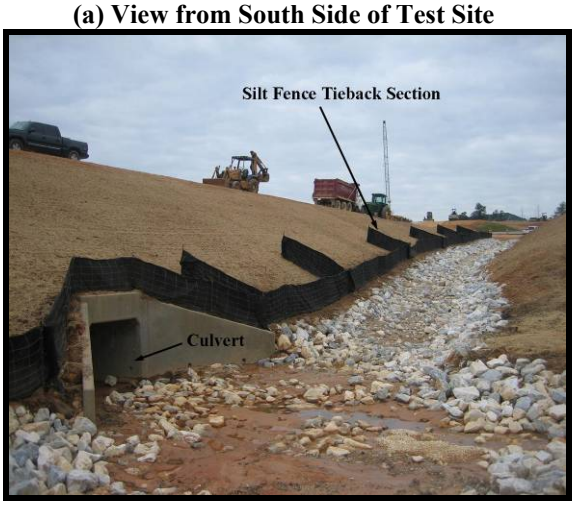
2.3.3.1 Site Description

The field test site used for this research was located on an ALDOT highway construction site at Exit 57 off of I-85 in Auburn, AL. This site contained an approximately 600 ft. symmetrical vertical curve section of road with a 3H:1V fill slope. For testing purposes, the road was divided into two sections using the crest of the curve as the division point. Linear silt fence was installed on half of the roadway section and tiebacks were installed on the other half. Figure 2.16 shows the field test site after installation of the two silt fence scenarios and the characteristics of the site are listed in Table 2.1.

(a) View from South Side of Test Site



(b) View from North Side of Test Site



(c) Silt Fence Tieback Section

(d) Linear Silt Fence Section

Figure 2.16 Experimental Test Site.

Table 2.1 Test Site Characteristics.

Variable	Value
Roadway Length (ft):	600
Roadway Width (ft):	50
Roadway CN:	82
Fill Slope Gradient (%):	33.3
Fill Slope CN:	82
Distance from Road to ROW (ft):	50
Riprap Ditch Slope (%):	5

As can be seen from Table 2.1, the roadway length and width at the field test site were approximately 600 ft. and 50 ft. respectively. The fill slope of the site was 3H:1V

and the riprap ditch at the bottom of the fill slope had approximately 5% gradient. The distance from the edge of the road to the ROW was 50 ft. at the crest of the curve. The roadway was not paved at the time; therefore, a single CN value of 82 was used for the roadway and fill slope. This CN value is representative of a dirt road with a Natural Resources Conservation Service (NRCS) Hydrologic Soil Group (HSG) classification of B. The HSG B classification corresponds to a soil with a final infiltration rate ranging from 0.15 to 0.3 in/h. Figure 2.17 shows a cross-section of the roadway at the crest of the curve.

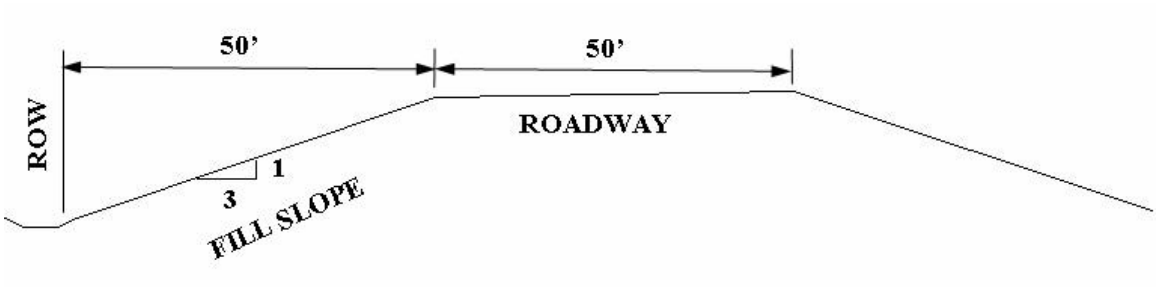
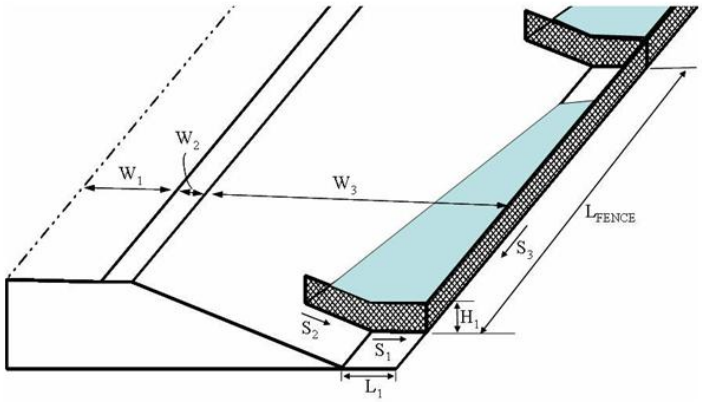


Figure 2.17 Cross-Section of Field Test Site Roadway.

2.3.3.2 Tieback Design

In order to determine the tieback configuration for the field test site, the characteristics shown in Table 2.1 were entered into the design tool. A roadway length of 300 ft. was used instead of the entire roadway length of 600 ft. since a tieback design was used on only half of the site and a linear silt fence system was used on the remaining half. Figure 2.18 shows a screen capture of the design tool and results for this field test site. Further details on how to use the design tool are shown in Appendix B.

Silt Fence Tieback Design Tool



Stormwater Runoff Volume Computation

Input:

Roadway CN:	82
Roadway Width from Centerline, W_1 (ft):	50
Roadway Length (ft):	300
Shoulder CN:	82
Shoulder Width, W_2 (ft):	0
Fill Slope CN:	82
Width from Shoulder to ROW, W_3 (ft):	50
2-yr, 24-hr Precipitation (in):	2

Results:

Stormwater Runoff Volume (gal):	12,131

Silt Fence Storage Capacity Computation

Input:

S_1 (ft/ft):	0
S_2 (ft/ft):	0.33
S_3 (ft/ft):	0.05
H_1 (ft):	3
L_1 (ft):	0

Results:

Silt Fence Length (ft)	Total Storage Volume (gal)
0	0
10	851
20	1,421
30	1,767
40	1,945
50	2,010
60	2,020

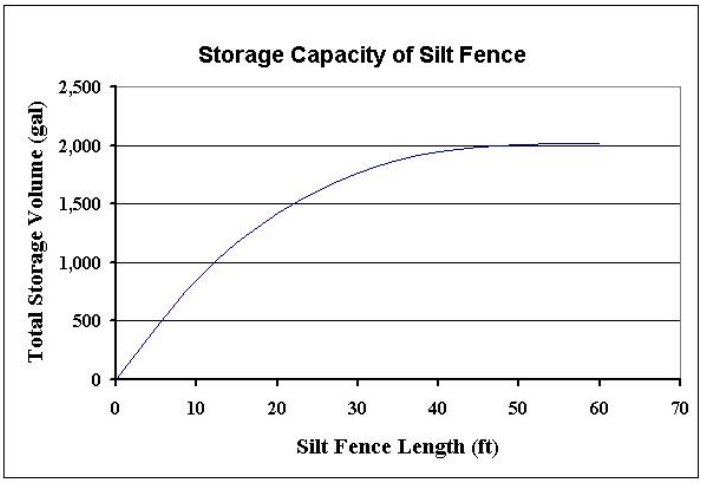


Figure 2.18 Silt Fence Design Tool Used for Test Site.

As shown in Figure 2.18, the design tool computed a total stormwater runoff volume of 12,131 gallons for the 2 in. design rainfall event. To accommodate this runoff volume, three tieback configurations were considered. The first tieback configuration was determined from equation 2.10 and consisted of five tiebacks spaced at 60 ft. intervals. This scenario only provided 10,100 gallons of storage which was much less than the computed stormwater runoff volume. The second tieback configuration consisted of six tiebacks spaced at 50 ft. intervals. This scenario provided 12,060 gallons of storage. Finally, the third scenario consisted of ten tiebacks spaced at 30 ft. intervals. The total storage volume for this scenario was 17,670 gallons. For ease of application and cost effectiveness, the research team decided to use the second scenario consisting of six tiebacks spaced every 50 ft. even though the storage volume provided by this scenario was slightly less than the total stormwater runoff volume. The reasoning behind this decision was that the benefit provided by the third scenario was not worth the extra time and money that it would take to install it.

2.3.3.3 Tieback System Performance

As highlighted previously in this chapter, the purpose of a silt fence tieback system is to create small detention basins using tiebacks that will impound stormwater runoff and allow suspended sediment to settle out of suspension. If designed and installed correctly, the tieback sections will capture and contain sediment transported from their contributing drainage areas which will reduce the likelihood of a failure due to excessive sediment loading at a single location commonly seen in linear silt fence systems. Failures of linear silt fence systems typically occur due to one of five failure

modes. These failure modes were outlined by Halverson (2006) and include the following:

1. The stormwater runoff is greater than the storage capacity of the silt fence which creates an overtopping condition.
2. The toe of the fence is undercut due to erosion caused by stormwater runoff accumulating and flowing along the toe of the fence.
3. The fence is not properly tied into the contour which allows sediment to pass around the fence onto adjacent property.
4. A large amount of sediment accumulates on the face of the fence at a single location and causes a structural failure.
5. Failure due to improper installation.

To evaluate the performance of the tieback and linear silt fence systems at the test site shown in Figure 2.16, erosion pins were installed to measure sedimentation and the site was monitored over four rainfall events. The erosion pins used at the site were two feet long and they were driven into the ground one foot. Three rows of pins were installed with the first row was being placed along the fence at 10 ft intervals. The second row was placed 5 ft. up the fill slope and the third row was placed 3 ft. upslope from the second row. After each rainfall event, the distance from the top of each erosion pin to the ground was measured to determine the approximate amount of sedimentation and the site was investigated to determine if any of the five failure modes listed previously had occurred. Multiple pictures were also taken to qualitatively compare the performance of the two systems. The dates and corresponding rainfall depths for the four rain events used in the study are shown in Table 2.2.

Table 2.2 Rainfall at Test Site.

Date	Rainfall Depth (in)
2/13/2007	1.0
2/21/2007	0.5
2/25/2007	0.4
3/1/2007	2.5

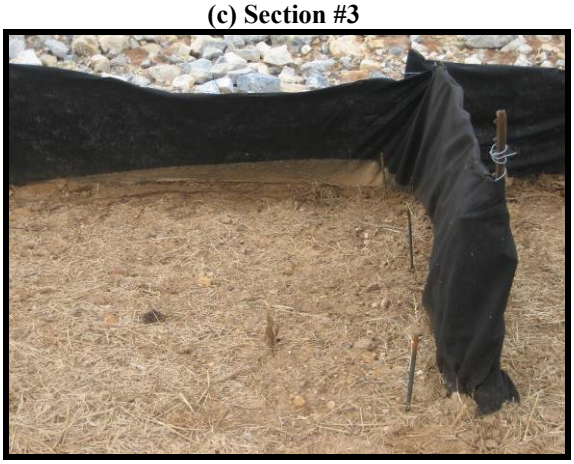
Due to wide spacing of the erosion pins, measurable sedimentation for both systems could only be obtained along the fence; however, the pictures taken provided valuable insight to the effectiveness of the tieback design. After the first three rainfall events, the pictures of the tieback system show that the tiebacks performed as expected by impounding stormwater runoff from their contributing drainage areas which allowed suspended sediment to settle out of suspension. This is evident from the visible mud line along the fence at the downslope end of the tieback sections 3, 4, and 5 shown in Figure 2.19. The temporary detention basins created by the tieback system also distributed the total sediment load throughout the system and prevented erosion along the toe of the fence by not allowing concentrated flow to travel in long distances along the fence. This is illustrated by the sedimentation profile along the fence shown in Figure 2.20. There was not a single location where ground profile along the fence after the first three rainfall events eroded below the ground profile before installation of the tieback system. The six tieback sections after the first three rainfall events are shown in Figure 2.19 and a profile of the ground along the fence is shown in Figure 2.20.

(a) Section #1

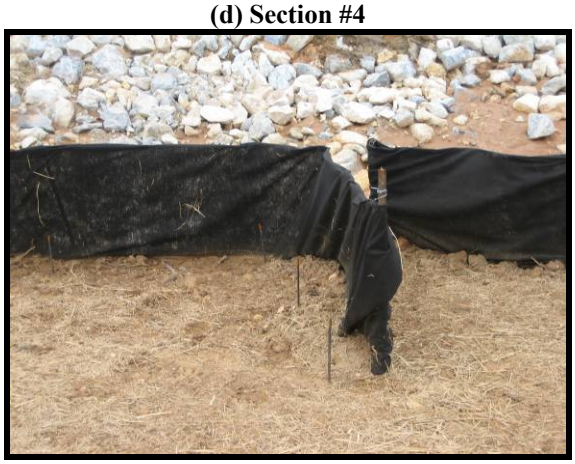
(b) Section #2

(c) Section #3

(d) Section #4



(e) Section #5



(f) Section #6

Figure 2.19 Six Tieback Sections After First Three Rainfall Events.

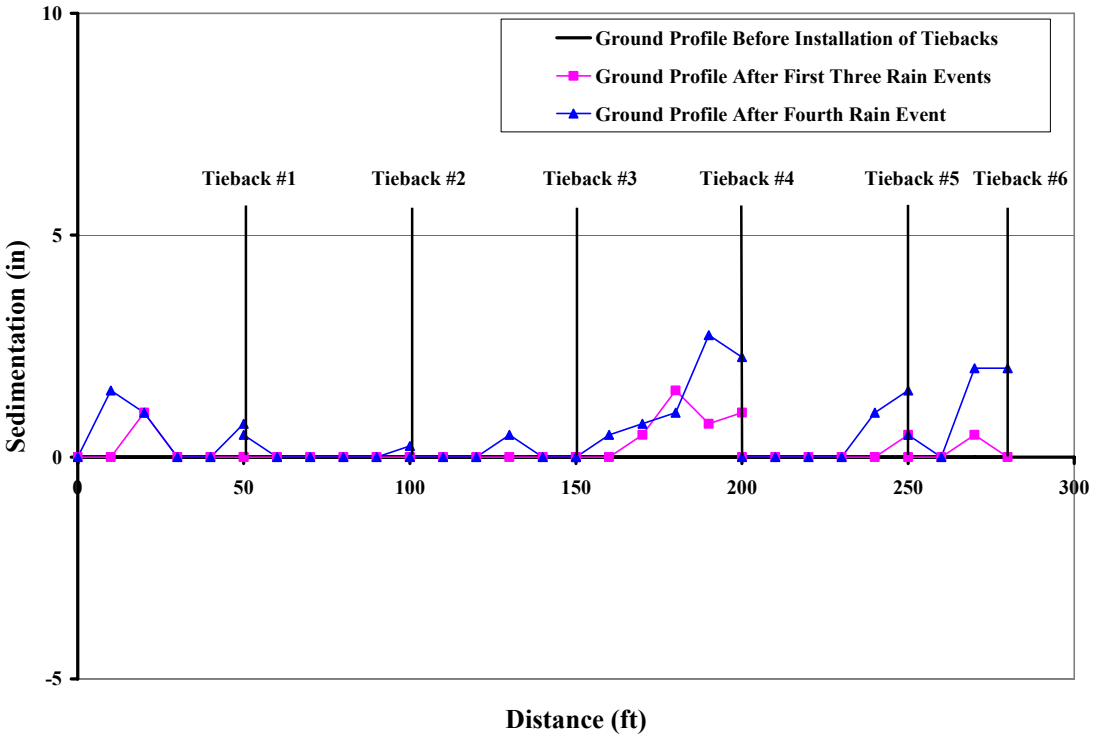


Figure 2.20 Sedimentation Profile Along the Fence of the Tieback System.

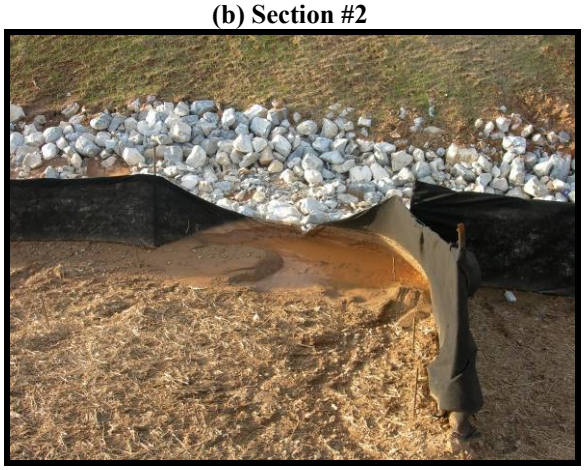
The fourth rainfall event that occurred during the research effort was much larger than the first three with a total rainfall depth of 2.5 in. This exceeded the design rainfall event for the tieback system by half an inch, but overall, the tieback system still performed as expected. Four of the six tieback sections were in good shape but the fence in two of the sections experienced partial structural failure due to excessive loads caused by heavy sedimentation and impounded water during the rainfall event. These near structural failures would not have occurred if the steel support posts of the silt fence system were closer together at the downslope end of the tieback sections. Even though these sections nearly failed structurally due to excessive loads, they still captured the eroded sediment from their contributing drainage areas. This can be seen from the heavy

sedimentation shown in Figure 2.21 and from the sediment profile shown in Figure 2.20 previously. After this event, extra steel posts were installed at the potential failure locations to provide added structural support and prevent future structural failures from occurring. During the very heavy fourth rainfall event, there were still no instances of erosion along the toe of the fence. The six tieback sections after the fourth rainfall event are shown in Figure 2.21.

(a) Section #1

(b) Section #2

(c) Section #3



(d) Section #4

(e) Section #5

(f) Section #6

Figure 2.21 Six Tieback Sections After the Fourth Rainfall Event.

The linear system, on the other hand, performed much differently than the tieback system. After the first three events, the linear system had the heaviest

sedimentation at a single location along the downslope end of the fence and erosion along the toe of the fence. This erosion, which was caused by stormwater runoff accumulating and flowing along the fence, exposed the toe of the fence in multiple upslope areas and could potentially lead to a system failure in the future. The concentrated sedimentation, though not a problem after the first three events, could also lead to a future failure in an event where more sedimentation occurs. The pictures of the linear system after the first three events are shown in Figure 2.22 through Figure 2.25 and the sedimentation profile along the fence is shown in Figure 2.26.

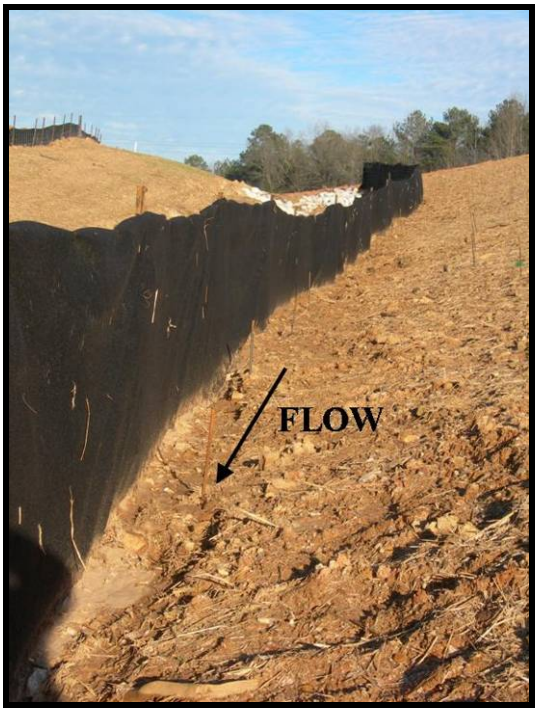


Figure 2.22 Upslope End of Linear Silt Fence w/ Little Sedimentation.

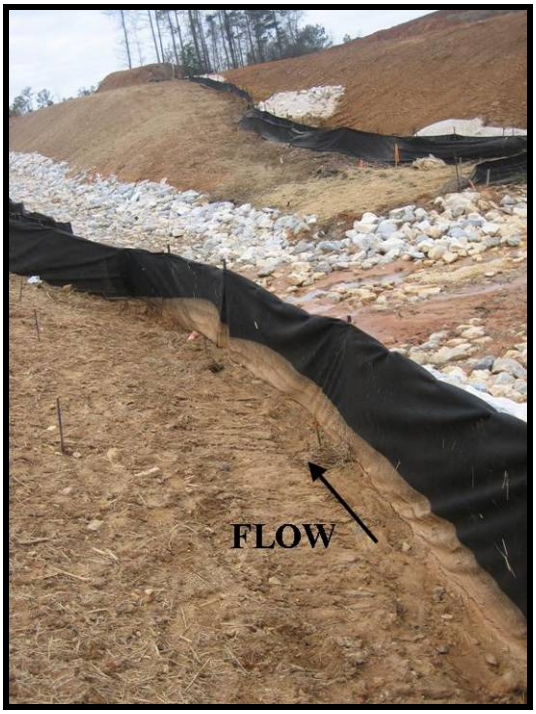


Figure 2.23 Downslope End of Linear Silt Fence w/ Heaviest Sedimentation.

Figure 2.24 Exposed Toe of Fence #1. **Figure 2.25 Exposed Toe of Fence #2.**

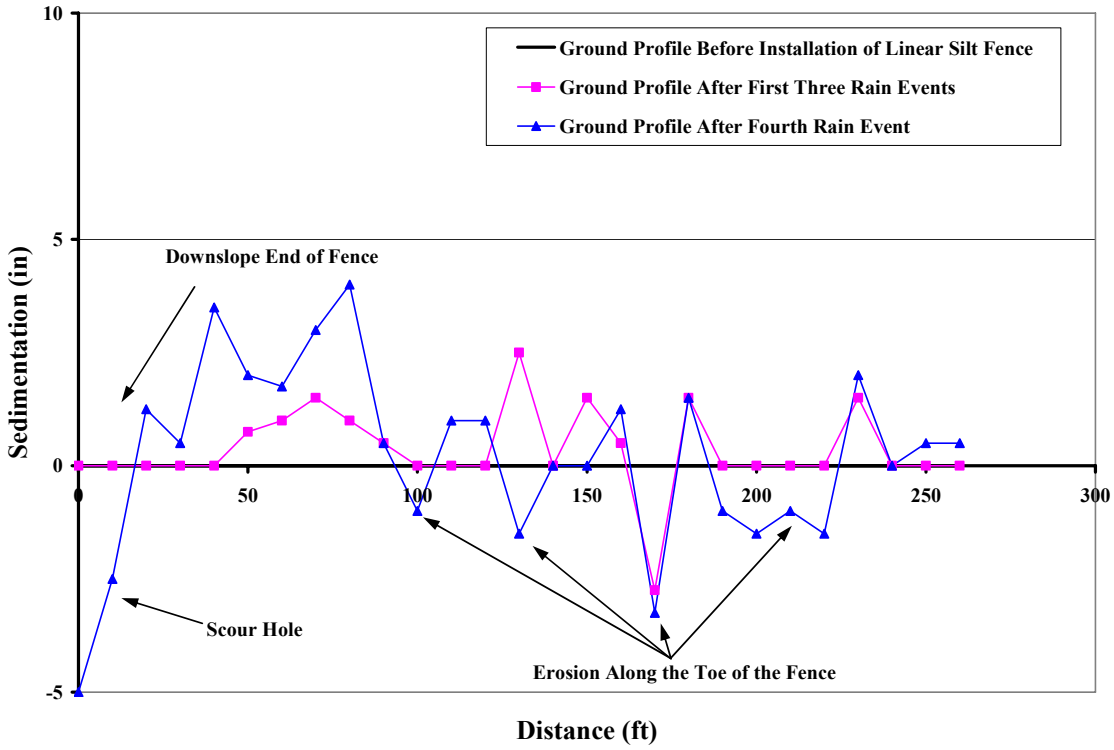


Figure 2.26 Sedimentation Profile Along the Fence of the Linear System.

The performance of the linear system during the fourth event was similar to its performance for the first three events. There was an obvious migration of sediment

towards the downslope end of the fence and toe of the fence was exposed even more at multiple upslope areas. One difference during the fourth event, though, was that a scour hole developed at the downslope end of the system and undercut the fence. This was probably due to the high velocity concentrated flow that occurred along the fence during the storm. When the high velocity flow reached the lowest point in the system, the shear stress caused by flow exceeded that of the underlying soil which resulted in a scouring effect. Pictures of the location of the scour hole before and after the fourth event are shown in Figure 2.27 and Figure 2.28 and the scour hole is also illustrated in the sedimentation profile shown in Figure 2.26 previously. Additional pictures of the linear system after the fourth storm are shown in Figure 2.29 through Figure 2.32.

Figure 2.27 Before Scour Hole at Downslope End of Linear Fence.

Figure 2.28 Scour Hole at Downslope End of Linear Fence.

Figure 2.29 Upslope End of Linear Fence w/ Little Sedimentation After Fourth Storm.

Figure 2.30 Downslope End of Linear Fence w/ Heavy Sedimentation After Fourth Storm.

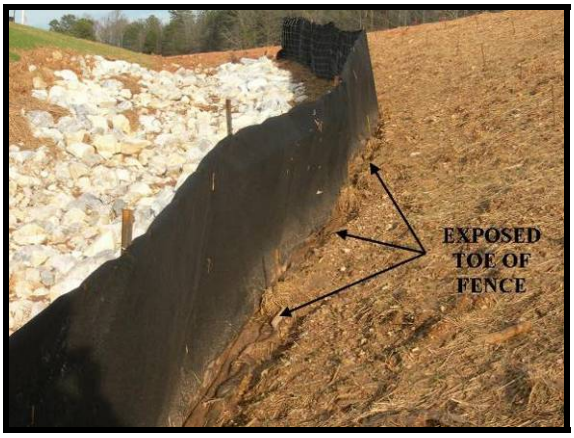


Figure 2.31 Exposed Toe of Fence After Fourth Storm.

Figure 2.32 Exposed Toe of Fence After Fourth Storm.

The sedimentation profiles and pictures shown in this section illustrate that both the silt fence tieback and linear systems performed as expected. The tieback system performed as expected by distributing the total sediment load between the six tieback sections and preventing erosion from occurring along the toe of the fence. The linear system, on the other hand, experienced concentrated flow along the fence which led to heavy sedimentation and scouring at the downslope end of the system and erosion along the toe of the fence at many upslope locations. This system, if not maintained after future

events, will eventually fail due to one or more of the modes discussed previously by Halverson (2006). The research team will continue to monitor this site during future rainfall events to quantitatively and qualitatively show that silt fence tieback designs are much more effective in controlling sediment and reducing system failures than traditional linear silt fence installations.

2.4 CONCLUSION

Sediment from poorly managed construction sites is a major environmental problem facing society today. This problem, though, can be addressed and prevented if the proper abatement procedures are designed and installed correctly. One such abatement method is the use of silt fence tieback systems. These systems serve as temporary sediment basins that promote the impoundment of construction site runoff allowing sediment and other suspended solids to settle out of suspension. By using the computational methods presented in this chapter, silt fence tieback systems can be designed correctly to effectively impound stormwater runoff, capturing sediment which will lead to a decrease in the amount of sediment leaving construction sites in the future. This containment of sediment on construction sites will help increase the integrity of our nation's water bodies and lead to a much healthier aquatic environment.

CHAPTER THREE

LITERATURE REVIEW: USE OF PAM AS AN EROSION AND SEDIMENT CONTROL BMP

3.1 INTRODUCTION

One potential method for preventing erosion on highway construction sites is the use of anionic polyacrylamide (PAM). PAM is a water soluble, negatively charged polymer chain that serves as a binding agent for soil particles. Typically, PAM is used in conjunction with ground cover practices such as seeding and mulching to promote soil structure and stability. The ground cover practices serve as the protection against detachment due to rain drop impact while the PAM serves as a soil stabilizing agent which maintains the soil structure and promotes infiltration. McLaughlin (2006) suggests that PAM should never be applied alone but always in conjunction with ground cover practices. Other studies have shown though that PAM applied to slopes without ground cover can serve as an effective erosion control alternative (Flanagan et al., 1997a, b; Flanagan et al., 2002a, b; Peterson et al., 2002; Roa-Espinosa et al., 1999). These conflicting results along with the conclusions of many other studies will be reviewed and discussed in this chapter.

The primary goal of this research was to determine from previous studies and our own research if PAM without ground cover can be an effective erosion control technology for highway construction sites where steep slopes are common. A secondary goal of this research was to determine whether PAM used for erosion control can also provide sediment control benefits by decreasing the settling time of suspended solids in surface runoff waters.

3.2 POLYMERS USED FOR EROSION AND SEDIMENT CONTROL

Some research suggests that PAM can be a viable erosion and sediment control alternative on construction sites if used correctly. This section will give an overview of PAM including the important variables to consider when selecting a polymer product, the different application methods of polymer products, and previous research addressing the effectiveness of polymers as erosion and sediment control alternatives.

3.2.1 Variables to Consider when Selecting a Polymer

PAM can be purchased in many forms and each form has its advantages and disadvantages. Four important variables to consider when selecting a polyacrylamide product are the i.) ionic strength, ii.) structure of the polymer, iii.) whether the polyacrylamide is in solid or liquid form, and iv.) the molecular weight. These four variables will be outlined in the following paragraphs to give a better understanding of the various forms of PAM available and how to select the proper PAM product for a construction site.

The first variable that should be considered in the PAM selection process is *ionic strength* or polymer charge. PAM is available in cationic, anionic, and non-ionic form.

Cationic PAM is positively charged and has been found to work significantly well as a flocculent for clay particles and other negatively charged substances. Currently, though, cationic PAM is proven to be environmentally harmful to aquatic habitat and therefore cannot be used in erosion and sediment control applications. Non-ionic (neutral charge) and anionic (negatively charged) PAM, on the other hand, have been approved for erosion and sediment control applications and are considered environmentally safe as long as they contain less than 0.05 percent free acrylamide. The non-ionic PAM is rarely used for erosion control due to its lack of interaction with charged soil particles, but anionic PAM has shown to be fairly effective in the control of sediment and erosion if used properly. For erosion and sediment control, PAM is typically used in conjunction with ground cover techniques such as seeding and mulching to provide soil structure stability

The next variable to consider when selecting a PAM product is the *polymer structure*. PAM is available in linear, fully cross linked, and branched form. These three polymer structures are shown in Figure 3.1. The linear form has a long snake-like structure and is most widely used in stormwater runoff applications. The fully cross linked form, on the other hand, has a net-like structure and is used in products such as diapers due to its water retaining capabilities. Finally, the partly cross linked form has a branched structure and is used in municipal sewer sludge applications. The polymer structure plays a very important role in its effectiveness for various applications and should be given considerable thought before choosing a PAM product. For erosion control in the construction industry, the linear polymer structure is the most widely used and provides the most effective results.

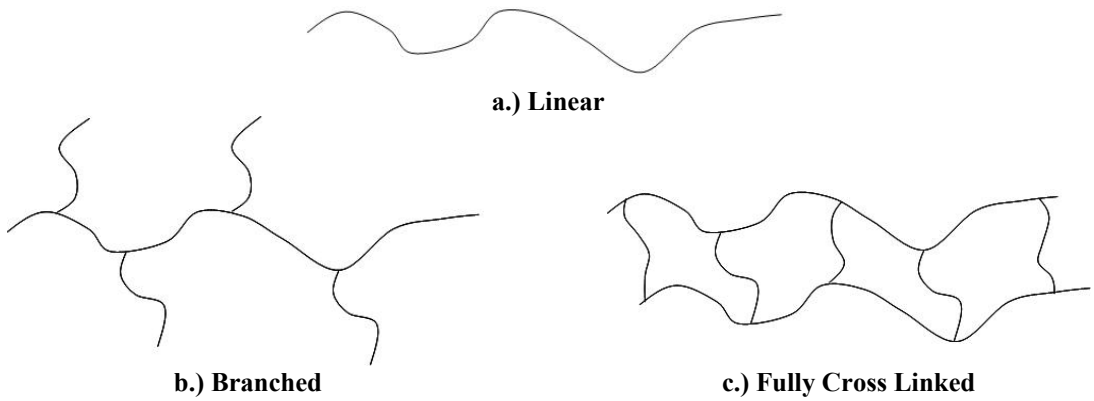


Figure 3.1 Polymer Structures

The third variable to consider is if the PAM is in *liquid or solid form*. There are advantages and disadvantages of both forms which should be considered in the product decision selection process. The solid form of PAM is typically available in powder or bead form with a polymer content ranging from 85% to 90% in the powder form and about 95% in the bead form. The powder form is cheaper than the liquid form and can be applied either in dry granular form or solution form mixed with water. When applied in solution form, it has to be carefully mixed because the water mixing process can be very sensitive and can lead to problems. When adding the solid granular PAM to water, it is important to introduce the granules slowly and under constant agitation. This will help prevent the formation of large globules caused by the granules sticking together which are hard to dissolve. The liquid PAM, on the other hand, is available as an inverse emulsion or dispersant with a polymer content ranging from 25% to 40% for emulsions and 50% for dispersants. The remaining contents of the liquid PAM mixture are typically oils which can lead to some environmental problems if used in areas of slow moving or stagnant water bodies such as ponds and lakes. The liquid form is more costly than the powder form but it is easier to handle because the mixing process is not required. The

advantages and disadvantages regarding the product form outlined above are very important in determining which PAM product to use.

The final variable that should be considered in the PAM selection process is the *molecular weight*. The molecular weight of a PAM product is a direct reflection of the size of the molecule. Therefore, as the molecular weight of the polymer increases, the size of the molecule also increases which leads to an increase in the number of bonding sites that are available along the polymer chain. An increase in molecular weight also leads to an increase in viscosity. The molecular weight of a PAM product cannot be directly measured due to limitations of current testing procedures; therefore, the PAM solution viscosity is commonly used for product comparison. The abovementioned four concepts play a major role in the performance of a polymer in the environment and should be carefully considered when choosing a PAM product.

3.2.2 Applying Polymers

PAM applications come in many different forms and can be applied in a number of ways for slope stabilization. The most common application methods of PAM are either applying it in the dry granular form or applying it as liquid solution using the dry granular form or liquid emulsion mixed with water. PAM is usually applied in the dry granular form using a spreader or by hand, and it is typically used in conjunction with additives such as seed and fertilizer and ground cover practices such as straw and mulch. PAM as a liquid solution is also typically mixed with a combination of seeds and mulches but is applied using a hydroseeder. When applying granular PAM using a hydroseeder, it is suggested by McLaughlin (2006) that approximately one pound of

PAM should be mixed per 100 gallons of water. If used at higher rates, the PAM solution may become very viscous leading to problems during the application process.

McLaughlin (2006) recommends that when applying granular PAM using a hydroseeder, the PAM should be added first and mixed for approximately 30 minutes with half a tank of clean water. The seed and mulch should then be added to the mixture along with the rest of the water to produce the hydromulch or hydroseed plus PAM solution. This solution can then be applied to the soil surface for erosion prevention. The application rate of PAM per acre can vary greatly depending upon the steepness of the land, but it has been recommended that, for steep slopes (≥ 10%), 20 pounds per acre is a minimum dose that can provide effective results (McLaughlin, 2006).

3.2.3 Previous Research on the Effectiveness of Polymers

In the construction industry, anionic PAM is typically the only PAM product used; therefore, the rest of this research will focus solely on the use of anionic PAM. Previous research in this area has provided conflicting results; therefore, more research is needed to determine if PAM can be an effective erosion control alternative for the highway construction industry. Most of the past research related to PAM was focused towards agricultural applications involving mildly sloped land (i.e. < 10%) (Flanagan et al., 1997a, b; Lentz et al., 2002; Bjorneberg et al., 2000; Shainberg et al., 1990). Results from these studies have demonstrated the benefits of using PAM, but the recommended application rates may not provide effective results in the highway construction industry where slopes are generally steeper. This was highlighted in research performed by Hayes et al. (2005) and McLaughlin and Brown (2006). Other studies, though, have shown that

PAM applied to steep slopes (i.e. ≥ 10%) at higher application rates can serve as an effective erosion control alternative even when used without ground cover practices (Flanagan et al., 1997a, b; Flanagan et al., 2002a, b). Results of these studies along with other research regarding the use of PAM as an erosion control technology are reviewed in the following sections.

3.2.3.1 PAM Applied to Mild Slopes (i.e. < 10%)

Flanagan et al. (1997a, b) evaluated the use of PAM as an erosion control technology under simulated rainfall conditions with an intensity of 64 mm/h. The experiments were performed near West Lafayette, Indiana on a Russell silt loam soil that was disked prior to testing. The research showed that PAM applied to fairly mild slopes of 6% to 9% at an application rate of 20 kg/ha significantly reduced runoff and sediment transport for the initial rain event. For the following rain events, sediment transport was still reduced but there was no significant reduction in runoff.

Shainberg et al. (1990) tested the effectiveness of PAM on a 5% slope using simulated rainfall with an intensity of 38 mm/h. These results showed that infiltration rates nearly tripled when PAM was applied at rates of 20 and 40 kg/ha. Other research on mild slopes using much lower application rates than the previous studies also showed the benefits of using PAM (Bjornberg et al., 2000; Lentz et al., 2002). Bjornberg et al. (2000) tested the effectiveness of PAM applied to a Roza loam on a 2.4% slope. The PAM was applied through sprinkler irrigation at rates of 2 and 4 kg/ha to bare soil and soil with straw cover. Simulated rainfall with an 80 mm/h intensity and 15 minute duration was used for this research. The results show that PAM applied to a 70% straw

covered surface reduced runoff by 75% to 80% while PAM applied to the bare soil reduced runoff by 30% to 50%. Lentz et al. (2002) applied PAM at a rate of 1.8 kg/ha in furrow irrigation water to a Portneuf silt loam at a 1.5% slope and found that sediment loss was reduced by an average of 82%. Each irrigation process used for this research applied approximately 68 mm of water over a 12 hour period. These studies show that PAM can be an effective erosion control alternative for mild slopes (i.e. < 10%).

3.2.3.2 PAM Applied to Steep Slopes (i.e. ≥ 10%)

We will now review research studies have evaluated the use of PAM on steeper slopes (i.e. ≥ 10%) commonly encountered on highway and other construction sites. The studies include work completed by Hayes et al. (2005), McLaughlin and Brown (2006), Flanagan et al. (2002a, b), Peterson et al. (2002), and Roa-Espinosa et al. (1999). Hayes et al. (2005) performed a study on three North Carolina Department of Transportation (NCDOT) job sites in the Piedmont and Coastal Plain areas to determine the effects of PAM when used alone and in conjunction with grass seeding and straw mulching applications. They characterized the reduction in runoff volumes, turbidity levels, and sediment losses after natural rain events. Two test sites were developed for the research effort in the Piedmont area and one test site was developed in the Coastal Plain area. The Piedmont sites were developed on 20% and 50% slopes while the Coastal Plain site was developed on a 20% slope. The two Piedmont sites received a total of 58 mm and 161 mm of precipitation respectively over six storm events, and the Coastal Plain site received a total of 115 mm of precipitation over seven storm events. At each of the sites, tests were completed with control plots consisting of bare soil (i.e. control), plots with

PAM only, and plots with PAM plus seed and mulch. Two different PAM products, Solifix from Ciba Specialty Chemicals and Siltstop 705 from Applied Polymer Systems, were applied according to the application rates recommended by the manufacturer. These products were also applied at half of the recommended rates for comparative purposes. The recommended application rate for Solifix and Siltstop 705 was 1.3 lb per acre and 9.3 lb per acre respectively.

The results from the study show that the application of seed and mulch was effective in reducing the turbidity and sediment loss at the three test locations but the addition of PAM did not significantly have an effect on the results. Neither the addition of PAM nor seed and mulch had an impact on the runoff volume from the three test locations. The reason why PAM did not reduce the runoff volume, turbidity, and sediment loss may be due to the low application rates.

Another study, performed by McLaughlin and Brown (2006), found similar results. McLaughlin and Brown (2006) evaluated the effects of PAM on erosion control when used alone and in conjunction with four different types of ground cover practices commonly used in the construction industry. The ground cover practices evaluated with and without PAM were straw, wood fiber, straw erosion control blankets (ECB), and mechanically bonded fiber matrix (MBFM). PAM was applied for testing at a rate of 19 kg/ha and control tests were also performed using bare soil plots. These tests were performed using natural rainfall events on field plots and simulated rainfall on 1 m wide by 2 m long and 9 cm deep wooden boxes filled with soil. The field plots had slopes of 4% and consisted of a Cecil silt loam material that was tilled prior to testing. These field plots experienced five natural rainfall events totaling 148 mm over a 36 day period. The

soil boxes, on the other hand, were sloped at 10% and 20% and three different soil types (sandy clay loam, sandy loam, loam) were used. The soil boxes were loaded with approximately 140 kg of soil and leveled by hand with no further compaction. Two tests were run on the soil boxes with the first test consisting of two consecutive rainfall events and the second consisting of four. The simulated rainfall events produced a rainfall intensity of 3.4 cm/h and were run for five minutes after the start of surface runoff.

The results from this study show that the use of ground cover practices significantly reduced the runoff volume, sediment loss, and turbidity in both the field plots and the soil boxes. The application of PAM did not provide a significant benefit in most cases. Exceptions were that it did increase vegetative cover overall, and it reduced turbidity on the field plots and in some cases on the soil boxes when used in conjunction with ground covers. PAM also worked well in reducing the turbidity for the 20% slope for successive rainfall events. This research concluded that, "PAM at the 19 kg/ha rate does not always provide water quality benefits beyond that of a ground cover alone" (McLaughlin and Brown, 2006) and that additional testing needs to be performed.

Other research was performed by Flanagan et al. (2002a) using higher application rates of PAM than used by McLaughlin and Brown (2006). This research evaluated the effects of two soil treatments under simulated rainfall conditions on silt loam topsoil at a 32% slope. The two soil treatments included: (1) PAM with a charge density of 32% and a molecular mass of 20 Mg/mol applied at a rate of 80 kg/ha and (2) the same PAM treatment in conjunction with 5 Mg/ha of gypsum. The PAM product used for this research was Percol 336 which is manufactured by Ciba Specialty Chemicals. A bare soil control was also evaluated for comparative purposes.

The three scenarios were tested on 2.96 m wide by 9.14 m long test plots and the experiments were replicated three times. The plots were rototilled prior to testing producing a disturbed surface. Three consecutive simulated rainfall events were used for the tests totaling 176 mm over 4.25 hours. The first event produced a 25 year storm with a rainfall intensity of 69 mm/h for one hour duration. The test plots were allowed to dry for an hour and a second event was simulated at the same intensity and duration as the first. Finally, the plots were allowed to dry for thirty more minutes before being rained on for an additional 45 minutes. The final 45 minutes of rain consisted of three 15 minute events with intensities of 64 mm/h, 28 mm/h, and 100 mm/h respectively. The cumulative rainfall event over the 4.25 hour period corresponds to a return period of greater than 100 years.

The results from the experiments show that the addition of PAM and PAM-and-gypsum can be an effective solution for reducing erosion on steep slopes. Overall, the PAM treatment reduced runoff by 40% and sediment yield by 83%, while the PAM-and-gypsum treatment reduced runoff by 52% and sediment yield by 91%. The added benefits from the addition of gypsum can be attributed to, according to Flanagan et al. (2002a), increased multivalent cation levels which reduced clay dispersion and improved the effectiveness of PAM. In conclusion, Flanagan et al. (2002a) suggests that PAM soil amendments can provide a viable alternative for erosion control on steep slopes due to their effectiveness and cost versus other conventional erosion control techniques.

This conclusion was expanded upon in Flanagan et al. (2002b). Flanagan et al. (2002b) studied the effects of PAM and PAM-and-gypsum on runoff, sediment yield, and vegetation establishment for steep slopes under natural rainfall conditions. In this

research, test plots 2.96 m wide by 9.14 m long were established at two experimental test sites. The first test site was at an Indiana Department of Transportation (INDOT) project on a clay loam highway cut slope with a 35% gradient, and the second site was at a Waste Management, Inc. recycle disposal facility (RDF) on a silt loam landfill cap with a slope of 45%. Three test plots were developed at the two sites consisting of a bare soil control plot, a plot with PAM only, and a plot with PAM-and-gypsum. The same PAM and PAM-and-gypsum treatments from the previously mentioned study were used and the experiments were replicated three times. The plots were tilled by a hand pick prior to testing to a depth of 4 to 5 cm. Nine natural runoff-producing rainfall events totaling 214 mm occurred over a two month period on the INDOT site while 17 runoff-producing events totaling 688 mm occurred over a five and a half month period on the RDF site.

The results from this study show that the use of PAM and PAM-and-gypsum can be an effective solution for reducing erosion and promoting vegetative growth on steep slopes. At the INDOT site, sediment yield was reduced 54% from the PAM treatment and 45% from the PAM-and-gypsum treatment. Runoff was also reduced at this site by an average of 33% for both treatments though runoff was not significantly reduced for the larger events where rainfall exceeded 25 mm. This could have been due to very wet antecedent moisture conditions from previous rain events. At the RDF site, sediment yield was reduced 40% and 53% respectively from the PAM and PAM plus gypsum treatments. Runoff for this site was reduced by 15% for the PAM treatment and 28% for the PAM plus gypsum treatment when compared to the control. The treatments though did not seem to have a significant effect for events with greater than 55 mm of rain. This could probably be contributed to the high antecedent moisture conditions from previous

rain events. The conclusions of this research is similar to that found previously by Flanagan et al. (2002a) in that PAM can be a good alternative for erosion control on steep slopes.

Other research that has shown PAM to be an effective alternative for erosion control was performed by Peterson et al. (2002). Peterson et al. (2002) performed a field study using simulated rainfall to evaluate the effectiveness of the method of application of PAM (dry or liquid) and the effectiveness of a multivalent electrolyte (Ca^{++}) source when used in conjunction with PAM. According to Peterson et al. (2002), "the benefits of PAM are enhanced by the introduction of an electrolyte source (multivalent cations) that helps to create a cation bridge for the polymer to absorb to the soil" (Peterson et al., 2002). To test this idea, there were three PAM treatments used in the research plus an untreated control. The treatments included: (1) PAM in liquid solution plus Nutra-Ash, (2) granular PAM plus Nutra-Ash, and (3) PAM in solution with SoilerLime. The PAM product used was Percol 336 which has a charge density of 32% and molecular mass of 20 Mg/mol. PAM was applied at a rate of 60 kg/ha for all treatments. The Nutra-Ash and SoilerLime were applied at rates that produced the same amount of Ca^{++} as provided by the 5 Mg/ha of gypsum used in previous research by Chaudhari (1999).

The Peterson et al. (2002) study developed 12 - 3.0 m wide by 9.1 m long test plots using silt clay topsoil on a hillslope in West Lafayette, Indiana. The average slope of the plots was 16.6% plus or minus 0.3%. Each plot contained approximately 12 cubic meters of soil that was raked and leveled by hand with no further compaction. The simulated rainfall events used for the experiments consisted of a combination of three successive storm events. The first rainfall event had an intensity of 75 mm/h for a one

hour period. The plots were then allowed to dry for an hour before the second rainfall event began. The second event also had an intensity of 75 mm/h and duration of one hour followed by a 30 minute break. The final 45 minutes of rain consisted of three 15 minute events with intensities of 75 mm/h, 28 mm/h, and 100 mm/h respectively. The cumulative rainfall event over the 4.25 hour period corresponds to a return period of greater than 100 years.

The results from this study show that PAM applied as a liquid solution in conjunction with a Ca^{++} source is much more effective in preventing erosion than PAM applied in dry granular form with a Ca^{++} source. PAM applied in the liquid form reduced total runoff by 62% to 76% and sediment yield by 93% to 98% while the PAM applied in the dry granular form provided almost no benefit. This research suggests that PAM can be an effective alternative for erosion control if applied in the liquid form with a Ca^{++} source. The effectiveness of PAM alone without a Ca^{++} source was not investigated in this study.

The last research that will be discussed was performed by Roa-Espinosa et al. (1999). In this study, four different soil treatments along with a bare soil control were tested on 1 m by 1 m plots on a 10% slope using simulated rainfall. The four soil treatments included: (1) liquid PAM solution applied to dry soil, (2) dry granular PAM applied to dry soil, (3) liquid PAM solution with seeding and mulching applied to dry soil, and (4) liquid PAM solution applied to wet soil. The PAM was applied at a rate of 22.5 kg/ha and the soil type used for the tests was a Dodge silt loam. A rainfall intensity of 6.4 cm/h was used, and the experiments were run for 40 to 50 minutes depending on the amount of runoff that was produced.

The results from this study show that all of the soil treatments significantly reduced the sediment yield of the test plots. The worst soil treatment was the liquid PAM applied to wet soil, and it still reduced average sediment yield by 77%. The PAM plus seeding and mulching provided the best results by reducing the average sediment yield by 93%, and the dry PAM mix reduced the sediment yield by 83%. Roa-Espinosa et al. (1999) concludes by stating, "the ease of application, low maintenance, and relatively low cost associated with PAM make it a practical solution to the costly methods being implemented today" (Roa-Espinosa et al., 1999).

3.3 SUMMARY

Anionic PAM is a negatively charged polymer chain that can potentially serve as an effective erosion control abatement technology if properly used. PAM is typically applied for slope stabilization in either a dry granular form using a spreader or as a liquid solution using a hydroseeder. Ground cover practices, such as seeding and mulching, are commonly used in conjunction with the application of PAM and serve as protection against soil detachment due to rain drop impact. The PAM product then acts as a soil stabilizing agent which maintains soil structure and reduces erosion.

Previous research suggests, in many cases, that PAM can be an effective erosion control technology. When used in agricultural applications on fairly mild slopes (i.e. < 10%), PAM has proved to be very effective (Flanagan et al., 1997a, b; Lentz et al., 2002; Bjornberg et al., 2000; Shainberg et al., 1990). When used on steeper slopes that are commonly encountered in the construction industry (i.e. ≥ 10%), there have been mixed results. Hayes et al. (2005) and McLaughlin and Brown (2006) found that there was not

an added benefit from using PAM when compared to using straw and mulch. This lack of benefits may be contributed to the low application rates (0.76 - 19 kg/ha) used in their studies. Other studies using higher application rates (22.5 – 80 kg/ha) found PAM to be a very effective erosion control technology even when used without ground cover techniques (Flanagan et al., 2002a, b; Peterson et al., 2002; Roa-Espinosa et al., 1999).

Of all the studies mentioned above, none were conducted with PAM on compacted slopes which are typical of highway construction sites. All of the studies, instead, have dealt with uncompacted slopes that were usually tilled prior to PAM application. The fact that uncompacted tilled slopes are not a realistic representation of slopes encountered on highway construction sites indicates the need for future research. This research should incorporate typical construction procedures and create a more realistic testing environment which can be applicable to the highway construction industry. Issues that need to be addressed for compacted steep slopes include: (1) the effectiveness of PAM applied alone in the dry granular form, (2) the effectiveness of PAM applied alone as a liquid solution (3) the effectiveness of PAM when used in conjunction with ground cover practices, (4) the effectiveness of ground cover practices alone, and (5) the effectiveness of PAM on various soil types. This research will attempt to address the first of these five issues in order to create a better understanding of the possible role of dry granular PAM when applied alone as an erosion control alternative on highway construction sites. It is recommended that future research should address the remaining four issues.

CHAPTER FOUR

INTERMEDIATE-SCALE EROSION CONTROL EXPERIMENTS USING PAM

4.1 INTRODUCTION

Previous research suggests that PAM can be an effective erosion abatement technology if used properly. To test this idea, intermediate-scale physical experiments were performed using dry granular PAM on a silty sand material. Three scenarios were modeled including a bare soil control and PAM applied at rates of 20 and 40 lb/ac. A series of three simulated rainfall events were used for the tests and each test was replicated three times. The details of the intermediate-scale model, experimental design, and test results will be discussed in the following sections. The results from this research will provide valuable insight on the effectiveness of granular PAM as an erosion control technology. This research will also attempt to determine the effect of PAM on the settling time of suspended solids in surface runoff when applied as a surface stabilization BMP for erosion control.

4.2 INTERMEDIATE-SCALE MODEL

An intermediate-scale physical model of a highway construction site was previously developed at Auburn University by Halverson (2006) to study the

effectiveness of silt fence tieback systems as a sediment control technology. This model was modified to meet the objectives of our study concerning PAM as an erosion control technology. The original model developed by Halverson (2006) was a one-sixth scaled down version of a 48 ft. by 48 ft. roadway section from the centerline of the road to the ROW. The model had a roadway deck and shoulder with a 2% cross slope, a 3H:1V fill slope, and a 2% existing ground section at the bottom of the slope. A five nozzle rainfall simulator was attached to the model and the model was also sloped 2% in the longitudinal direction. Further details of this design can be found in Halverson (2006). The original intermediate scale model as designed by Halverson (2006) is shown in Figure 4.1.

Figure 4.1 Intermediate-Scale Model Designed by Halverson (2006).

The model shown in Figure 4.1 was modified slightly to meet our research objectives. We wanted to develop a model where multiple replications of the same scenario could be tested simultaneously. Therefore, the road section was completely blocked off and the model was divided into three equal sections. The modified design divided the previously 96 in. wide by 69 in. long by 6 in. deep fill slope section into three 32 in. wide by 69 in. long by 6 in. deep soil plots. A new six nozzle rainfall simulator was also designed and installed by the research team to replace the old five nozzle system. The modified intermediate-scale model is shown in Figure 4.2 and the details of the model components are discussed in the following sections.

Figure 4.2 Modified Intermediate-Scale Erosion Model.

4.2.1 Soil Plot Design

The model shown in Figure 4.2 consisted of three identical soil plot sections. Each section had a 57 in. long fill slope with a 33.3% gradient and a 12 in. long existing ground section with a 2% gradient at the bottom of the fill slope. The plots were 6 in. deep and had drains to collect both the surface runoff and infiltration. Prior to testing, the plots were loaded with two 3 in. layers of fill materials. The top 3 in. of the plots contained a compacted silty sand material. A Unified Soils Classification System (USCS) classification was conducted on this material by Halverson (2006) and the material classified as a poorly graded sand (SP). The bottom 3 in. consisted of a lightweight, porous Expanded Polystyrene (EPS) material that was overlaid with a SKAPS W200 Woven Geotextile Fabric. The EPS material was used for the bottom 3 in. of the plots to reduce the overall load on the supporting structure caused by the weight of the material in the plots. The EPS layer also had a very high hydraulic conductivity which allowed the research team to measure the amount of water that infiltrated through the above soil layer. The geotextile filter fabric separating the two layers served as a barrier to prevent the fine soil particles from entering the EPS layer. The intermediate scale model after installation of the ESP material, geotextile filter fabric, and silty sand material is shown in Figure 4.3 through Figure 4.5 and a cross-sectional view of the plots is shown in Figure 4.6. The specifications for the SKAPS W200 Woven Geotextile Fabric are shown in Appendix C.

Figure 4.3 Intermediate-Scale Model After Installation of EPS Material.

Figure 4.4 Intermediate-Scale Model After Installation of Geotextile Filter Fabric.

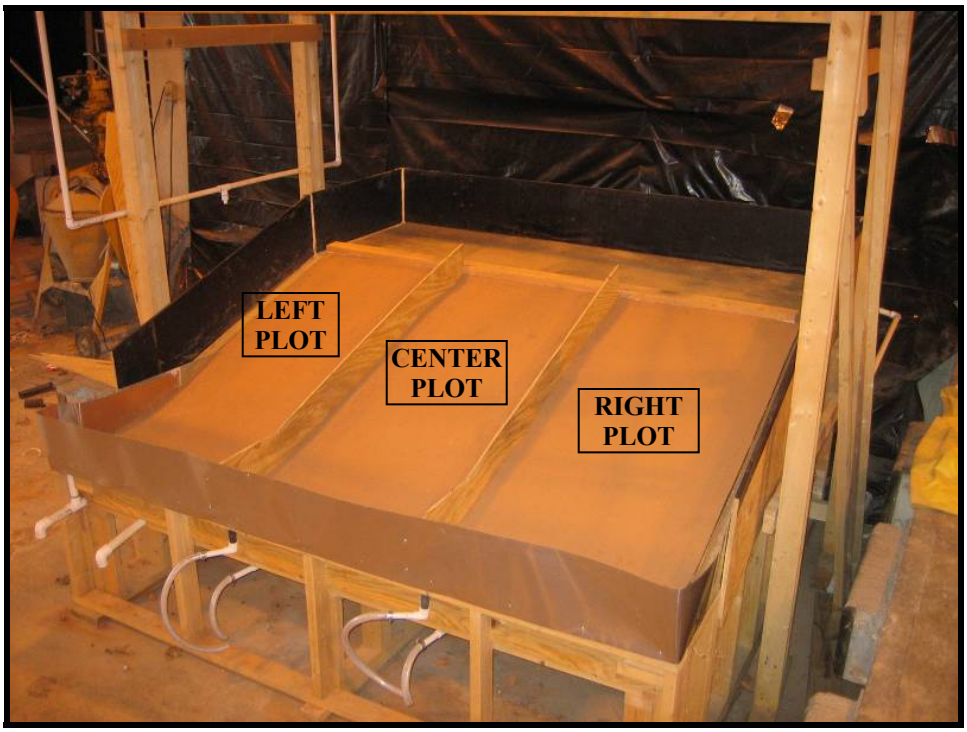


Figure 4.5 Intermediate-Scale Model After Installation of Silty Sand Material.

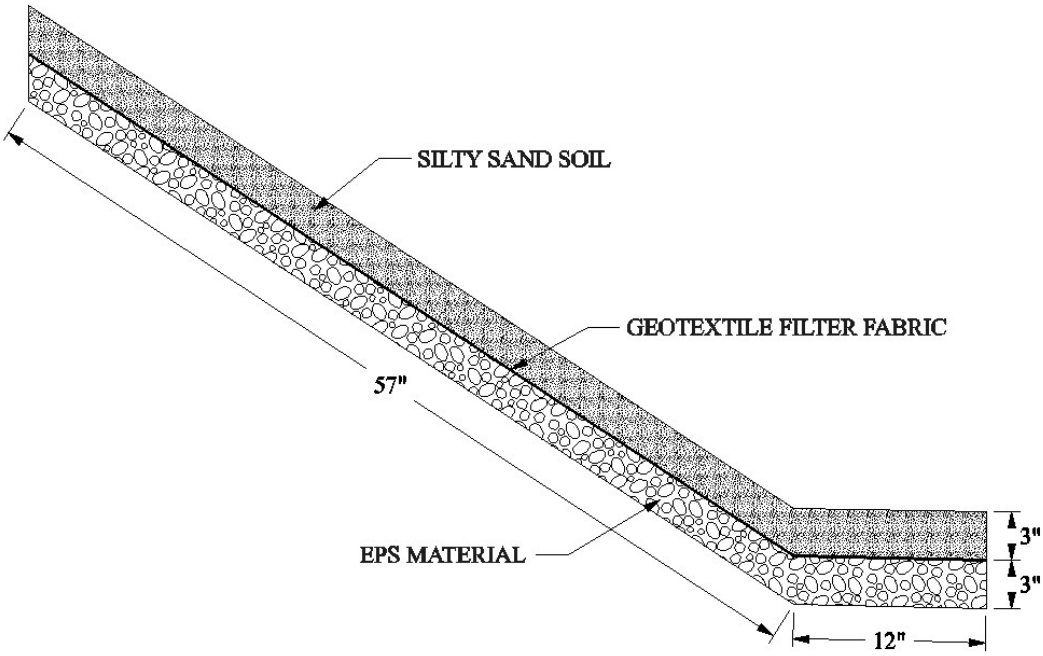


Figure 4.6 Cross-Section of Soil Plots.

4.2.2 Rainfall Simulator Design

A new rainfall simulator was designed by the research team to provide uniform coverage over the three soil plot sections. The simulator was made from ¾ in. schedule 40 PVC pipe and consisted of six 1/8HH-3.6SQ Fulljet spray nozzles and a F-405 Series In-Line Flow meter. These components were the same as those used in the previous simulator designed by Halverson (2006). The six spray nozzles were configured in a rectangular grid and were spaced 32 in. apart in both directions providing each soil plot with two spray nozzles. The spray pattern of these two nozzles provided nearly uniform coverage for their corresponding soil plots. The configuration of the spray nozzles is shown in Figure 4.7. One of the 1/8HH-3.6SQ Fulljet spray nozzles and the F-405 Series In-Line Flow meter are shown in Figure 4.8 and Figure 4.9 respectively and the specifications are included in Appendix D and E.

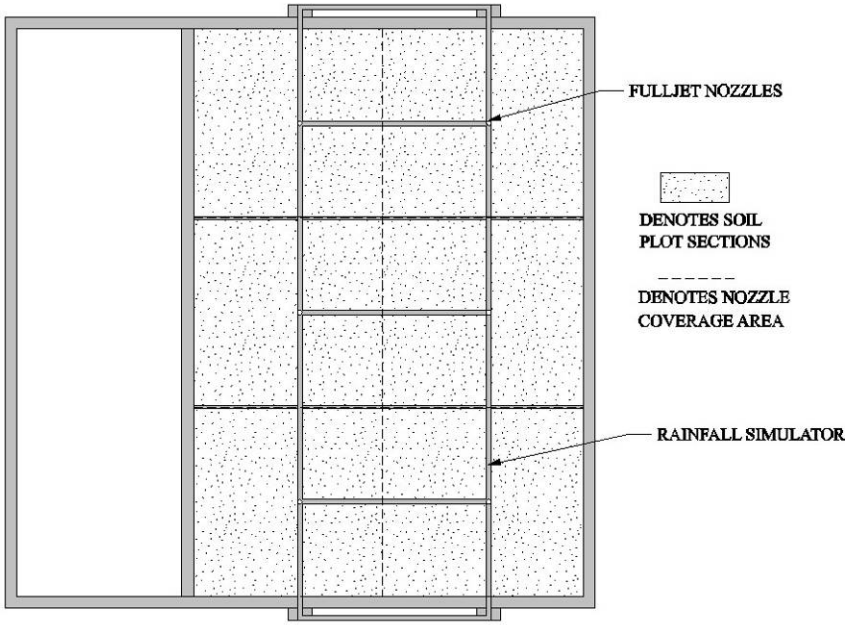


Figure 4.7 Rainfall Simulator Configuration.

Figure 4.8 1/8HH-3.6SQ Fulljet Spray Nozzle.

Figure 4.9 F-405 Series In-Line Flow Meter

4.3 EXPERIMENTAL DESIGN

Three different experimental scenarios were tested using a silty sand material on the intermediate-scale model developed at Auburn University. These three scenarios consisted of a bare soil control and dry granular PAM applied at rates of 20 and 40 lb/ac. To yield reproducible results, each soil plot was prepared the same way and the same rainfall regimen was used throughout testing. The details of the polymer selection, soil plot preparation, rainfall regimen, and data collection procedure used for the modeling effort will be discussed in the following sections.

4.3.1 Polymer Selection

Prior to using a PAM product, testing should be performed to determine which PAM product provides the best results for a particular type of soil. A sample of the silty sand material being used for this research was sent to Applied Polymer Systems (APS) in Woodstock, GA. APS recommended using the 705 Silt Stop powder applied at an

application rate of 35 to 45 lb/ac to provide the best results. Therefore, the 705 Silt Stop powder was applied at the recommended rate (40 lb/ac) and half the recommended rate (20 lb/ac). The 705 Silt Stop powder is shown in Figure 4.10 and the Material Safety Data Sheet (MSDS) for the product is attached in Appendix F.

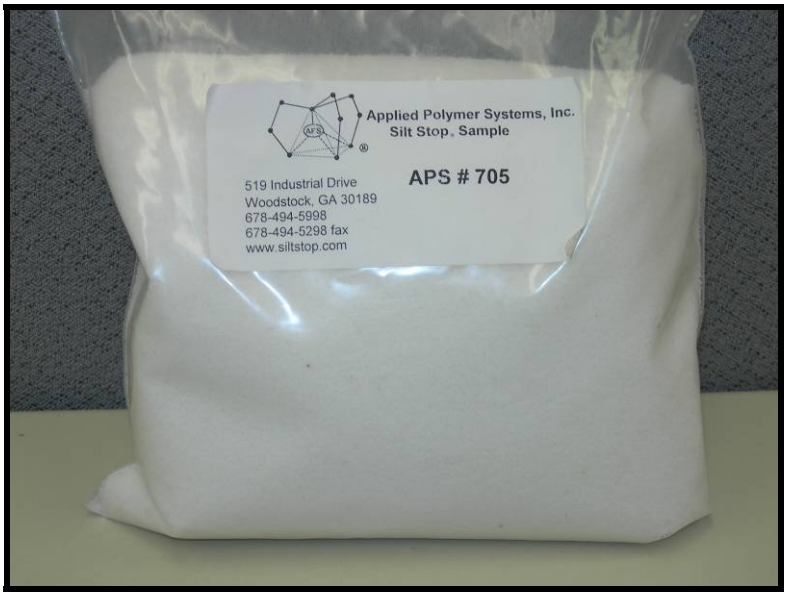


Figure 4.10 705 Silt Stop Powder.

4.3.2 Soil Plot Preparation

Prior to each test, the 6 in. deep soil plots shown in Figure 4.2 were loaded with 3 in. of EPS material and covered with a SKAPS W200 Woven Geotextile Fabric. The geotextile fabric was then fastened down and the silty sand material was loaded into the model in three 1 in. lifts. Each lift was rolled 20 times for compaction using an aluminum weighted hand held roller that was fabricated at Auburn University. The process of compaction by rolling each lift 20 times was determined by Halverson (2006). Halverson (2006) performed a standard proctor test on the silty sand material and the results showed that the optimum moisture content was 13.0% which corresponded to a

compacted dry unit weight of 117.2 lb/ft^3. Additional testing by Halverson (2006) on this material showed that 20 passes over a 1 in. lift with the aluminum weighted hand held roller resulted in approximately 90% compaction at a moisture content of 7%. Therefore, for our research, the water content of the material was raised to approximately 13% before loading it into the model and the material was compacted following the method used by Halverson (2006).

On the day of testing, the soil plots were saturated and the 705 Silt Stop powder was applied. Since the tests started from a saturated condition, surface runoff began immediately which increased the amount of erosion occurring on the model. The 705 Silt Stop powder was applied to the model using a salt shaker. The 40 lb/ac application rate translated to 6.4 grams of polymer powder per soil plot.

4.3.3 Rainfall Regimen Used for Testing

The simulated rainfall used in this research effort consisted of a combination of three successive high intensity, short duration storm events. These high intensity, short duration storms were intended to simulate a worst case scenario situation and provide valuable information on the efficiency of the granular PAM as an erosion control technology. The rainfall events used for the tests were approximately 5-yr, 15-minute storms for Mobile, AL with each having an intensity of 6 in/hr and duration of 15 minutes. There was a one hour break between each storm and the cumulative rainfall depth for the three successive storms was 4.5 in. over a 165 minute period. A storm for Mobile, AL was used because it provided the most conservative 5-yr, 15-minute rainfall event for the State of Alabama.

4.3.4 Data Collection Procedure

During each model run, the total surface runoff and infiltration flow were collected in one minute intervals. These samples were collected in clear, five quart buckets with volume markings up the sides. The total runoff and infiltration volumes for each minute were recorded and a 50 mL grab sample was taken from each surface runoff collection bucket for turbidity analysis. Prior to taking this turbidity sample, the surface runoff was stirred to represent the actual turbidity of the surface runoff when leaving the soil plots. Once the turbidity samples were collected, the surface runoff was poured into Hayward single-length filter bags with one micron pore sized pores. The water was allowed to flow out of these bags and the bags were placed in the oven to obtain the dry weight of solids leaving the soil plots. Each filter bag contained the transported sediment from five minutes of testing. Therefore, there were a total of 27 bags used per experiment. The buckets used for collection of the surface runoff and Hayward single-length filter bags are shown in Figure 4.11 and Figure 4.12 below.

Figure 4.11 Collection Buckets for Surface Runoff.

Figure 4.12 Hayward Single-Length 1 Micron Filter Bags.

After the tests, the 50 mL turbidity samples were taken to the lab and analyzed. Each of the samples was shaken up and a turbidity reading was taken using a Hach 2100AN Tubidimeter to determine the turbidity of the surface runoff while leaving the soil plots. This data was then plotted versus time to determine the effectiveness of PAM on reducing the turbidity of surface runoff. Further analysis was done on samples from the first, fifth, tenth, and fifteenth minutes of each experiment. These samples were shaken up, placed into the turbidity meter, and turbidity readings were recorded in one minute intervals for fifteen minutes. These data sets showed turbidity reduction versus time and were used to determine the effect that PAM had on the settling time of the suspended solids in the surface runoff. The procedures outlined in this section were repeated for every experimental scenario (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM) and the results are discussed in the following section.

4.4 RESULTS AND DISCUSSION

For each of the three tests, the cumulative volume (runoff plus infiltration) versus time, the cumulative surface runoff volume versus time, cumulative soil loss versus time, and turbidity of the surface runoff versus time were plotted to compare the results. Turbidity samples from the first, fifth, tenth, and fifteenth minutes were also analyzed to observe the effectiveness of the two application rates of PAM on the settling time of fine particles in the surface runoff. These five data sets for each test will be discussed in detail in the following sections.

4.4.1 Cumulative Volume versus Time

For each model run, the surface runoff and infiltration volumes were collected to determine if the three soil plot sections were receiving approximately the same amount of rainfall for each experimental scenario. The cumulative volume (runoff plus infiltration) versus time was plotted for each soil plot section and the results are shown in Figure 4.13 through Figure 4.15 below. There was a one hour break in between each 15 minute rain event (Run 1- Run 3) but for illustrative purposes the data was plotted continuously.

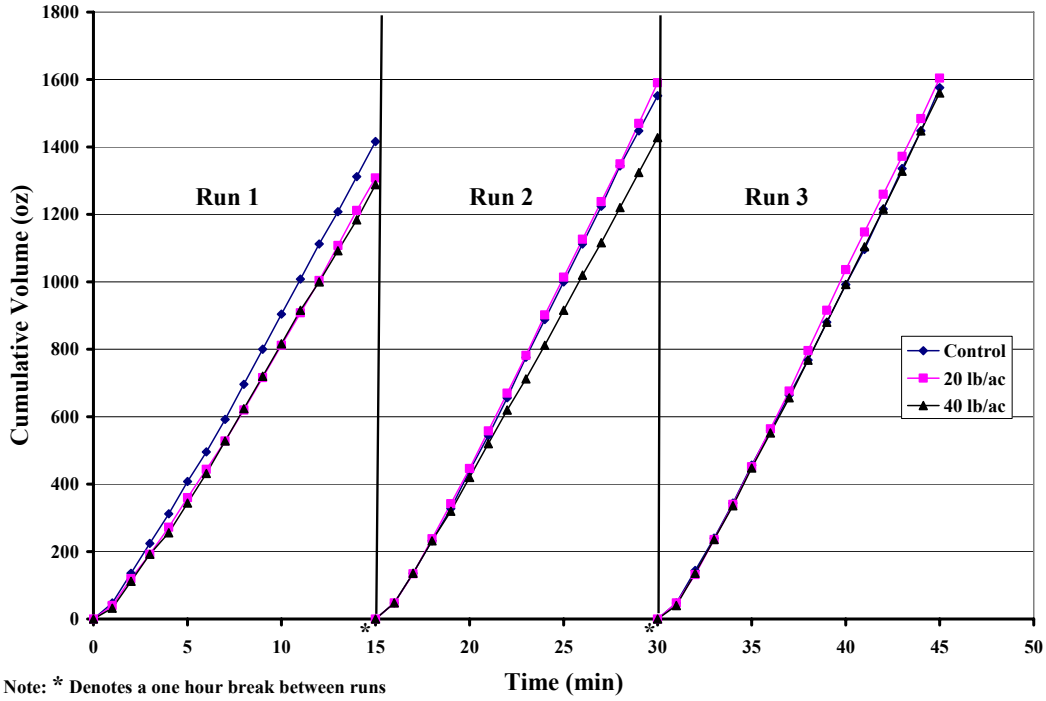


Figure 4.13 Cumulative Volume vs. Time: Left Soil Plot.

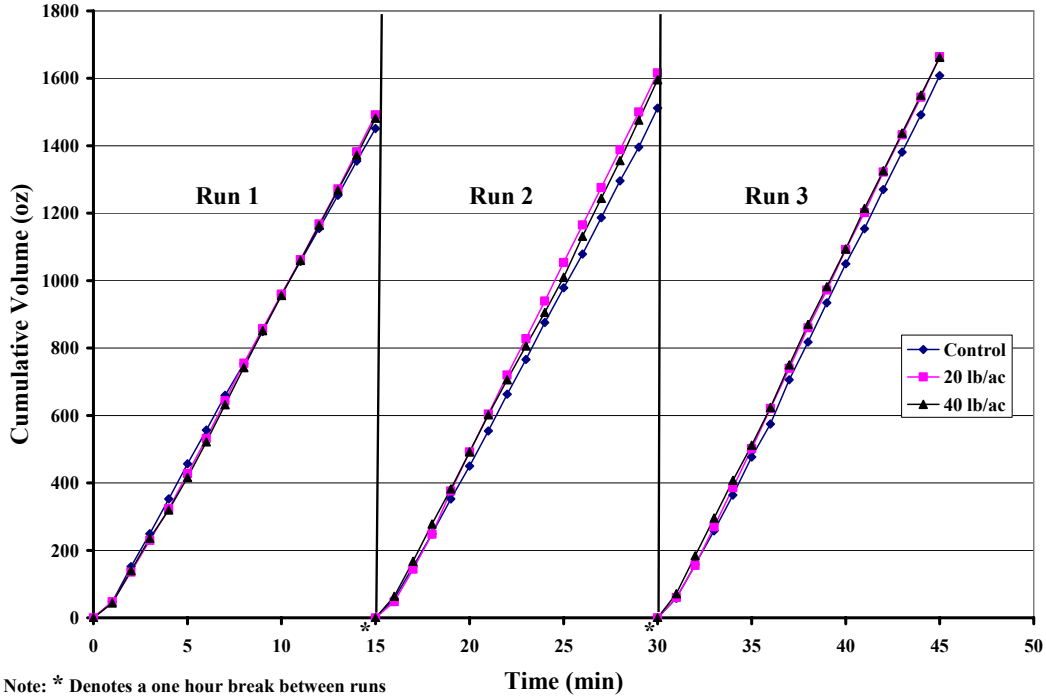


Figure 4.14 Cumulative Volume vs. Time: Center Soil Plot.

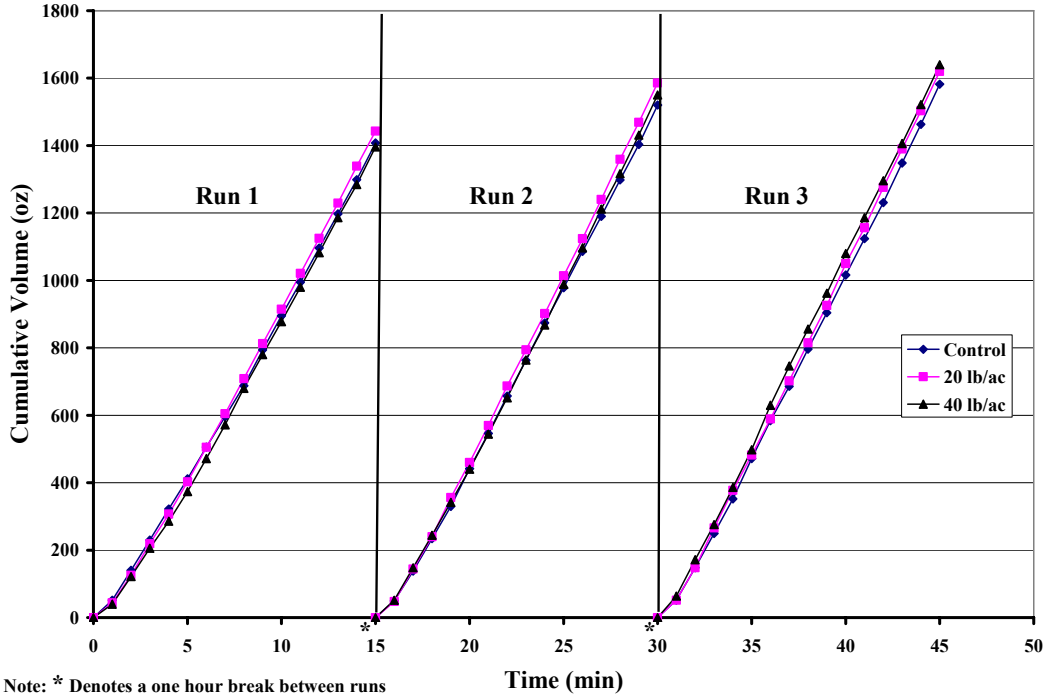


Figure 4.15 Cumulative Volume vs. Time: Right Soil Plot.

As shown in Figure 4.13 through Figure 4.15, the cumulative volume (runoff plus infiltration) was approximately the same for each soil plot section (left, center, right) in each of the three experiments (control, 10 lb/ac PAM, 20 lb/ac PAM). To take the comparison a step further, the cumulative volume of the three soil plots was compared to the theoretical rainfall volume over the three rain events to determine if mass balance was achieved. A theoretical applied volume of 1,706 oz. per plot per event was used which correlated to the 6 in/hr, 15 minute storm event. There were three rainfall events per experiment resulting in a total theoretical applied volume of 5,120 oz. The difference between the measured cumulative volume (runoff plus infiltration) and theoretical applied volume for the three soil plot sections is shown in Table 4.1 through Table 4.3 below.

Table 4.1 Water Balance: Left Section.

Experimental Scenario	Cumulative Runoff Volume (oz.)	Cumulative Infiltration Volume (oz.)	Cumulative Total Volume (oz.)	Theoretical Volume Applied (oz.)	Percent Difference (%)
Control	4184	568	4752	5120	7.2
20 lb/ac PAM	4172	742	4914	5120	4.0
40 lb/ac PAM	4176	444	4620	5120	9.8

Table 4.2 Water Balance: Center Section.

Experimental Scenario	Cumulative Runoff Volume (oz.)	Cumulative Infiltration Volume (oz.)	Cumulative Total Volume (oz.)	Theoretical Volume Applied (oz.)	Percent Difference (%)
Control	4544	224	4768	5120	6.9
20 lb/ac PAM	4396	672	5068	5120	1.0
40 lb/ac PAM	4732	230	4962	5120	3.1

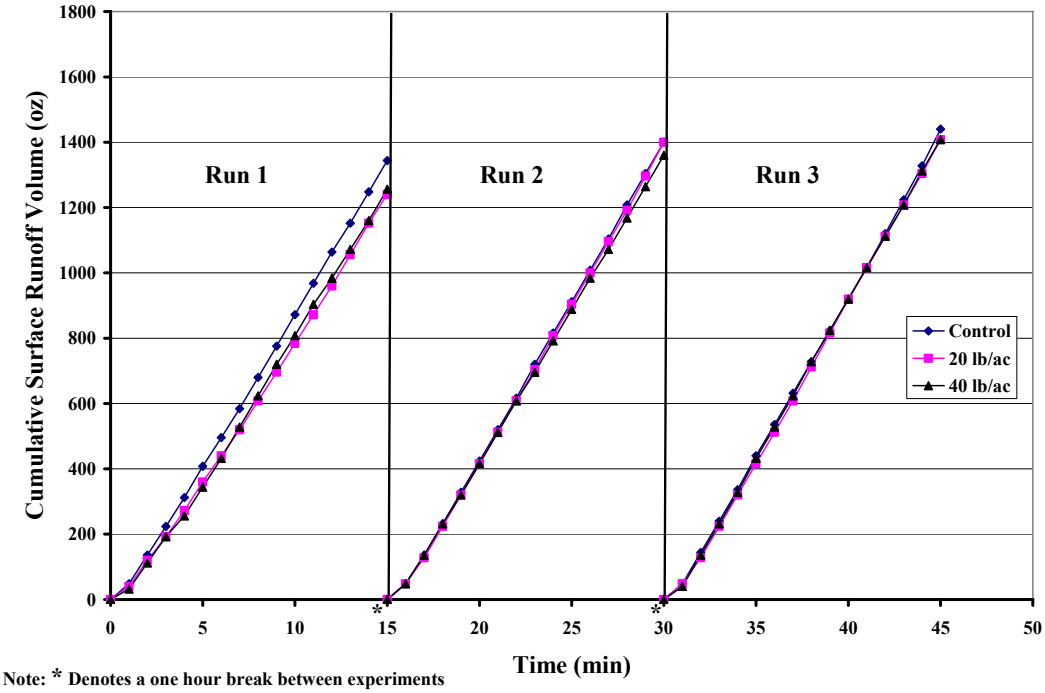
Table 4.3 Water Balance: Right Section.

Experimental Scenario	Cumulative Runoff Volume (oz.)	Cumulative Infiltration Volume (oz.)	Cumulative Total Volume (oz.)	Theoretical Volume Applied (oz.)	Percent Difference (%)
Control	4370	402	4772	5120	6.8
20 lb/ac PAM	4381	574	4955	5120	3.2
40 lb/ac PAM	4572	238	4810	5120	6.1

As shown in Table 4.1 through Table 4.3, the three soil plot sections were close to attaining water balance for the three experimental scenarios (Control, 20 lb/ac PAM, 40 lb/ac PAM). The 40 lb/ac PAM experiment on the left soil plot had the largest percent difference at 9.8%, and the 20 lb/ac PAM experiment on the center soil plot had the smallest percent difference at 1%. The difference in volume between the measured and theoretical volumes can probably be attributed to the fluctuation of the flow through the rainfall system due to pressure variances from the source and also to overspray lost off the model.

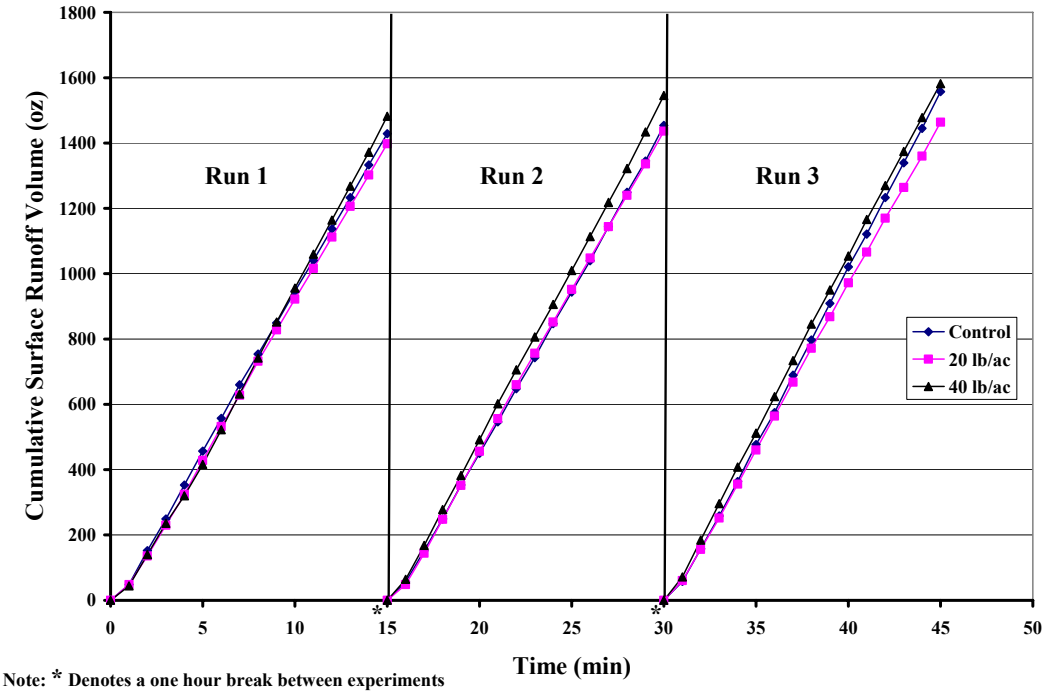
4.4.2 Cumulative Surface Runoff Volume versus Time

Now that the three soil plot sections have been checked for water balance, the cumulative surface runoff versus time was plotted for each soil plot section (left, center, right) to determine whether or not the surface runoff was approximately the same for each experimental scenario (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM). This data is shown Figure 4.16 through Figure 4.18 below. There was a one hour break in between each 15 minute rain event (Run 1- Run 3) but for illustrative purposes the data was plotted continuously.



Note: * Denotes a one hour break between experiments

Figure 4.16 Cumulative Surface Runoff Volume vs. Time: Left Soil Plot.



Note: * Denotes a one hour break between experiments

Figure 4.17 Cumulative Surface Runoff Volume vs. Time: Center Soil Plot.

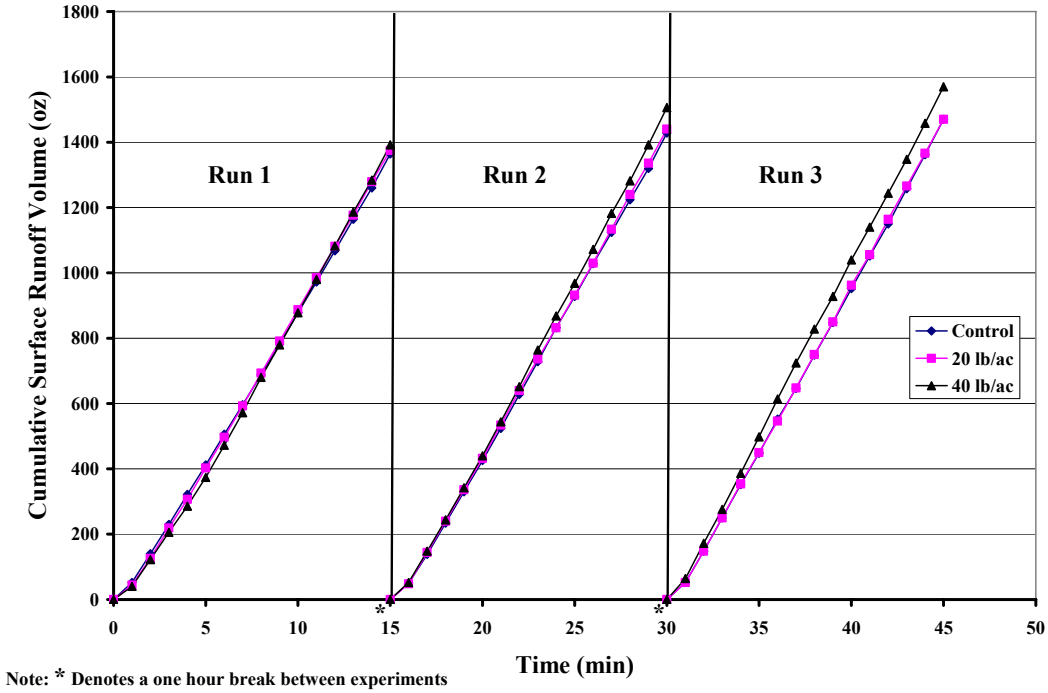


Figure 4.18 Cumulative Surface Runoff Volume vs. Time: Right Soil Plot.

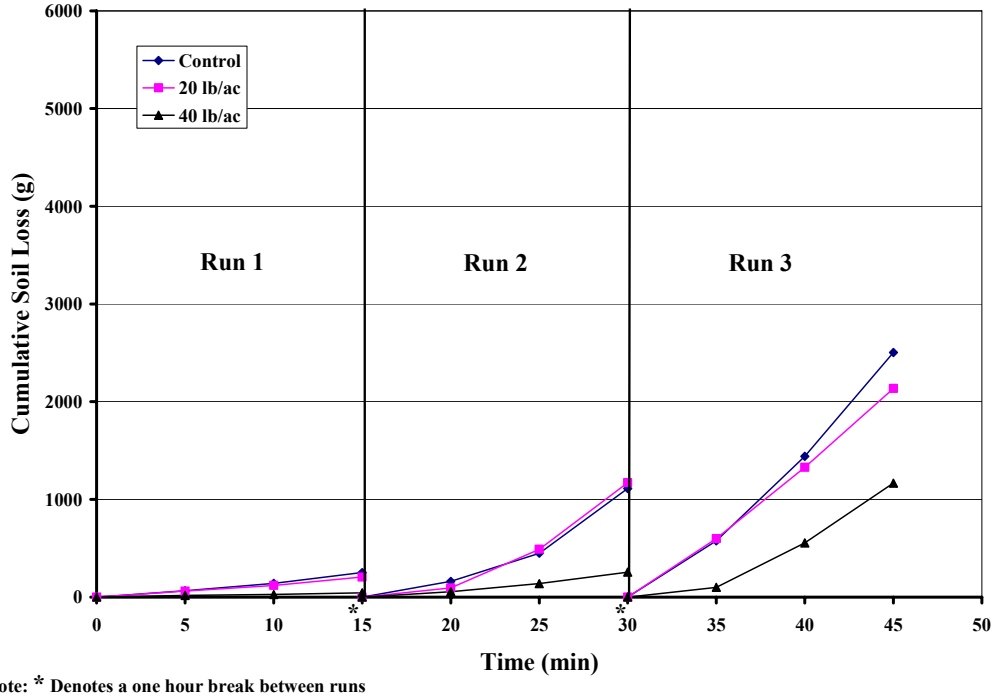
As shown in Figure 4.16 through Figure 4.18, each soil plot section (left, center, right) experienced approximately the same amount of surface runoff volume in each of the three experiments (control, 10 lb/ac PAM, 20 lb/ac PAM). The largest difference was during the third rainfall event on the right soil plot. There was a 6.8% difference between the control and the 40 lb/ac application rate of PAM. When Figure 4.16 through Figure 4.18 are compared to one another, it can also be concluded that the runoff volumes are approximately equal in the right, center, and left soil plot sections. Therefore, the erosion results should not be biased because the surface runoff volume for the three experimental scenarios and the three soil plot sections were similar. The summary statistics for the surface runoff of the three soil plots combined are shown in Table 4.4.

Table 4.4 Surface Runoff Statistics: Three Soil Plots Combined.

Rainfall Event	Mean (oz.)	Standard Deviation (oz.)
Run 1	1364	77.2
Run 2	1441	56.5
Run 3	1485	67.6

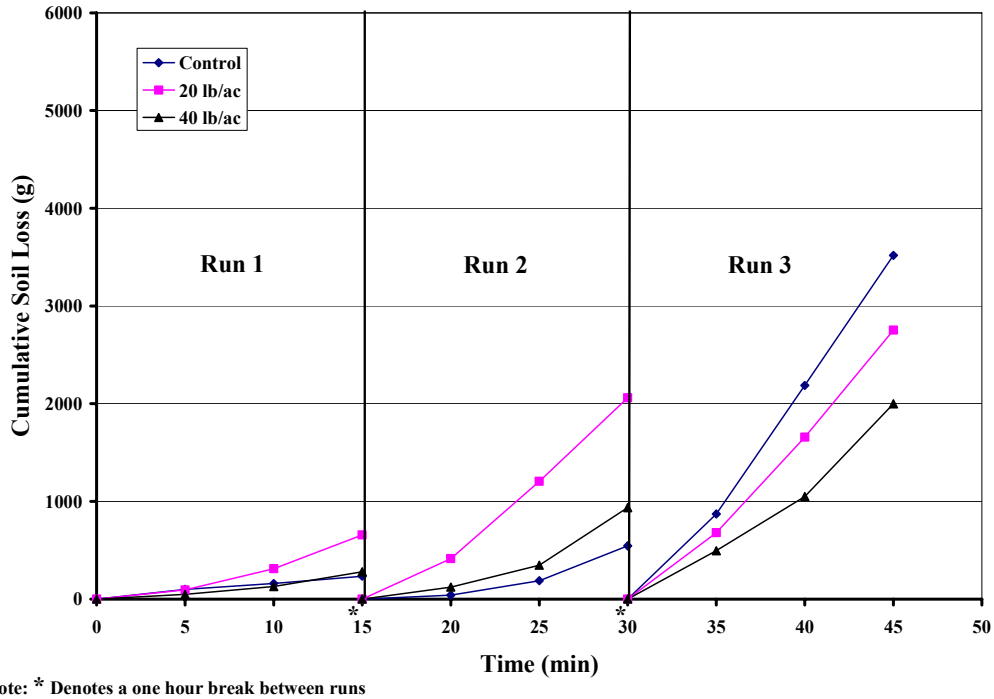
4.4.3 Cumulative Soil Loss versus Time

The cumulative soil loss versus time for the three soil plot sections was plotted to determine the effectiveness of the two application rates (20 and 40 lb/ac) of PAM as an erosion control technology. The results of the three individual soil plots along with the average of all three plots for the three consecutive rainfall events (Run 1 – Run 3) are shown in Figure 4.19 through Figure 4.22 below. There was a one hour break in between each 15 minute rain event but for illustrative purposes the data was plotted continuously.



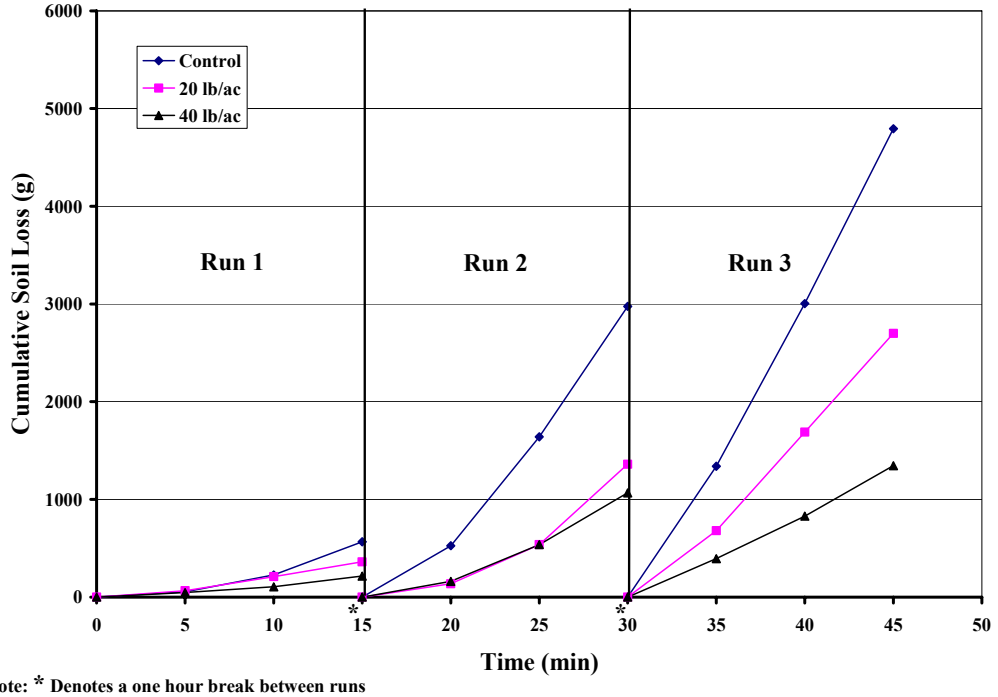
Note: * Denotes a one hour break between runs

Figure 4.19 Cumulative Soil Loss vs. Time: Left Soil Plot.



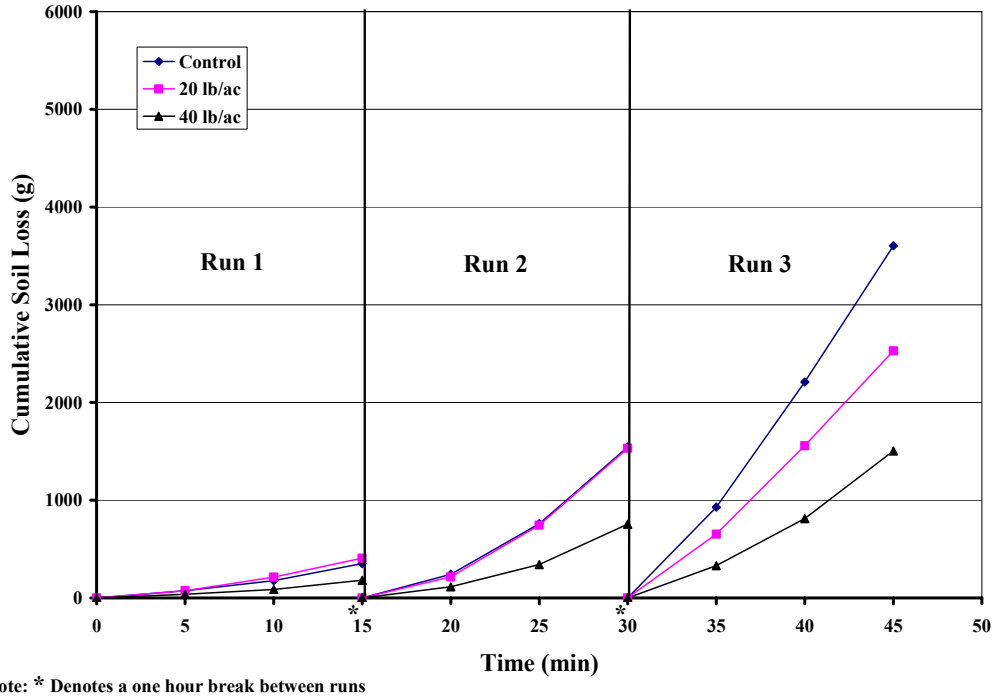
Note: * Denotes a one hour break between runs

Figure 4.20 Cumulative Soil Loss vs. Time: Center Soil Plot.



Note: * Denotes a one hour break between runs

Figure 4.21 Cumulative Soil Loss vs. Time: Right Soil Plot.



Note: * Denotes a one hour break between runs

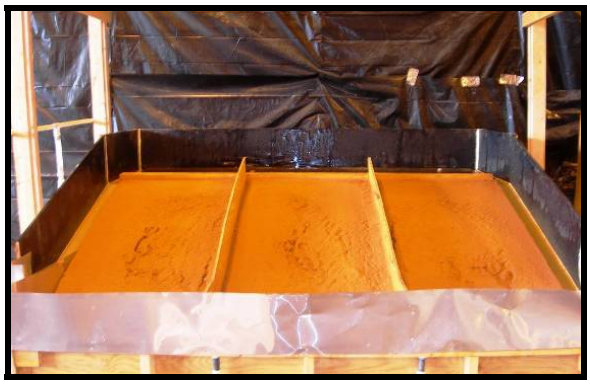
Figure 4.22 Average Cumulative Soil Loss vs. Time for all Three Soil Plots

As shown in Figure 4.19 through Figure 4.22, the cumulative soil loss over time increased in each of the soil plots during the three rainfall events for all three modeling scenarios (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM). The PAM applications, however, did provide a soil loss reduction compared to the control in most cases. The 40 lb/ac PAM application reduced the average soil loss compared to the control for all three rainfall events and the 20 lb/ac PAM application provided a reduction in two of the three rain events. The details of the model results for all three rainfall events are discussed below.

During the first rainfall event (Run 1), PAM applied at 20 lb/ac reduced soil loss in the left and right soil plots by 17.8% and 36.4% respectively, but there was an increase of 180% for the center section. PAM applied at 40 lb/ac reduced soil loss by 82.2% and 62.2% for the left and right plots respectively, but soil loss increased by 21% for the center section. Since the surface runoff for all three sections was approximately the same, the increase in soil loss in the center section could be attributed to the randomness associated with erosion. On average, PAM applied at 20 lb/ac provided a 16% increase in soil loss while PAM applied at 40 lb/ac provided a reduction of 49% for the three soil plots during the first rainfall event. Pictures of the three soil plots after the first rainfall event for the three testing scenarios (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM) are shown in Figure 4.23 below.

a.) Control

b.) PAM Applied at 20 lb/ac



c.) PAM Applied at 40 lb/ac

Figure 4.23 Soil Plots After Run 1

The results from the second event (Run 2) were similar to the first. However, the 20 lb/ac application rate only provided a reduction in soil loss for the right section (54%) when compared to the control. Soil loss increased for the other two sections (5% in the left and 278% in the center). On average, PAM applied at 20 lb/ac reduced soil loss by 1% for the second rainfall event. PAM applied at 40 lb/ac, on the other hand, reduced soil loss in the left and right sections by 77% and 64% respectively while soil loss for the center section increased by 72%. Once again, the increase in soil loss from the center section can probably be attributed to the randomness associated with erosion. The average soil loss for the three sections during the second rainfall event decreased by 51%

for the 40 lb/ac application rate. Pictures of the three soil plots after the second rainfall event (Run 2) for the three testing scenarios are shown in Figure 4.24.

a.) Control

b.) PAM Applied at 20 lb/ac

c.) PAM Applied at 40 lb/ac

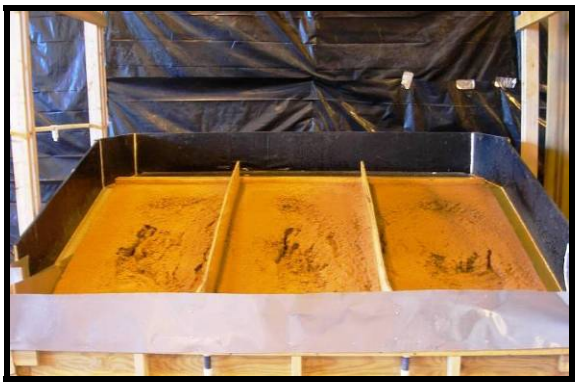
Figure 4.24 Soil Plots After Run 2

For the final rainfall event (Run 3), soil loss was reduced in all three sections for both the 20 and 40 lb/ac application rates when compared to the control. PAM applied at 20 lb/ac reduced soil loss for the left, center, and right sections by 15%, 22%, and 44% respectively. PAM applied at 40 lb/ac reduced soil loss for the left, center, and right sections by 53%, 43%, and 72% respectively. The average soil loss reduction for the third event was 30% for PAM applied at 20 lb/ac and 58% for PAM applied at 40 lb/ac. Pictures of the three soil plots after the third rainfall event for the three testing scenarios

are shown in Figure 4.25 and the reduction in soil loss compared to the control for the 20 and 40 lb/ac application rates of PAM are summarized in Table 4.5 and Table 4.6.

a.) Control

b.) PAM Applied at 20 lb/ac



c.) PAM Applied at 40 lb/ac

Figure 4.25 Soil Plots After Run 3

Table 4.5 Soil Loss Reduction for PAM Applied at 20 lb/ac.

	Left Soil Plot	Center Soil Plot	Right Soil Plot	Average of Plots
Run 1	18%	-180%	36%	-16%
Run 2	-5%	-278%	54%	1%
Run 3	15%	22%	44%	30%

Table 4.6 Soil Loss Reduction for PAM Applied at 40 lb/ac.

	Left Soil Plot	Center Soil Plot	Right Soil Plot	Average of Plots
Run 1	82%	-20%	62%	49%
Run 2	77%	-72%	64%	51%
Run 3	53%	43%	72%	58%

4.4.4 Turbidity Results

Turbidity samples were collected every minute from the surface runoff of all three soil plots for the three rainfall events (Run 1 – Run 3). These samples were taken to the lab, agitated, and turbidity measurements were taken using a Hach 2100AN Turbidimeter. The turbidity of the surface runoff versus time for the bare soil control and PAM applied at rates of 20 and 40 lb/ac for the three soil plot sections is shown in Figure 4.26 through Figure 4.28 below. The turbidity of all the samples collected during the control run was greater than 10,000 NTU. However, a value of 10,000 NTU was used because the Hach 2100AN Turbidimeter would not read turbidities any higher

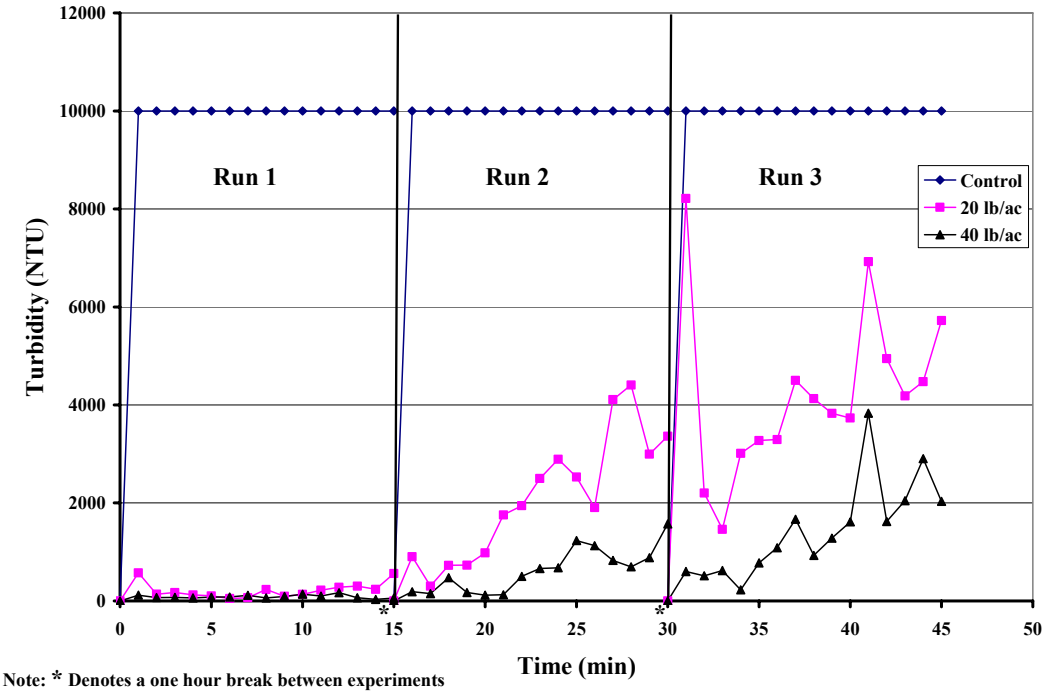
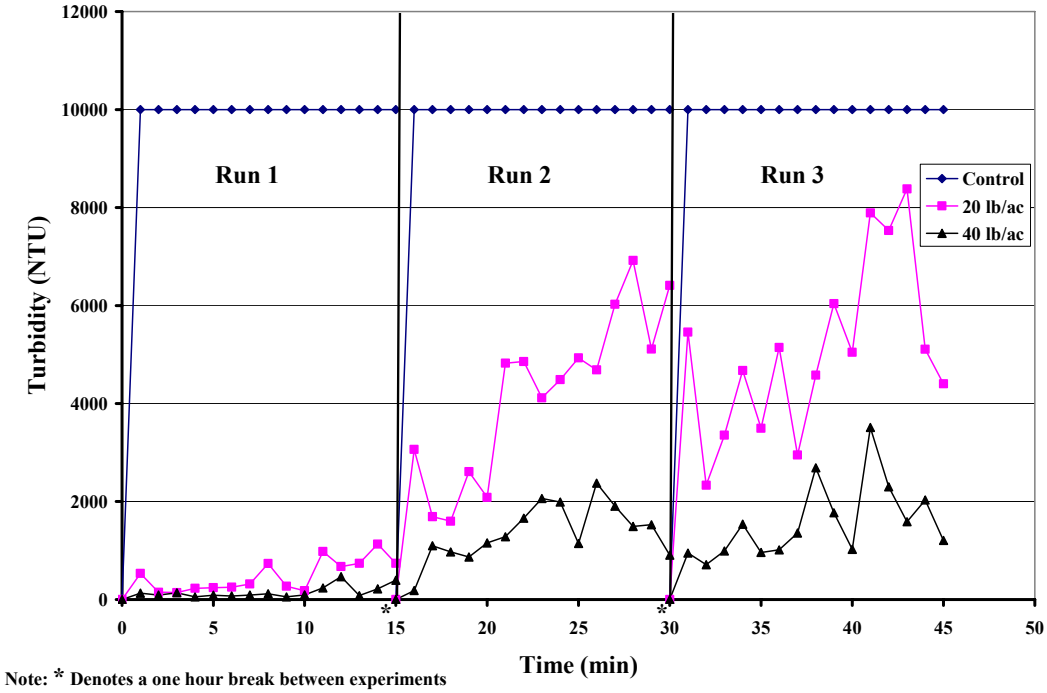
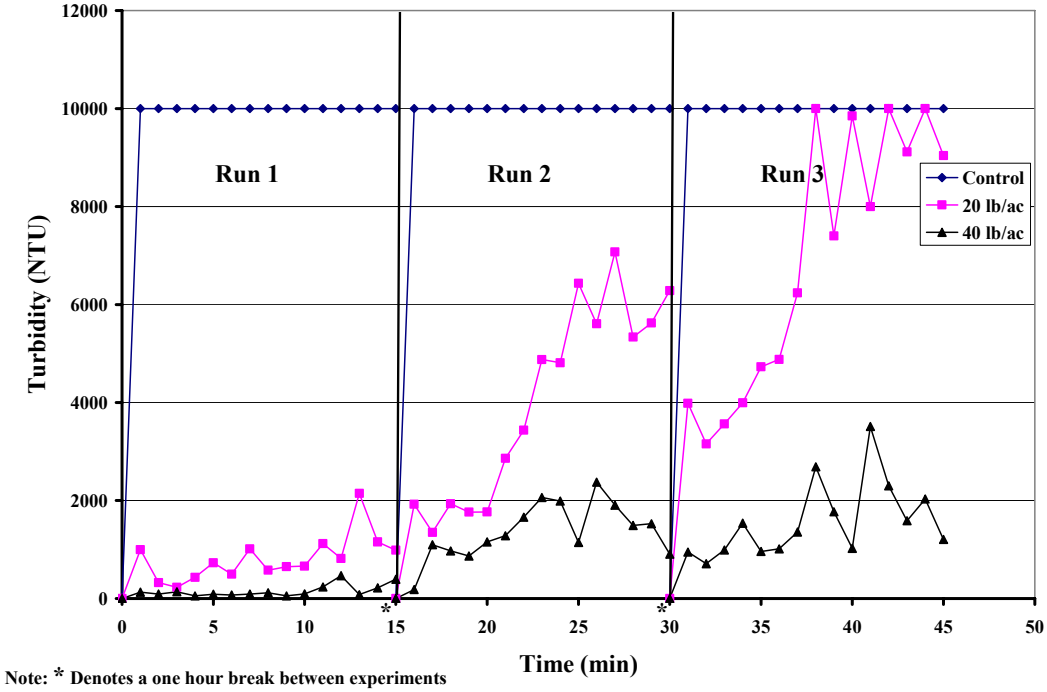


Figure 4.26 Turbidity of Surface Runoff vs. Time: Left Soil Plot.



Note: * Denotes a one hour break between experiments

Figure 4.27 Turbidity of Surface Runoff vs. Time: Center Soil Plot.



Note: * Denotes a one hour break between experiments

Figure 4.28 Turbidity of Surface Runoff vs. Time: Right Soil Plot.

As shown in Figure 4.26 through Figure 4.28, the turbidity of the surface runoff was greatly reduced by the application of PAM. PAM applied at 20 lb/ac reduced the average turbidity of the surface runoff for the three rainfall events by 95%, 65%, and 46% respectively compared to the control. The 40 lb/ac application of PAM performed even better and reduced the average turbidity of the surface runoff by 99%, 88%, and 83% for the three rainfall events respectively. These results show that PAM can be very effective at reducing the turbidity of surface runoff leaving construction sites.

Further analysis was done on turbidity samples from the first, fifth, tenth, and fifteenth minutes of each rainfall event to determine if PAM applied directly to the soil surface promoted the flocculation of fine particles in the surface runoff and decreased their settling time. To perform this analysis, each sample was agitated, placed in the Hach 2100AN Turbidimeter, and monitored for fifteen minutes. An initial turbidity reading was taken and readings were taken in one minute intervals thereafter. This data for the three rainfall events (Run 1 – Run 3) is shown below.

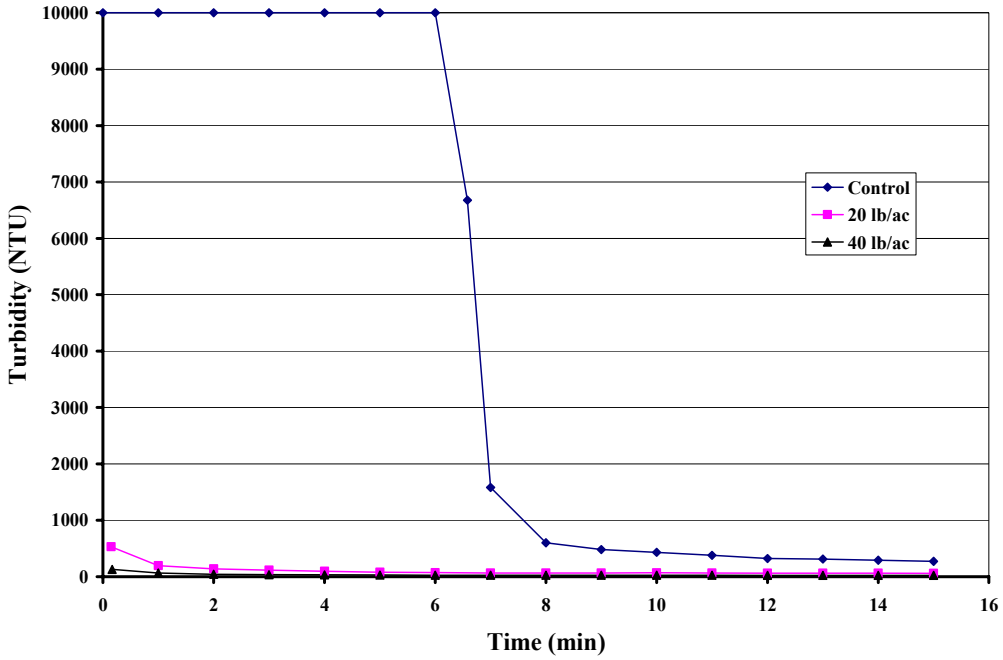


Figure 4.29 Turbidity vs. Settling Time for Run 1 (1 min).

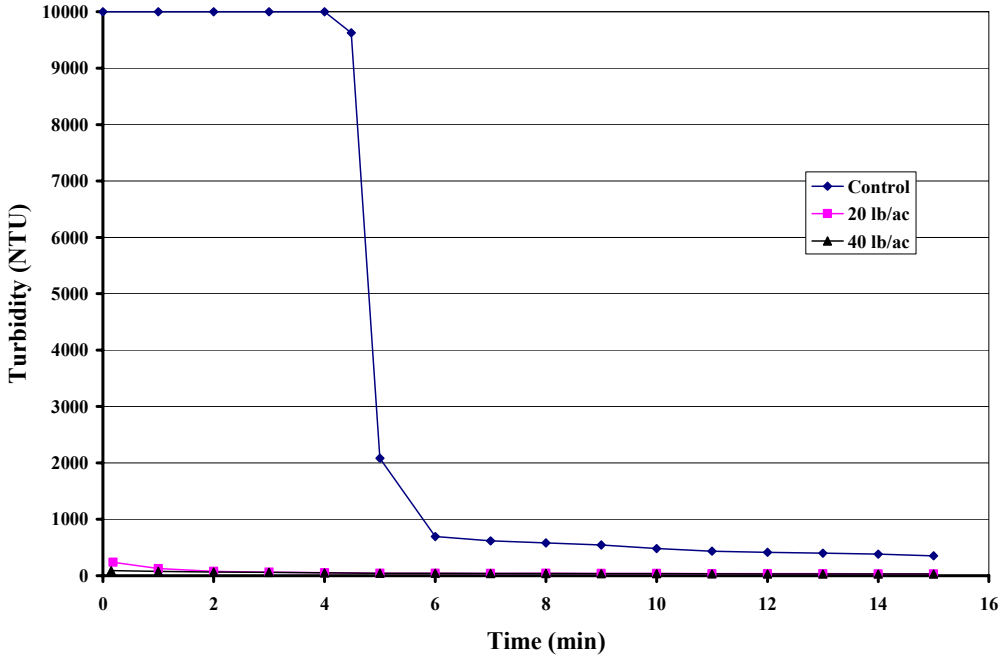


Figure 4.30 Turbidity vs. Settling Time for Run 1 (5 min).

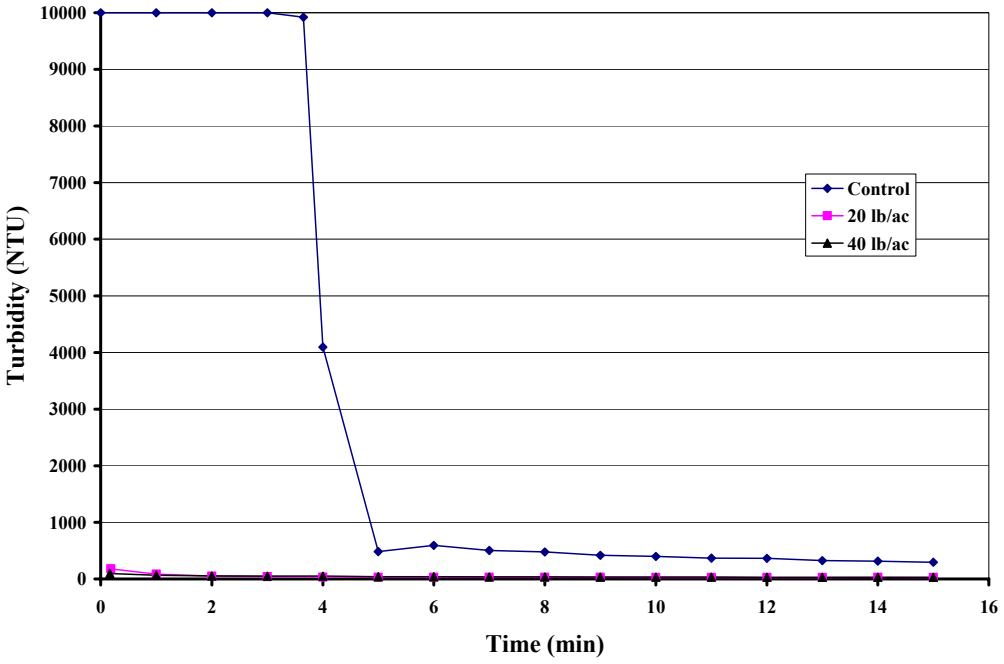


Figure 4.31 Turbidity vs. Settling Time for Run 1 (10 min).

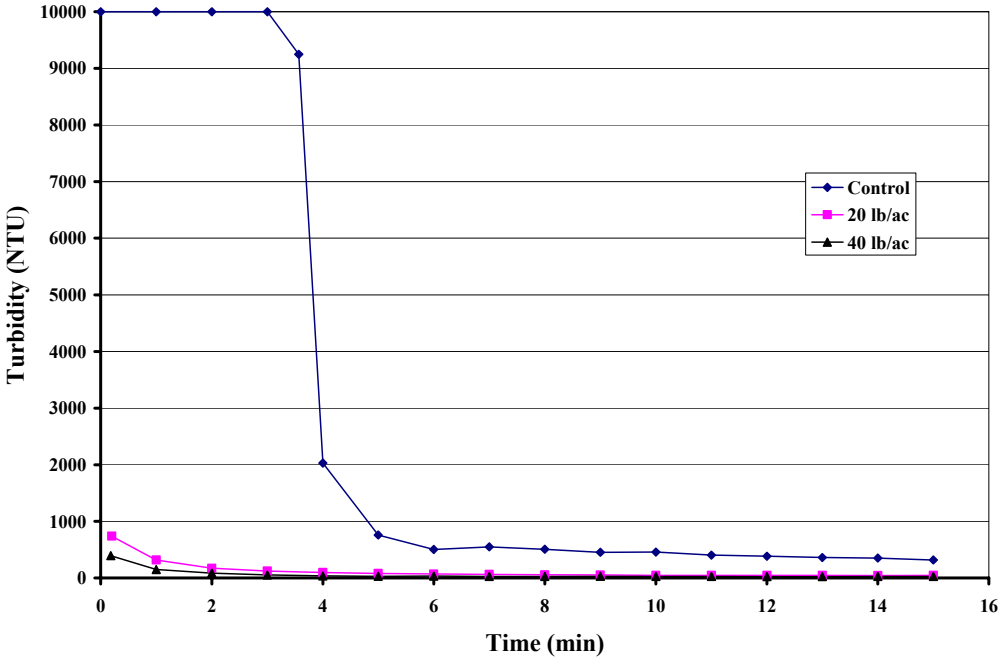


Figure 4.32 Turbidity vs. Settling Time for Run 1 (15 min).

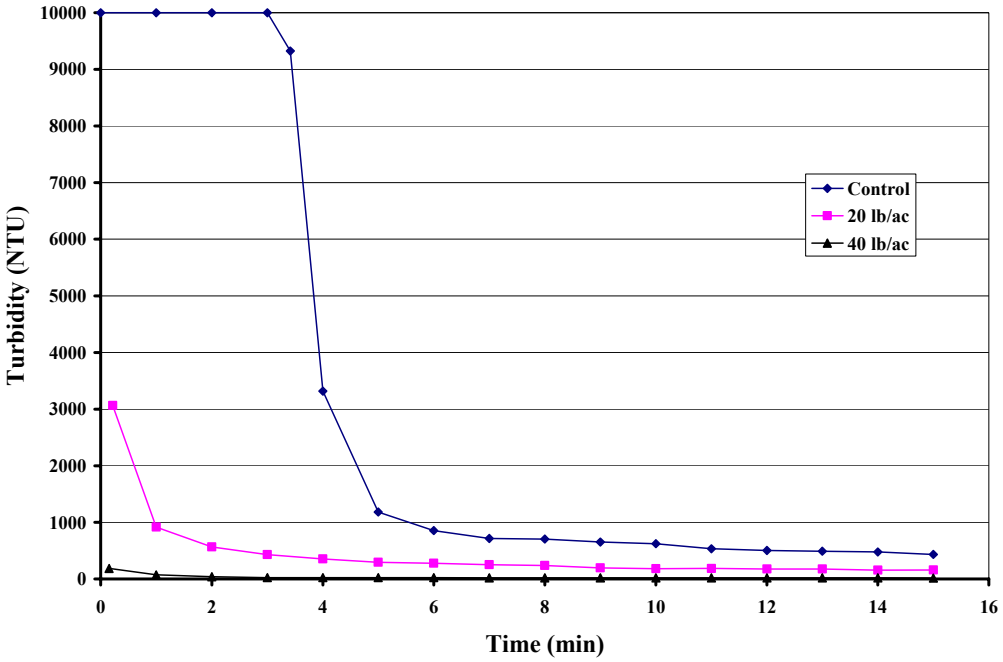


Figure 4.33 Turbidity vs. Settling Time for Run 2 (1 min).

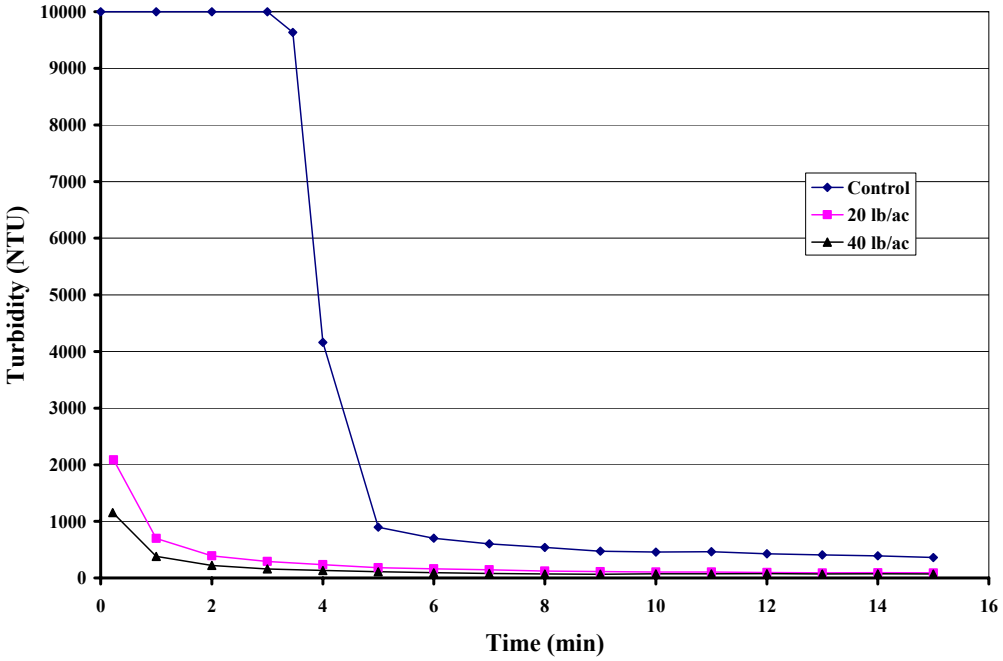


Figure 4.34 Turbidity vs. Settling Time for Run 2 (5 min).

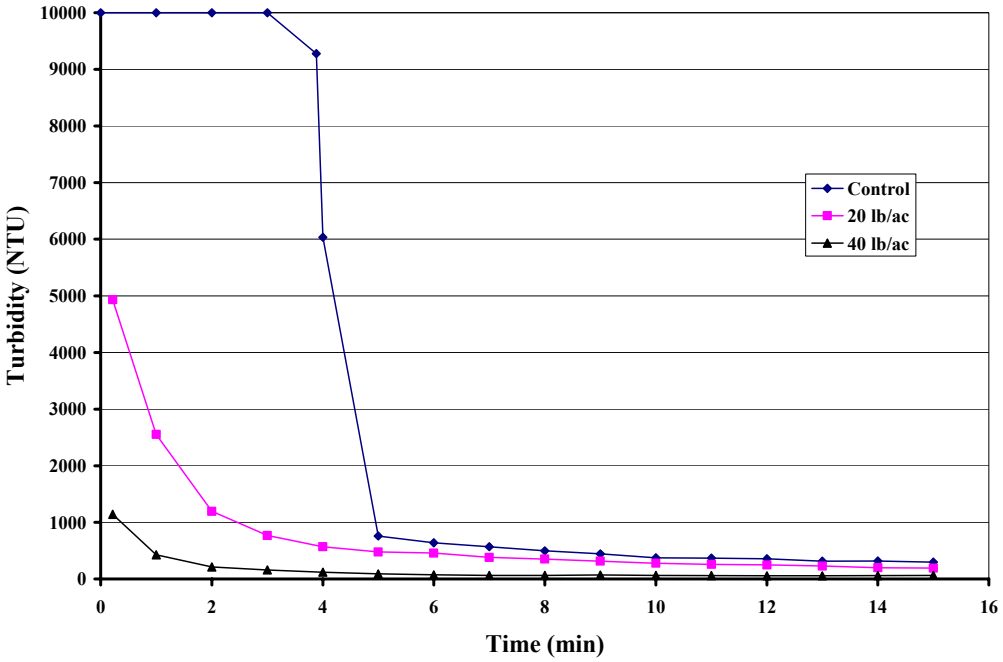


Figure 4.35 Turbidity vs. Settling Time for Run 2 (10 min).

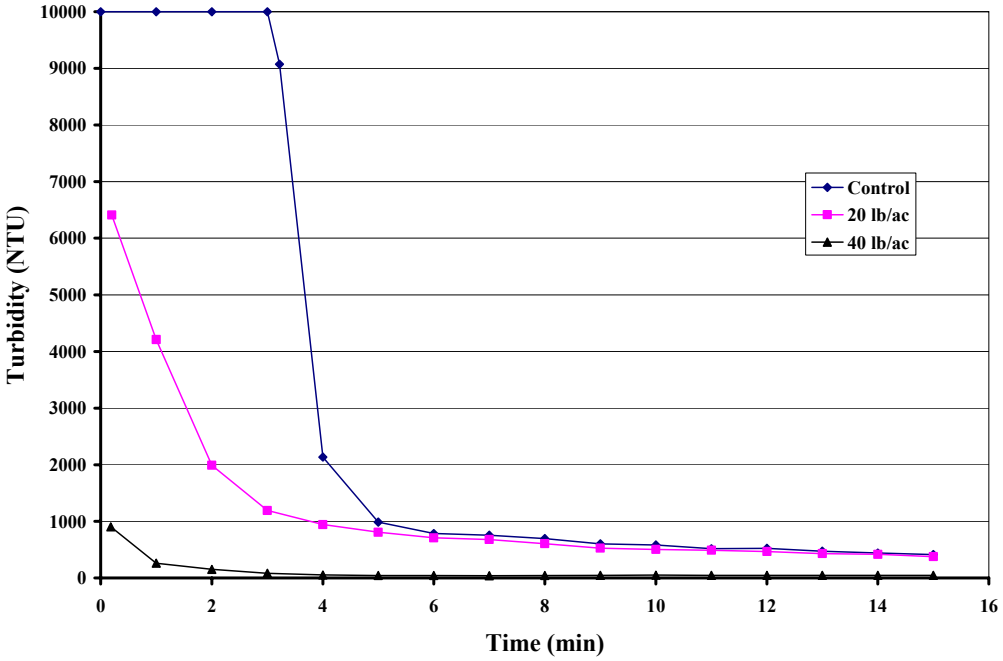


Figure 4.36 Turbidity vs. Settling Time for Run 2 (15 min).

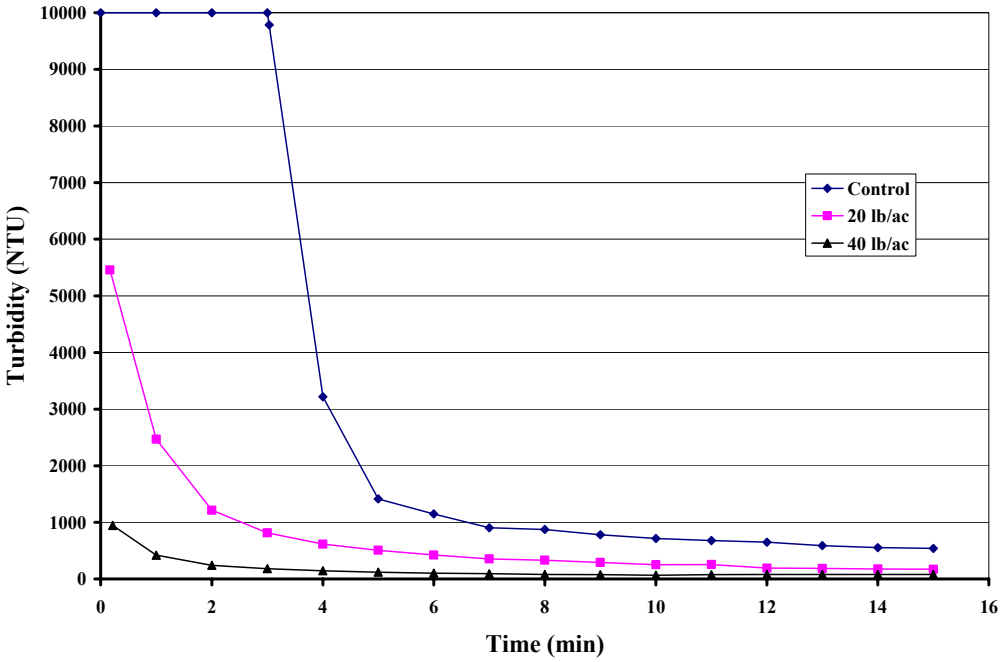


Figure 4.37 Turbidity vs. Settling Time for Run 3 (1 min).

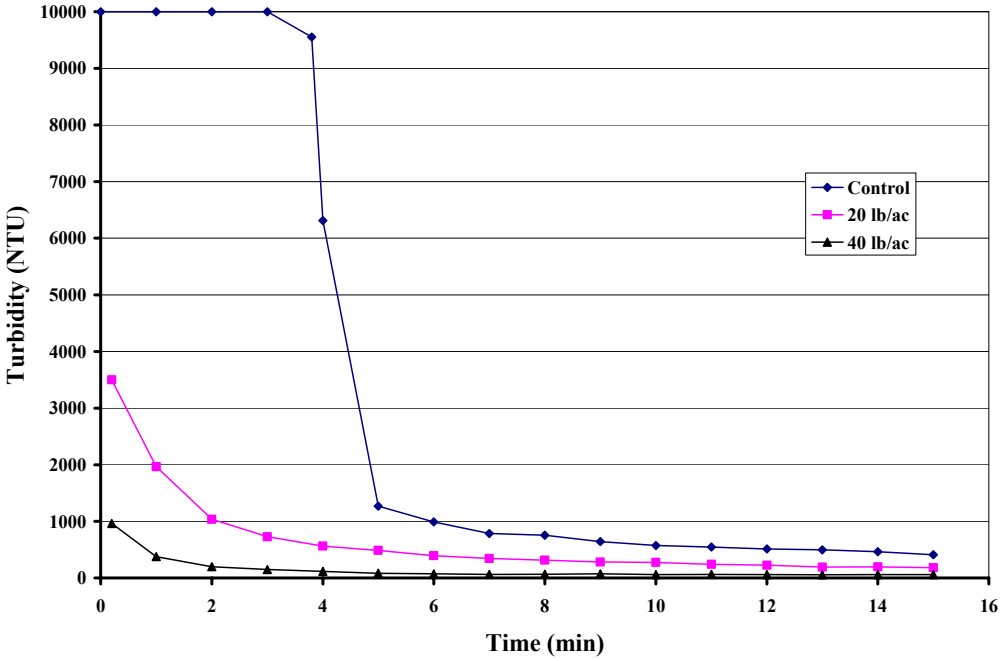


Figure 4.38 Turbidity vs. Settling Time for Run 3 (5 min).

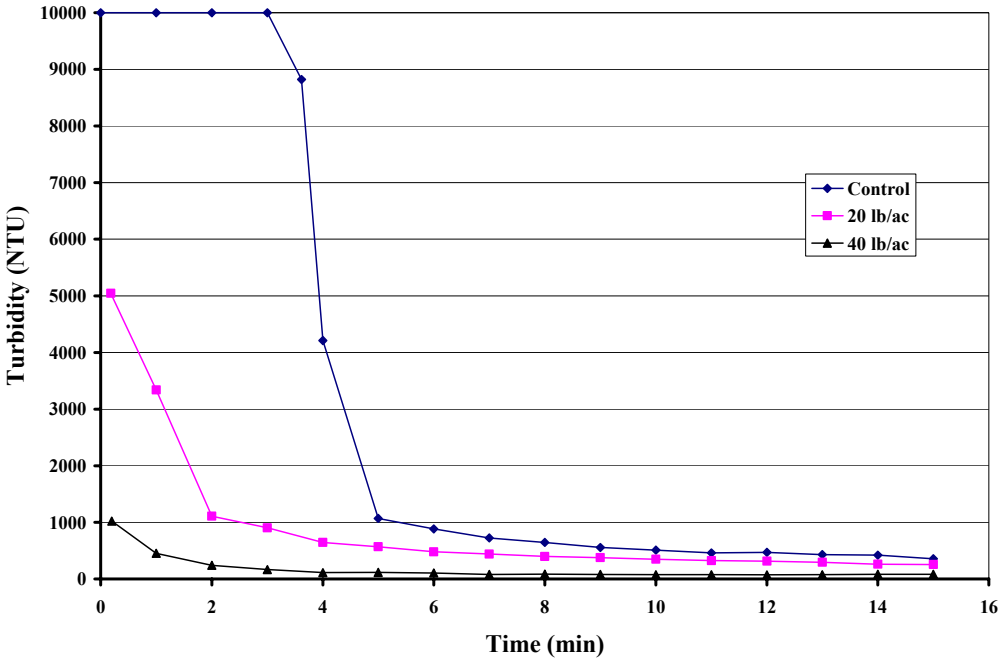


Figure 4.39 Turbidity vs. Settling Time for Run 3 (10 min).

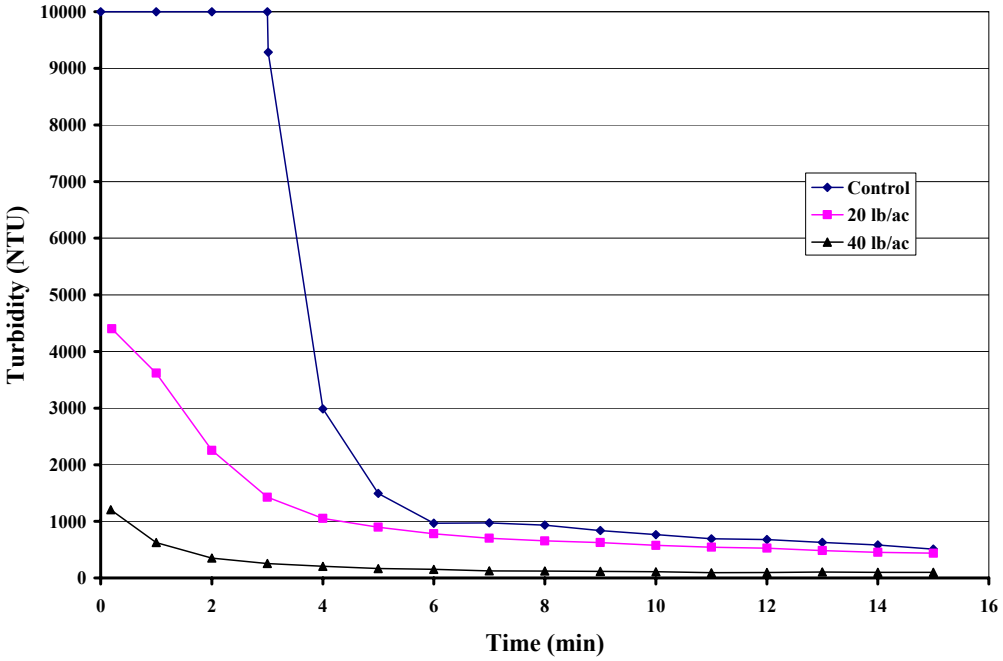


Figure 4.40 Turbidity vs. Settling Time for Run 3 (15 min).

As shown in Figure 4.29 through Figure 4.40, the application of PAM dramatically reduced the settling time of the suspended particles in the surface runoff. The results for the 20 lb/ac PAM application show that during the first rainfall event (Run 1) the initial turbidity was reduced on average of 96% compared to the control and was even as low as 180 NTU for the 10 minute sample. The turbidity after 15 minutes of settling time dropped as low as 28 NTU for the same sample and the average turbidity after 15 minutes of settling time for Run 1 was 42 NTU. The effect of PAM began to reduce a little bit during the second and third events, but the 20 lb/ac PAM application still provided a pretty good reduction compared to the control. During the second and third events the average initial turbidity of the surface runoff was 4123 NTU and 4601 NTU respectively and the average turbidity after 15 minutes of settling time was 204 NTU and 262 NTU respectively. The control for the second and third events had an average of 10,000 NTU for the initial turbidity and 377 NTU and 454 NTU respectively after 15 minutes of settling time.

The results from the 40 lb/ac PAM application were even better. The initial turbidity was as low as 89 NTU for the 5 minute sample of Run 1 and the turbidity after 15 minutes was as low as 23 for the 1 minute sample. The average initial turbidity for the first event was 177 NTU and the average turbidity after 15 minutes of settling time was 27 NTU. These reductions continued into the second event. The average initial turbidity for the second event was 847 NTU and the average turbidity after 15 minutes of settling time was 50 NTU. The turbidity reductions for the third event, though a little worse than the first two, were still very good. The average initial turbidity for the third event was 1034 NTU and the average turbidity after 15 minutes of settling time was 81 NTU.

Table 4.7 through Table 4.8 show the average initial turbidity after 15 minutes of settling time for the three experimental scenarios (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM).

Table 4.7 Initial Turbidity.

Experimental Scenario	Average Initial Turbidity (Run 1)	Average Initial Turbidity (Run 2)	Average Initial Turbidity (Run 3)
Control	10000	10000	10000
20 lb/ac PAM	423	4123	4601
40 lb/ac PAM	177	847	1034

Table 4.8 Turbidity After 15 Minutes of Settling Time.

Experimental Scenario	Average Final Turbidity (Run 1)	Average Final Turbidity (Run 2)	Average Final Turbidity (Run 3)
Control	315	377	454
20 lb/ac PAM	42	204	262
40 lb/ac PAM	27	50	81

4.5 CONCLUSION

Intermediate-scale experiments were performed to determine if dry granular PAM could be used as a potential erosion and sediment control technology in the highway construction industry. The tests were performed on a physical model developed at Auburn University that consisted of three identical soil plot sections. These sections were used to produce three replications of each experimental scenario. A silty sand soil was used for the research and the experimental scenarios consisted of a bare soil control and PAM applied at rates of 20 and 40 lb/ac. Three consecutive 6 in/hr, 15 minute storms were used for the experimental effort with a one hour break between each storm.

These high intensity, short duration storms, which were approximately 5-year, 15-minute rainfall events for the Mobile, AL area, were used to simulate a worst case scenario situation and provide valuable data on the longevity of granular PAM as an erosion control alternative.

During each experimental run, the total surface runoff was collected in one minute intervals using clear five quart buckets. A 50 mL turbidity sample was taken from each bucket and the buckets were then poured into Hayward single-length filter bags with a one micron pore size. These bags were then placed in the oven to dry in order to determine the cumulative soil loss of each of the plots. After testing was completed, the turbidity samples for every minute were taken to the lab, shook up, and a turbidity reading was recorded using a Hach 2100 AN Turbidimeter. These readings were intended to represent the turbidity of the surface runoff when leaving the soil plots. Turbidity samples from the first, fifth, tenth, and fifteenth minutes of each rainfall event analyzed further. These samples were shook up, placed in the turbidity meter, and readings were recorded in one minute intervals for fifteen minutes. This data was used to determine the effect PAM had on the settling time of the fine particles in the surface runoff.

The results from this research show that PAM applied at 20 lb/ac reduced the average soil loss for two of the three rainfall events and PAM applied at 40 lb/ac reduced the average soil loss for all three rainfall events when compared to the control. This data shows that PAM applied in the dry granular form to a silty sand material could be a potential erosion control alternative if applied at the proper application rate. From a turbidity reduction standpoint, the 20 lb/ac PAM reduced the average initial turbidity of

the three rainfall events by 95%, 65%, and 46% respectively and reduced the turbidity after 15 minutes of settling time by 87%, 46%, and 42% respectively compared to the control. The 40 lb/ac PAM reduced the average initial turbidity for the three rainfall events by 99%, 88%, and 83% respectively and reduced the average turbidity after 15 minutes of settling time by 91%, 87%, and 82% respectively compared to the control. The fact that the application of PAM greatly reduced not only the initial turbidity but the turbidity over settling time shows that PAM applied for surface stabilization can provide some sediment control benefits. The turbidity of surface runoff can be greatly reduced if PAM applied for surface stabilization is used with other sediment control practices such as silt fence tieback systems and detention basins that impound stormwater runoff and provide adequate time for the suspended particles to settle out of suspension.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This research focused on evaluating the use silt fence tieback (a.k.a. "j-hook") systems and dry granular PAM as erosion and sediment control technologies on highway construction sites. The first portion of the research focused on silt fence tieback systems as a sediment control technology and the objectives were to: (1) develop a computational method to determine the storage capacity of a silt fence tieback system, (2) develop a Visual Basic (VBA) coded spreadsheet design tool for practitioners to use in the construction industry that predicts the amount of stormwater runoff generated from a user specified rainfall event and provides design guidance for a tieback configuration to accommodate the generated runoff, and (3) use the tool to design a tieback system on a local construction project and evaluate its performance over time during a case study.

The second component of the research investigated the effectiveness of anionic polyacrylamide (PAM) as an erosion and sediment control technology. The objectives of this component were to: (1) perform intermediate-scale experiments to determine the effectiveness of dry granular PAM applied to a typical 3H:1V slope for erosion control, (2) determine whether PAM, when used for erosion control, can also

provide sediment control benefits by decreasing the settling time of suspended solids in the surface runoff, and (3) provide recommendations for future erosion and/or sediment control testing using PAM. The successes and failures of the work performed in these two areas and recommendations for future work will be discussed in the following sections.

5.2 SILT FENCE TIEBACK SYSTEMS

The first component of this research focused on silt fence tieback systems and was a continuation to the work performed by Halverson (2006). A computational procedure was developed to determine the storage capacity of silt fence tieback systems and these procedures were used to create a Visual Basic (VBA) coded spreadsheet design tool to assist practitioners in the proper design of these systems. This design tool was then used to design a tieback configuration to accommodate a 2 in. rainfall event on an ALDOT construction site in Auburn, AL. The site consisted of an approximately 600 ft. symmetrical vertical curve section of road with a 3H:1V fill slope. For comparative purposes, tiebacks were installed on half the site and a linear silt fence system was also installed on the rest. The site was monitored over four storm events that totaled 4.4 in of rain.

Throughout the four rainfall events, each of the tiebacks in the silt fence tieback system performed as expected by impounding stormwater runoff from their contributing drainage areas. This allowed the suspended sediment in the surface runoff to settle out of suspension and be contained on site. However, the fourth rainfall event had a cumulative depth of 2.5 in. which exceeded the design capacity of the system. During this event, two

of the tiebacks were overtopped with water and nearly failed structurally from the excessive force associated with the large amount of impounded stormwater runoff. These two tiebacks, though, still effectively contained sediment during the heavy rainfall event and the tieback system experienced no erosion along the toe of the fence in any of the four rainfall events. To prevent structural failures from occurring in the future, additional steel support posts were installed at the locations where overtopping was experienced.

The linear system, throughout the four rainfall events, performed much differently. It experienced heavy sedimentation at the downslope end of the fence and erosion along the toe of the fence in multiple upslope areas. This erosion was caused by stormwater runoff accumulating along the fence and flowing in the downslope direction. Also, a scour hole developed at the lowest point in the system during the fourth event. This was probably due to the high velocity concentrated flow that occurred along the fence during the storm. When the high velocity flow reached the lowest point in the system, the shear stress caused by flow exceeded that of the underlying soil which resulted in a scouring effect. This scour hole, if not fixed, will become deeper with every rainfall event and allow sediment to escape under the fence and leave the project.

The results from this research show that silt fence tieback systems, if designed and installed correctly, are much more effective at distributing the total sediment load and containing sediment than linear systems. In this study, the linear system experienced heavy sedimentation at a single location and erosion along the toe of the fence. These are two of the five most prevalent failure modes of silt fence systems outlined by Halverson (2006). The tieback system, on the other hand, did not experience any of these failure modes. Therefore, the tieback configurations performed more effectively than the linear

system during the four rainfall events. For future installations of tieback systems, the research team suggests that a spacing of no more than 5 ft. should be used for the support posts for the last 10 ft. of fence before the fence is tied into the fill slope. This will provide extra structural support for the tieback system if an there is an overtopping condition.

5.3 INTERMEDIATE-SCALE EROSION CONTROL EXPERIMENTS USING PAM

The second portion of this research focused on the effectiveness of dry granular PAM as an erosion control technology. Testing was performed on an intermediate-scale physical model developed at Auburn University and three experimental scenarios (bare soil control, 20 lb/ac PAM, 40 lb/ac PAM) were investigated. Three consecutive 6 in/hr, 15 minute storm events were used for the experiments with a one hour break between each storm. The 20 lb/ac application rate of PAM reduced the average soil loss for the second and third rainfall events by 1% and 30 % respectively, and PAM applied at 40 lb/ac reduced the average soil loss for all three rainfall events by 49%, 51%, and 58% respectively. The average turbidity of the surface runoff was also reduced by the 20 and 40 lb/ac application rates of PAM. PAM applied at 20 lb/ac reduced the average initial turbidity for the three rainfall events by 95%, 65%, and 46% respectively and the 40 lb/ac application rate reduced the average initial turbidity by 99%, 88%, and 83% respectively. Additional analysis was done to determine if PAM, when used as an erosion control technology, provided sediment control benefits by reducing the settling time of suspended sediment in the surface runoff. This data showed that PAM applied at 20 lb/ac

reduced the average turbidity after 15 minutes of settling time by 87%, 46%, and 42% for the three rainfall events respectively. The 40 lb/ac application rate provided even better results by reducing the average turbidity after 15 minutes of settling time by 91%, 87%, and 82% for the three rainfall events respectively.

The results from this research suggest that dry granular PAM could serve as a potential erosion control technology if applied at the right application rate. Prior to using PAM, soil specific testing should be done to determine exactly which PAM product to use and what the proper application rate should be. Applied Polymer Systems recommended using the Silt Stop 705 powder for this research at an application rate of between 35 and 45 lb/ac. Therefore, a rate of 40 lb/ac was used and provided a reduction in the average soil loss and turbidity for all three rainfall events. Half of the recommended rate was also used (20 lb/ac) and still provided an reduction in average soil loss and turbidity but the results were not nearly as good as the 40 lb/ac application rate. From a sediment control standpoint, PAM applied as an erosion control BMP greatly decreases the settling time of suspended sediment in the surface runoff. Therefore, the turbidity of runoff leaving construction sites can be greatly reduced if PAM applied for surface stabilization is used with other sediment control practices such as silt fence tieback systems and detention basins that impound stormwater runoff and provide adequate time for the suspended particles to settle out of suspension.

5.4 RECOMMENDED FURTHER RESEARCH

5.4.1 Silt Fence Tieback Systems

The field study performed on the ALDOT construction site comparing silt fence tieback and linear systems established the fact that silt fence tieback systems, if designed and installed correctly, perform much more effectively than linear systems in containing sediment and reducing potential failure modes. More research should be done comparing the two systems to further strengthen the case for using silt fence tieback systems and determine if silt fence tieback systems consistently perform better. Other research in this area should address possible construction methodologies of tieback systems and determine which methodology provides the most structurally sound system and is still cost effective. If these issues are addressed and the information is shared throughout the construction industry, structurally sound, cost effective silt fence tieback systems can be designed and sediment leaving construction sites can be greatly reduced.

5.4.2 PAM as an Erosion Control Technology

Further research needs to be conducted to determine the exact role of PAM as an erosion control BMP in the highway construction industry. This study evaluated PAM applied in dry granular form without ground cover practices to a silty sand material. Future work should evaluate the effectiveness of dry granular PAM used with ground cover practices such as straw and erosion control blankets (ECBs). This includes the so-called "soft armoring" technique included in the *Polymer Enhanced Best Management Practice (PEBMP) Application Guide* by Applied Polymer Systems, Inc., the University of Central Florida, and the Stormwater Management Academy. Other research should

investigate the effectiveness of PAM applied in the liquid form both with and without ground cover and ground cover practices should also be evaluated by themselves. This work should be done on both intermediate-scale physical models and field-scale plots to determine if there is a direct correlation between what works in the lab and what works in the field. These experiments should also be performed on multiple soil types to establish a clear understanding of the interaction and effectiveness of PAM when applied to different materials. Finally, a comprehensive guide should be written documenting all of these studies and provided to ALDOT to give them a good understanding of the advantages and disadvantages of using PAM on highway construction sites.

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APPENDICES

APPENDIX A

CURVE NUMBERS FOR SCS METHOD

Table 4.5 Runoff Curve Numbers for Hydrologic Soil Cover Complexes[a]

Land-Use Description and Cover	Average Imperviousness (%)	Hydrologic Conditions	Hydrologic Soil Groups A	B	C	D
Residential lot size[b]						
0.05 ha (⅛ acre)	65		77	85	90	92
0.10 ha (¼ acre)	38		61	75	83	87
0.15 ha (⅓ acre)	30		57	72	81	86
0.20 ha (½ acre)	25		54	70	80	85
0.4 ha (1 acre)	20		51	68	79	84
Paved parking lots, driveways, etc.[c]			98	98	98	98
Streets and roads						
Paved with curbs and storm sewers			98	98	98	98
Gravel			76	85	89	91
Dirt			72	82	87	89
Commercial and business	85 (av.)		89	92	94	95
Industrial districts	72		81	88	91	93
Open spaces, lawns, golf courses, cemeteries, etc.						
Good condition, grass cover on 75% or more of the area			39	61	74	80
Fair conditions, grass cover on 50 to 75% of the area			49	69	79	84
Fallow						
Straight row		—	77	86	91	94
Row crops						
Straight row		Poor	72	81	88	91
Straight row		Good	67	78	85	89
Contoured		Poor	70	79	84	88
Contoured		Good	65	75	82	86
Contoured and terraced		Poor	66	74	80	82
Contoured and terraced		Good	62	71	78	81
Small grain						
Straight row		Poor	65	76	84	88
Straight row		Good	65	75	83	87
Contoured		Poor	63	74	82	85
Contoured and terraced		Poor	61	72	79	87
Contoured and terraced		Good	59	70	78	81
Close-seeded legumes[d] or rotational meadow						
Straight row		Poor	66	77	85	89
Straight row		Good	58	72	81	85
Contoured		Poor	64	75	83	85
Contoured		Good	55	69	78	83
Contoured and terraced		Poor	63	73	80	83
Contoured and terraced		Good	51	67	76	80

Table 4.5 ***Continued***

Land-Use Description and Cover	Average Imperviousness (%)	Hydrologic Conditions	Hydrologic Soil Groups A	B	C	D
Pasture or range, contoured		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
		Poor	47	67	81	88
		Fair	25	59	75	83
		Good	6	35	70	79
Meadow, grass		Good	30	58	71	78
Woods or forestland		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		—	59	74	82	86

Source: Soil Conservation Service (1975).

[a] Antecedent soil moisture conditions AMC II.

[b] Curve numbers are computed assuming that the runoff from the house and driveway is directed toward the street, with a minimum of roof water directed to lawns where additional infiltration could occur. The remaining pervious areas (lawns) are considered to be in good pasture conditions for these curve numbers.

[c] In some warmer climates of the country, a curve number of 95 may be used.

[d] Close-drilled or broadcast.

APPENDIX B

SILT FENCE TIEBACK DESIGN TOOL

DESIGN PROCEDURE

Step 1). Enter the input parameters and execute the design tool by pressing Ctrl+z.

To determine an adequate tieback configuration, follow Steps 2-6:

Step 2). Divide the total length of the road by the largest silt fence length given in the Silt Fence Storage Capacity Computation Results to determine the minimum number of tiebacks required.

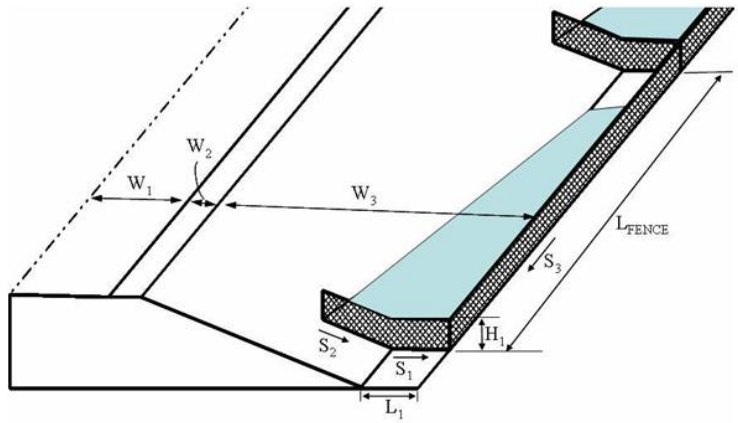
Step 3). Multiply the minimum number of tiebacks required with the total storage volume associated with the largest silt fence length in the Silt Fence Storage Capacity Computation Results.

Step 4). Compare this storage capacity with the results from the Stormwater Runoff Volume Computation.

Step 5). If the Storage Capacity given by Step 3 is greater than the stormwater runoff volume, use the tieback spacing from Step 2.

Step 6). If not, repeat Steps 2-5 using the next largest tieback spacing given in the Silt Fence Storage Capacity Computation Results.

Silt Fence Tieback Design Tool



Stormwater Runoff Volume Computation

Input:

Roadway CN:	82
Roadway Width from Centerline, W_1 (ft):	50
Roadway Length (ft):	300
Shoulder CN:	82
Shoulder Width, W_2 (ft):	0
Fill Slope CN:	82
Width from Shoulder to ROW, W_3 (ft):	50
2-yr, 24-hr Precipitation (in):	2

Results:

Stormwater Runoff Volume (gal):	12,131

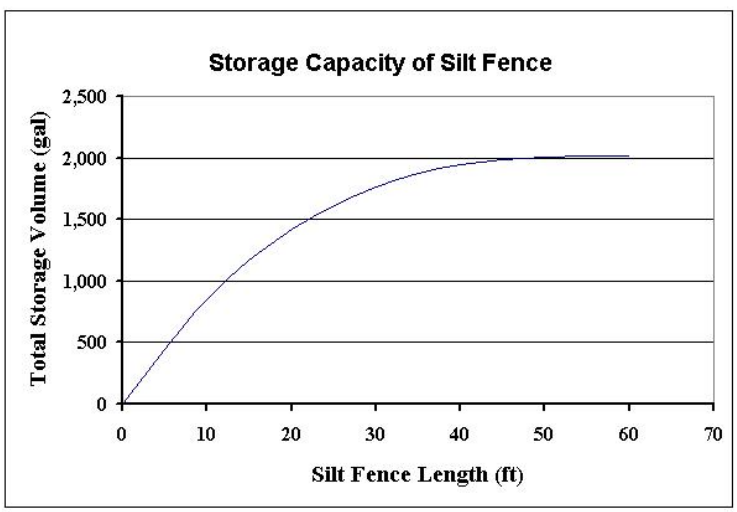
Silt Fence Storage Capacity Computation

Input:

S_1 (ft/ft):	0
S_2 (ft/ft):	0.33
S_3 (ft/ft):	0.05
H_1 (ft):	3
L_1 (ft):	0

Results:

Silt Fence Length (ft)	Total Storage Volume (gal)
0	0
10	851
20	1,421
30	1,767
40	1,945
50	2,010
60	2,020



APPENDIX C

SKAPS W200 WOVEN GEOTEXTILE FABRIC SPECIFICATION

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GeoNet | GeoComposite | NonWoven | Woven

SKAPS W200
Woven Geotextiles

SKAPS geotextile fabrics are woven polypropylene materials offering optimum performance when used in stabilization applications. Produced from first quality raw materials, they provide the perfect balance of strength and separation in styles capable of functioning exceptionally well in a wide range of performance requirements. Unless indicated below, all listed properties are Minimum Average Roll Values:

:: Go Back ::

PROPERTY	TEST METHOD	UNIT	M.A.R.V. (Minimum Average Roll Value)
Weight (Typical)	ASTM D5261	oz/yd^2 (g/m^2)	4.0 (136)
Grab Tensile	ASTM D4632	lbs (kN)	200 (.889)
Grab Elongation	ASTM D4632	%	15
Trapezoid Tear Strength	ASTM D4533	lbs (kN)	75 (0.333)
Puncture Resistance	ASTM D4833	lbs (kN)	90 (.400)
Mullen Burst	ASTM D3786	psi (kPa)	400 (2756)
Permittivity*	ASTM D4491	sec^{-1}	.05
Water Flow*	ASTM D4491	gpm/ft^2 (l/min/m^2)	5 (203)
A.O.S.*	ASTM D4751	U.S. Sieve (mm)	50 (.300)
U.V. Resistance	ASTM D4355	%/hrs	70/500

* At the time of manufacturing. Handling, storage, and shipping may change these properties.

PACKAGING	
Roll Dimension (W x L) - Ft	12.5x432 / 17.5 x 309
Square Yards per Roll	600
Estimated Roll Weight - lbs	180

APPENDIX D

1/8HH-3.6 SQ FULLJET NOZZLE SPECIFICATION

Square / Oval Pattern Full Cone Nozzles

Ordering Number: 1/8HH-3.6SQ
Description: FullJet Spray Nozzles, Square Spray, Small Capacity

Image is representative only, actual part may vary.

Printable Page | Add to RFQ

Common Applications

Cooling and quenching, Product washing, Air and gas washers, Scrubbers, Liquor washers, Dust control, Fire protection

Design Features

Smaller capacity, square spray FullJet nozzles feature a solid cone-shaped spray pattern with a square impact area and spray angles of 40° to 82°. They produce a uniform spray of medium to large drops across their entire spray area and over a wide range of pressures and flow rates. This uniform spray distribution is the result of a unique vane design with large flow passages and superior spray control characteristics.

- Well suited for installations requiring complete coverage of rectangular areas or spray zones. *Model G-SQ and GG-SQ nozzles feature removable caps and vanes that allow the removal and inspection of these components without the removal of the nozzle body from its header or manifold.*
- *The sides of the square spray pattern are offset approximately 20° to 25° from the groove positions of the nozzles, depending upon spraying pressure and spray distance.*

Specifications

Nozzle Inlet Connection	Male NPT
Capacity @ 40 psi	0.69
Nozzle Type	HH
Inlet Connection (inches)	1/8
Capacity Size	3.6SQ
Material	Brass
Length (inches)	7/8
Hex (inches)	1/2
Net Weight (oz)	1/2
Orifice Diameter Nom.	.063
Spray Angle @ 7 psi	40
Spray Angle @ 20 psi	52
Spray Angle @ 80 psi (degrees)	47
Maximum Free Passage Diameter	0.05
Capacity Size (SQ)	3.6
Spray Pattern	Square
Minimum PSI	5
Maximum PSI	150
Accessories	Split-eyelet Connector, Adjustable Ball Fittings, Strainers, Check Valves

Experts in Spray Technology

ISO 9001 Certified by BVQI 14001

Spray Nozzles — Spray Control — Spray Analysis — Spray Fabrication

APPENDIX E

F-405 SERIES IN-LINE FLOWMETER SPECIFICATION

Blue-White Industries, Ltd.

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Acrylic Tube Flowmeter - F-400 series

Features include

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- Machined from solid cast acrylic rod, polished to a clear finish.
- Rod guided float
- Strong polypropylene float stops (guide rod holders)
- Permanently silkscreened direct reading dual scale
- Permanently silkscreened white back reflector for enhanced readability
- Annealed for added strength and chemical resistance.

Specifications:

- Pipe Sizes available:
  - 1/4" Female NPT
  - 3/8" Female NPT
  - 1/2" Female NPT
- Maximum Temperature (on most models):
  - 150°F / 65°C at 0 pressure
- Maximum Pressure:
  - 150 psig / 10.3 Bar at 70°F/21°C
- Accuracy:
  - +/- 5% Full scale
- Max. Pressure Drop:
  - 2 PSI
- Dimensions:
  - Height: 8-3/16 inches
  - Width (diameter): 1-1/4 inches
- Flow ranges (dual scale reading). These are some of our most popular flow ranges.
  The files below can be printed to see actual size of scale.

  Liquid Ranges:
  - .025 - .250 GPM / .1 - 1 LPM (PDF)
  - .1 - 1 GPM / .4 - 4 LPM (PDF)
  - .2 - 2 GPM / 1 - 7.5 LPM (PDF)
  - .3 - 3 GPM / 1 - 11 LPM (PDF)
  - .5 - 5 GPM / 2 - 20 LPM (PDF)

  Air Ranges:
  - 0.2 - 2.0 SCFM / .4 - 3.2 M^3/HR (PDF)
  - 1 - 12 SCFM / 2 - 20 M^3/HR (PDF)
  - 2 - 20 SCFM / 4 - 34 M^3/HR (PDF)

Calculate for your Specific Gravity. (Liquid only) Web tool.

Please call the factory for other calibrations (such as air), or check ordering information.

Wetted material:

Chemical Resistance guide for standard and optional wetted materials.
Chemical Resistance.

- Meter tube:
  - Cast Acrylic Rod
- Adapters / Float Stops:
  - Polypropylene, reinforced with aluminum stress rings for added strength
- Float:
  - 316 Stainless Steel -or- Hastelloy C-276 -or- PVC, depending on calibration
- Guide Rod:
  - 316 Stainless Steel
- O-ring
  - Viton

See our full line of Acrylic Tube Rotameters.

See About Us for additional company information.
phone: 714-893-8529 | fax: 714-894-9492
Contact us (e-mail): Sales | Tech Support | Webmaste

APPENDIX F

MSDS FOR 705 SILT STOP POWDER

Applied Polymer Systems, Inc.

Material Safety Data Sheet

1. IDENTIFICATION OF THE PRODUCT AND THE COMPANY

Product Name: APS 705 Silt Stop

Supplied: Applied Polymer Systems, Inc.
519 Industrial Drive
Woodstock, GA 30189

Tel. 678-494-5998
Fax. 678-494-5298
www.siltstop.com

2. COMPOSITION/INFORMATION ON INGREDIENTS

Identification of the preparation: Anionic water-soluble Co-polymer

3. HAZARD IDENTIFICATION

Aqueous solutions or powders that become wet render surfaces extremely slippery.

4. FIRST AID MEASURES

Inhalation: Move to fresh air. Use dust mask when handling.

Skin contact: Contact with wet skin could cause chapping and dryness. Wash with water and soap. In case of persistent skin irritation, consult a physician.

Eye contact: Rinse thoroughly with plenty of water, also under the eyelids; seek medical attention in case of persistent irritation.

Ingestion: Consult a physician

5. FIRE-FIGHTING MEASURES

Suitable extinguishing media: Water, water spray, foam, carbon dioxide, dry powder.

Special fire-fighting precautions: Aqueous solutions or powders that become wet render surfaces extremely slippery.

Protective equipment for firefighters: No special equipment required.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions: No special precautions required.

Methods for cleaning up: Do Not flush with water. Clean up promptly by sweeping or vacuum. Keep in suitable and closed containers for disposal. After cleaning, flush away traces with water.

7. HANDLING AND STORAGE

Handling: Avoid contact with skin and eyes. Avoid dust formation. Do not breath dust. Use dust mask during handling. Wash hands after handling.

Storage: Keep in a cool, dry place. (0-30^0 C)

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Engineering controls: Use local exhaust if dusting occurs. Natural ventilation is adequate in absence of dust.

Personal protection equipment

Respiratory Protection: Dust safety masks are recommended where dusting may occur.
Hand protection: Dry cloth, leather or rubber gloves.
Eye Protection: Safety glasses with side shields or face masks. Do not wear contact lenses.
Skin protection: No special protective clothing required.
Hygiene measures: Wash hands before breaks and at end of work day.

9. PHYSICAL AND CHEMICAL PROPERTIES

Form: Granular solid
Color: White
Odor: None
pH: 5-6
Melting point: N/A
Flash point: N/A
Vapor density: N/A

10. STABILITY AND REACTIVITY

Stability: Product is stable, no hazardous polymerization will occur.
Materials to avoid: Oxidizing agents may cause exothermic reactions.
Hazardous decomposition products: Thermal decomposition may produce nitrogen oxides (NOx), carbon oxides.

11. TOXICOLOGICAL / ECOLOGICAL INFORMATION

Acute toxicity: (EPA/600/4-90/027F)

LD 50 / ***Rattus norvegicus*** / oral / > 5000 mg/kg
LC 50 / ***Oncorhynchus mykiss*** / 96h / 530 mg/L
LC 50 / ***Daphnia magna*** / 48h / >420mg/L
EC 50 / ***Selenastrum capricornutum*** / 96h / >500mg/L

Chronic Toxicity : (EPA/600/R-98/182)

IC_{25} (Survival) / ***P. promelas*** / 7 day / 358 ppm
NOEC (Survival) / ***P. promelas*** / 7 day / 840 ppm

IC_{25} (Survival) / ***C. dubia*** / 7 day / 157.5 ppm
NOEC (Survival) / ***C. dubia*** / 7 day / 105 ppm

IC_{25} (Growth) / ***P. promelas*** / 7 day / 94 ppm
NOEC (Growth) / ***P. promelas*** / 7 day / 105 ppm

IC_{25} (Reproduction) / ***C. dubia*** / 7 day / 27.7 ppm
NOEC (Reproduction) / ***C. dubia*** / 7 day / 26.25 ppm

Inhalation: The product is not expected to be toxic by inhalation.

Dermal: The results of testing on rabbits showed no toxicity even at high dose levels.

Bioaccumulation: The product is not expected to bioaccumulate.

Persistence / degradability: Not readily biodegradable: (~40% after 28 days).

Chronic toxicity: A 2 yr feeding study on rats did not reveal adverse health effects.
A 1 yr feeding study on dogs did not reveal adverse health effects.

13. TRANSPORT AND REGULATORY INFORMATION

Not regulated by DOT, RCRA status-Not a hazardous waste

NFPA and HMIS ratings:

NFPA	Health:	3	Flammability:	0	Reactivity:	1
HMIS	Health	2	Flammability	0	Reactivity	1