EVALUATION OF ANIONIC POLYACRYLAMIDE AS AN EROSION

CONTROL MEASURE USING INTERMEDIATE-SCALE

EXPERIMENTAL PROCEDURES

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EVALUATION OF ANIONIC POLYACRYLAMIDE AS AN EROSION CONTROL MEASURE USING INTERMEDIATE-SCALE EXPERIMENTAL PROCEDURES

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Alexander L. Shoemaker, son of William L. Shoemaker and Colleen P. Shoemaker, was born on May 24th, 1984, in Auburn, AL. He graduated high school from Hudson High School in Hudson, OH in 2003. After graduating, he attended Auburn University in Auburn, AL and graduated with a Bachelor of Civil Engineering degree in May of 2007. That same month, he entered the Graduate School at Auburn University to pursue a Master of Science in Civil Engineering.

THESIS ABSTRACT

EVALUATION OF ANIONIC POLYACRYLAMIDE AS AN EROSION CONTROL MEASURE USING INTERMEDIATE-SCALE EXPERIMENTAL PROCEDURES

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The United States Environmental Protection Agency (EPA) has been working to establish stricter guidelines and limitations pertaining to stormwater and the various pollutants transported by runoff. This transport is primarily prevalent in runoff exiting exposed and disturbed land common to construction sites. Therefore, understanding the effectiveness of many different erosion and sediment control technologies is becoming a high priority to the construction industry. In this research, the effectiveness of a chemical stabilizer known as anionic polyacrylamide (PAM) was examined using intermediate-scale testing procedures that mimic conditions similar to a highway embankment with a compacted 3:1 fill slope. The first phase of this research focused on intermediate-scale testing procedures that were developed from previous research efforts and further

modified to enable researchers to rapidly generate large quantities of valuable data. The rain regime selected for this research consisted of a 2-year, 24-hour storm event for Montgomery, AL which was divided into four 15 minutes rain events with 15 minute breaks in between that produced 1.10 in. of rainfall per event and a total cumulative amount of 4.4 in.

The second phase of research focused on conducting intermediate-scale experiments to examine the effectiveness of PAM with different application rates and application methods. These different application methods included: (1) dry granular PAM applied directly to test plots and (2) dry PAM mixed with water to form a liquid spray application. Application rates were determined through manufacturer recommendations (i.e. 25 to 35 lbs/acre) and this research conducted additional experiments to examine the performance at PAM at rates lower than the recommended rate (i.e. 15 lbs/acre). Liquid PAM applications were not allowed to dry prior to being subjected to rainfall to simulate a ‘worst-case scenario’ for treatments. The results from this phase of research showed that dry PAM applied at the recommended rate of 35 lbs/acre performed the best out of the various PAM treatments by significantly reducing initial turbidity levels by 97% and eroded soil by 50% when compared to the bare soil control condition. Collected runoff samples indicated that runoff from test plots treated with dry PAM applied at 35 lbs/acre reduced turbidity to the proposed EPA effluent limits of 13 NTU within 20 seconds.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The discharge of sediment laden stormwater from construction sites proves to be a major environmental concern. Stormwater discharge is a form of nonpoint source pollution (NPS), which is the result of rainfall or snowmelt traversing though an area and can carry natural and non-natural pollutants, into lakes, rivers, and ground water. In addition, the effect of stormwater discharge can significantly increases the occurrence of erosion and sedimentation (two specific consequences of NPS) when occurring over disturbed land, such as construction sites. Therefore, to provide a level or protection for humans, wildlife, and the environment, federal and state regulations require construction site owners and operators to manage stormwater discharge and prevent NPS. In 1987, Congress passed the Clean Water Act, of which Section 319 established a national program focusing on the control of nonpoint sources of water pollution. Due to Section 319, all States have adopted management programs to help in the control and reduction of NPS (U.S. EPA 2003).

Since active construction sites, or any other land-disturbing activities, are identified as one of the leading contributors to NPS, a great deal of effort goes into eliminating the dangers attributed to stormwater and generated runoff. For the U.S. alone, it is estimated that the total amount of sediment washed from construction sites into surface bodies of water is over 80 million tons each year (Novotny, 2003). Much of this sediment laden runoff could have been mitigated through the use of effective erosion and sediment control programs.

1.2 EROSION AND SEDIMENTATION PROCESSES

Construction site erosion and sedimentation are two primary contributors to NPS pollution in the construction industry. This section will cover the basics pertaining to the process of erosion and sedimentation. The Alabama Soil and Water Conservation Committee (ASWCC) identifies the main factors contributing to the erosion process to be climate, topography, soils and vegetative cover (ASWCC, 2003). Climate includes rainfall, temperature, and wind, with rainfall being the main contributor to erosion. The amount, duration, and intensity of rainfall are all major factors that can increase the severity of runoff. However, with proper ground cover, such as vegetation, the amount of erosion and sedimentation will be greatly reduced. To assist in understanding and reducing these processes that increase the amount of erosion and sedimentation, the ASWCC published a handbook entitled, "*Alabama Handbook for Erosion Control, Sediment Control, and Stormwater Management on Construction Sites and Urban Areas",* to help contractors with their erosion control plans.

The handbook states that the process of erosion is, "when the land surface is worn away by the action of water, wind, ice or gravity" (ASWCC, 2003). Rainfall water tends to be the common source of erosion. The effect rainfall has on soils includes the force of raindrops impacting the ground and physical movement of surface stormwater runoff, resulting in shear forces on the soil. Both of these actions cause soil particles to become detached and increase potential for NPS pollution. However, since physical properties involving raindrop impacts and surface runoff are different, multiple methods to address, reduce, and eliminate the amount of erosion and sedimentation on construction sites are available (ASWCC, 2003).

The other concern of stormwater discharge is sedimentation. Once the velocity of stormwater runoff decreases, detached soil particles begin to settle out of suspension. The larger and heavier particles (i.e. gravel and sand) in runoff will settle out faster. However, smaller particles, (i.e. silt and clay), require longer detention times to promote settlement. To compound the issue further, these smaller particles are also more easily detachable from the surface due to runoff. This process of soil particles settling out of suspension is known as sedimentation. To measure the severity of sedimentation, a unit of measure called turbidity is used. If water is highly turbid, it indicates that more suspended particles are present in the runoff (ASWCC, 2003). It is important to control/reduce sedimentation because these suspended particles can be detrimental to aquatic wildlife.

The U.S. Environmental Protection Agency (EPA) has a program available to assist with the management of stormwater discharge from construction sites that result in the process of erosion and sedimentation, known as the National Pollutant Discharge Elimination System (NPDES). This program requires that any construction site disturbing an area of one acre or larger must obtain authorization to discharge stormwater under a NPDES construction stormwater permit (U.S. EPA, 2008a). This program also requires operators of regulated construction sites to implement erosion and sediment control best management practices (BMPs) to prevent NPS pollution. Therefore, the need to develop cost effective measures that help control and prevent erosion and sedimentation is becoming an important issue in the industry.

1.3 BEST MANAGEMENT PRACTICES (BMPs)

Best management practices (BMPs) is the process of implementing methods to assist with minimizing erosion and sedimentation on disturbed land. These BMPs are outlined in detail in the ASWCC Handbook and provides contractors with the available methods to assist with controlling stormwater discharge, such as installation and maintenance instructions. Specific examples of these BMPs are listed below in Table 1.1.

Table 1.1 Examples of Different BMPs for Protecting Against Erosion, Sedimentation, and Stormwater Discharge

Techniques	Best Management Practices
Surface Stabilization	Chemical Stabilization; Erosion Control Blankets; Mulching; Permanent Seeding; Retaining Walls; Sodding; Temporary Seeding
Runoff Conveyance	Check Dams; Diversions; Drop Structures; Outlet Protection; Subsurface Trains; Swales
Sediment Control	Brush/Fabric Barriers; Drop Inlet Protection; Filter Strips; Floating Turbidity Barriers; Inlet Protection; Sediment Barriers; Sediment Basins; Sediment Traps
Stormwater Management	Porous Pavement; Stormwater Detention Basins
Stream Protection	Buffer Zones; Channel Stabilization; Streambank Protection; Temporary Stream Crossings

The examples of BMPs shown in Table 1.1 only provide a small sampling of the available measures. This research focuses on one type of chemical stabilization that use anionic polyacrylamide (PAM). PAM is a negatively charged chemical and when applied to soil surfaces it bonds with soil particles to help maintain soil structure and reduce erosion. In addition to acting as an erosion control measure, PAM also serves as a binding agent to flocculate soil particles that have become detached during the erosion process. This flocculation of fine particles occurs when the negative charge of PAM polymers combine together with suspended soil particles. The resulting increase in combined particle sizes aids flocculation. Therefore, PAM applied as a chemical stabilization technique will assist in reducing erosion and sedimentation caused by stormwater. The U.S. Environmental Protection Agency (U.S. EPA) states in its chemical stabilization section of the NPDES, that PAM effectiveness as a stabilization method can range from 70% to 90% (2006). Anionic PAM can be applied in three different forms: (1) dry, granular form, (2) liquid form (granular PAM/water mixture), and (3) emulsified form.

1.4 RESEARCH OBJECTIVES

The research presented herein is based on a continuing effort by the Department of Civil Engineering at Auburn University to study and test erosion and sediment control BMPs that are typically used on highway construction sites. The intent of this research effort is to expand on a previous study that tested anionic PAM in the dry granular form. This research incorporates a new facility, specifically designed to test various erosion and sediment control measures. The facility is located at the National Center for Asphalt

Technology (NCAT) Test Facility near Opelika, AL. The focus of this research was to conduct experiments for the purpose of examining the effectiveness of both dry and liquid PAM applications for erosion and sediment control. The research effort was divided into two phases. Phase 1 focuses on the development of the test facility, rainfall simulator, testing apparatus, and new methods to evaluate treatments. Phase 2 of the research focuses on the experimentation of the anionic PAM as either applied in dry or liquid form with different application rates. The specific phases of this research effort are described in detail below.

PHASE 1: TESTING FACILITY

1. Design and develop a testing apparatus that will allow for efficient experimental setup and to achieve reproducible results.
2. Design and construct a rainfall simulator that models realistic rainfall events.
3. Develop a unified testing methodology to obtain reproducible results for the comparison of all possible experiments.

PHASE 2: EXPERIMENTATION

1. Examine the effectiveness of various application rates of dry and liquid PAM for use as an erosion control measure on compacted, 3:1 slopes.
2. Compare experimental results to provide recommendations for using PAM on highway construction sites.

1.5 ORGANIZATION OF THESIS

This thesis is divided into five chapters. Following this chapter, Chapter 2: *Literature Review*, examines the body of knowledge pertaining to research and experiments conducted to evaluate PAM as an erosion and sediment control measure. This chapter discusses the designs, procedures, and experimental results that were presented in previous research efforts. Also discussed are advantages and disadvantages of performing experiments at different scales (i.e. field vs. intermediate). Chapter 3: *Intermediate-Scale Methods and Procedures*, outlines the designs, methods, procedures used in conducting intermediate-scale experiments, and methods of analysis used in this research. This chapter includes details on the design of the new test facility, test plots, rainfall simulator, and procedures used to prepare and perform experiments. Chapter 4: *Experimental Results*, presents the results generated from all the experiments performed and includes ANOVA statistical analyses to determine if experimental results were statistically significant. Chapter 5: *Conclusions and Recommendations*, provides insight on the use and performance of PAM (i.e. dry vs. liquid application) as an erosion and sediment control technology. This chapter also provides recommendations for future research using PAM in conjunction with other erosion and sediment control measure to determine the optimum combination of technologies to prevent NPS pollution.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

The use of anionic polyacrylamide (PAM) as an erosion control measure is a topic that has been gaining attention recently. Several researchers have investigated the use of PAM in a multitude of applications, however, testing methods vary, and there exists a lack of uniform agreement on the effectiveness of PAM. Differences include different methods for applying PAM (i.e. how PAM should be applied and in what quantities), whether PAM is effective when applied alone without any other BMPs, or whether PAM should be used in conjunction with additional erosion control measures. In addition, there are concerns on the effectiveness of PAM on steep slopes, which are primarily used in conjunction with construction projects. Previous research conducted by McDonald (2007) covered the initial investigation performed by Auburn University to test the effectiveness of anionic PAM applied in a granular form as an erosion and sediment control BMP and is further reviewed in this chapter.

One of the primary goals of this research was to develop new procedures for testing the effectiveness of PAM and provide a uniform methodology for future research. Therefore, the focus of this literature review will examine: (1) procedures and methods used when testing anionic PAM, (2) experimental results, and (3) types of analysis used in quantifying experimental data.

2.2 PROCEDURES AND METHODS USED FOR EXPERIMENTATION

Procedures used for testing anionic PAM vary from study to study without a unified system for evaluation. This section provides an overview of procedures, methods, and testing apparatus' used throughout the literature. This includes examining different methods used to generating runoff via rainfall, experimental scale, experimental setup, data collection procedures, and data analyses.

2.2.1 Generation of Runoff

For the erosion process to occur, a source of runoff needs to be generated, which will cause soil particles to become detached. This detachment of soil particles and resulting transport in stormwater is one of the main contributors to NPS pollution and a source of concern in practice. Sources of runoff could include: (1) natural rainfall, (2) simulated rainfall, (3) irrigation, or (4) channelized flow. All four methods of generating runoff can be used to test the effectiveness of erosion control BMPs. A project's research goals and objectives will be the main driving force in selecting the optimal method for generating runoff for experimental purposes. The research documented in this report focuses on typical highway embankments (i.e. fill slopes) exposed to surface runoff (i.e. sheet flow), therefore the use of simulated and natural rainfall from previous research studies was primarily examined and is discussed in the following sections.

2.2.1.1 Simulated Rainfall Designs

Rainfall simulators can be used to produce and represent natural rainfall conditions, with the added benefit of having complete control over the system. The desired rainfall intensity, droplet impact velocity, duration, and resulting storm event can all be selected and controlled depending on experimental requirements. This level of control provides a distinct advantage over natural rainfall. However, an improperly designed rainfall simulator can lead to unrealistic rainfall conditions, jeopardizing the authenticity of any experimental results. The following five components when designing a rainfall simulator are critical to overall performance: (1) appropriate density of drop formers under constant head and intensity; (2) application uniformity; (3) droplet size distribution; (4) control of application rate; and (5) obtaining terminal velocity for the droplet distribution (Regmi and Thompson, 2000).

Research performed by Hall (1970) investigated three problems in simulating rainfall: (1) controlling application rate in both time and space; (2) reproduction of drop size distribution observed in different intensities; and (3) reproduction of terminal velocities of drops. This study found that a general purpose rainfall simulator could not adequately be developed that addresses all three of these problems equally. The research indicated that by controlling one of the issues; the other issues would be adversely affected. Hall recommends that a rainfall simulator should be able to create artificial conditions that begin the hydrologic process and any laboratory results should be extrapolated to field conditions.

2.2.1.2 Simulated Rainfall Applied on Experiments

While research and experiments examining erosion and sedimentation issues vary procedurally, many used a simulated rainfall to generate runoff on their experiments (Petersen et al., 2007; McLaughlin and Brown, 2006; Sepaskhah and Bazrafshan-Jahromi, 2006; Benik et al., 2003; Flanagan et al., 2002a; Peterson et al., 2002; Bjorneberg et al., 2000; Roa-Espinosa et al., 1999; Flanagan et al., 1997a; Flanagan et al., 1997b). While it appears using simulated rainfall is generally accepted, the actual designs and methods involved with individual rainfall simulators are varied.

Experiments conducted by McLaughlin and Brown (2006) and Petersen et al. (2007) referenced the design of a solenoid-operated, variable intensity rainfall simulator by Miller (1987). Miller’s design included a WSQ nozzle threaded directly into a solenoid valve. The original simulator design included a one or three nozzle setup. Tests conducted by Miller (1987) indicated that a one nozzle configuration performed slightly better than multiple nozzles, in regards to uniform spray coverage, attributed to the lack of overlapping caused by a three nozzle configuration. The final component of the Miller rainfall simulator uses the solenoid valve during operation by changing the duration of an open/closed cycle to reduce the intermittent nature of simulated rainfall.

The intensity of rainfall simulated by McLaughlin and Brown was 34 mm/hr, which was obtained by an on/off-cycle at 10-second intervals. An optional pressure regulator was installed to maintain a constant water pressure of 34 kPa. This rainfall event lasted 5 minutes after runoff was initiated. The rainfall intensity reported by Petersen et al. was 75mm/hr and simulations were conducted for 30 minutes after the initial start of runoff. The water pressure of the system was not specified in the literature by Petersen et al (2007).

A similar rainfall simulator used in the research conducted by Peterson et al. (2002) was modeled from recommendations provided by Foster et al. (1982). This design also included the ability to program the simulator for different types of rainfall. This configuration allowed rainfall durations and intensities to vary throughout an experiment. During experimentation of dry and liquid PAM applications as an erosion control measure, four test runs were used, modeling different rain events. The first test run (i.e. 'sub-run') used an intensity of 75 mm/hr for one hour. After a one hour break, another test run (i.e. 'wet run') was conducted with the same rainfall intensity used previously, over a 30 minute period. Following a 30 minute break with no rainfall, a third "very wet" run was broken down into three stages: (1) 75 mm/hr for 15 minutes; (2) 28 mm/hr for 15 minutes; and (3) 100 mm/hr for 15 minutes. These different test runs were selected to simulate the effect of the treatments on different soil conditions (i.e., dry soil, moist field, saturated field). Peterson states that the initial dry run represented a 1-hr, 100-yr rain event (for West Lafayette, Indiana) and the wet and very wet test runs both represented events exceeding a 100-yr return period for their respective durations.

A rotating-boom simulator was used in research conducted by Benik et al. (2003), which referenced a design recommended by Swanson (1979). This device applied rainfall in a relatively uniform circular pattern of 15.2 m. The simulator used spray nozzles attached to pressure regulators to maintain a constant pressure of 55 kPa. This configuration provided a rainfall intensity of approximately 60 mm/h. Rainfall was applied in two different intervals, classified as a ‘dry’ and ‘wet’ run of 90 and 60 minutes, respectively.

Another rainfall simulator used for experiments consisted of an oscillating sprinkler as described by Meyer and Harmon (1979) (Bjorneberg et al., 2000). This setup contained a Veejet nozzle mounted approximately 3 m above the test surface. The desired rainfall intensity was 80 mm/hr at a constant pressure of 76 kPa providing droplet sizes of 1.2 mm. The rainfall duration for their experiments lasted 15 minutes.

A non-specified rainfall simulator design was used in research conducted by Roa-Espinosa et al. (1999). In this research, it states that the simulator produced a rainfall intensity of 64 mm/hr for an average duration of 40 to 50 minutes (or until the runoff collection tank was filled). No additional information on the rainfall simulator was provided.

The rainfall simulator designed by Foster et al. (1982) was used on multiple experiments that examined the effect of different soil treatments on infiltration, surface runoff, and erosion, including the use of PAM (Flanagan et al., 1997a; Flanagan et al., 1997b; Flanagan et al., 2002a). This design was programmable, which allowed an instantaneous change in rainfall intensity by controlling the frequency of nozzle oscillations. The research conducted in 1997 used a rainfall intensity of approximately 64 mm/hr until a generated runoff hydrograph had achieved a steady-state for a time period of at least 5 minutes (Flanagan et al., 1997a and 1997b). For the study done in 2002, a more sophisticated setup was used that consisted of multiple test runs. The initial test run (i.e. ‘dry’ run) consisted of a target intensity of 64 mm/hr for a one hour duration.

Following a one hour break, the second test run (i.e. ‘wet’ run) had an intensity of 64 mm/hr for one hour. Following a 30 minute break, a third stage “very-wet run” was conducted using intensities of 75 mm/hr, 28 mm/hr, and 100 mm/hr, for a duration of 15 minutes each (Flanagan et al., 2002a). The initial dry run was representative of a 25-yr storm even for west-central Indiana. The succeeding wet runs represented a return period greater than a 100-yr storm event.

2.2.1.3 Natural Rainfall used in Experimental Tests

Instead of using simulated rainfall, an experiment could be designed to use natural rainfall. Natural rainfall has inherent advantages and disadvantages in comparison to simulated rainfall. One advantage of natural rainfall is that experimental results will accurately model real-life or actual field conditions. The potential treatment is exposed to realistic conditions, similar to when the product would be used in practice. One primary disadvantage is that by using natural rainfall, the research is at the mercy of weather, possibly being delayed due to long periods without rainfall. An area could experience drought conditions, severely hampering the experiment. These unpredictable qualities of natural rainfall can lead to undesirable experimental results and conditions.

A study conducted by Hayes et al. (2005) used three field test locations exposed to natural rainfall. Each site was set up in succession to handle the effort of post-storm data sampling. This also ensured no overlap between the three test sites existed. Rainfall intensity for all subsequent storm events was not reported, but the accumulated rainfall for each event was recorded. For their first test location, eight different storm events produced amounts ranging from 1 mm to 66 mm of rain, with a failure of the sediment collection device on the last storm event. The second experiment test location received six rain events ranging from 8 mm to 42 mm. The final test location experienced seven rain events ranging from 5 mm to 34 mm of accumulated rainfall (Hayes et al., 2005).

The last study examined here was a continuation of the research conducted by Flanagan et al. (2002). As discussed earlier, the first part of the study used simulated rainfall to test PAM under controlled conditions (Flanagan et al., 2002a). This research was expanded to see how PAM preformed under natural rainfall using 26 test plots spread over two locations. The first site encountered 9 different storm events for a total of 185 mm of rainfall. The second site experienced 17 storm events for a cumulative rainfall of 636 mm (Flanagan et al., 2002b). The results of this study showed similar trends in runoff depth when compared to the previous research effort.

2.2.1.4 Rainfall Summary

The application of water to a test site to generate runoff is a critical component to the overall design, methodology, and success of an experiment. Different methods exist to achieve this depending on a project's overall research goals. Therefore, care must be taken in selecting the proper design to generate runoff.

When designing a rainfall simulator, Hall (1970) and Regmi and Thompson (2000) identified key components to ensure simulated rainfall accurately models natural rainfall. Many of the designs presented here adequately addressed these issues to justify the quality of their rainfall simulators. By taking steps to properly design a rainfall simulator, the quality of reported results could be considered accurate. None of the studies indicated any major issues or concerns pertaining with simulated rainfall versus natural rainfall. It is important to note, that the design of any rainfall simulator could affect the size of an experiment, due to limited spray area. A simulator design with one nozzle may constrain the size of test plots. Conversely, simulators can be designed to work on large test section, but may require a greater amount of resources and materials. Table 2.1 provides a summary of the five different factors discussed in this section: (1) type of rainfall (i.e. simulated vs. natural), (2) simulator height, (3) rainfall intensity, and (4) storm duration.

Selection of different types of rainfall to use depends on the resources available and overall research goals. Typically, the convenience associated with having a rainfall simulator outweighs the use of natural rainfall. The random nature and uncertainty associated with natural rainfall events (e.g. undesirable amount of rainfall being produced or periods of no rainfall) could seriously impact an experiment. This was seen in some of the studies documented in this section where an unanticipated amount of rainfall occurred, causing failures in the experimental design. Conversely, simulated rainfall might not accurately reflect the properties of natural rainfall, so care must be taken to ensure a simulator is correctly designed, operates effectively, and realistically models natural rainfall events.

Table 2.1 Summary of Experimental Rainfall Regimes from Literature

Study	Type	Height (m)	Rainfall Intensity (mm/hr)	Duration
Petersen et al. (2007)	Simulated	UNK	75	30 min after start of runoff
McLaughlin and Brown (2006)	Simulated	4	34	5 min after start runoff
Sepaskhah and Bazrafshan-Jahromi (2006)	Simulated	2.65	96	15 min
Hayes et al. (2005)[1]	Natural	UNK	1 to 66[c]	UNK
			8 to 42[c]	UNK
			5 to 34[c]	UNK
Benik et al. (2003)	Simulated	NA	60	90 min
			60	60 min
Flanagan et al. (2002)a	Simulated	2.4	64	1 hr followed by 1 hr break
			64	1 hr followed by 30 min break
			64	15 min
			28	15 min
			100	15 min
Flanagan et al. (2002)b	Natural	UNK	185[a,c]	UNK
		UNK	636[b,c]	UNK
Peterson et al. (2002)	Simulated	2.4	75	1 hour followed by 1 hour break
			75	1 hr followed by 30 min break
			75	15 min
			28	15 min
			100	15 min
Bjorneberg et al. (2000)	Simulated	3	80	15 min
Roa-Espinosa et al. (1999)	Simulated	UNK	64	40-50 min or until collection tank was filled
Flanagan et al. (1997)a Flanagan et al. (1997)b	Simulated	UNK	64	Until runoff hydrograph on flume chart recorder leveled off for at least 5 min

Notes: 'UNK' indicates that data was not specified in the literature.
'1' Three field locations were tested
'a' Total of 9 events (Location 1)
'b' Total of 17 events (Location 2)
'c' Cumulative Rainfall

2.2.2 Experiments and Procedures

In this section, the different devices and methods researchers used to test the effectiveness of PAM on soil surfaces are investigated, along with results reported from the experiments conducted. One method for experimental setup is accomplished by using test plots outdoors that represented field conditions on pre-existing slopes (Petersen et al., 2007; Hayes et al., 2005; Leib et al., 2005; Benik et al., 2003; Flanagan et al., 2003a; Flanagan et al., 2003b; Flanagan et al., 2002a; Flanagan et al., 2002b; Lentz et al., 2002; Peterson et al., 2002; Roa-Espinosa et al., 1999). The site location can vary in size and configuration depending on resources available and the goals established by the researchers. These sites have the ability to produce results that would realistically represent processes observed in the field. Conversely, small or intermediate-scaled test plots (usually conducted indoors under laboratory conditions) allow for a more controllable setup (Sepaskhah and Bazrafshan-Jahromi, 2006; McLaughlin and Brown, 2006; Bjorneberg et al., 2000). Either method has advantages and disadvantages associated with each setup. In addition to looking at the equipment and setups, procedures and methods used during experimentation will be examined. These will include plot preparation procedures, data collection methods, and any additional pertinent information. The following sections will investigate these topics and review results of using PAM as an erosion control BMP included within each research effort.

2.2.2.1 Field-Scale Experiments

Typically, experimental setups pertaining to outdoor field conditions are large in size when compared to similar experiments conducted in laboratory conditions. Field-scale setups could be supplemented with large rainfall simulators to offer a level of control similar to that used in an indoor, laboratory setting (Peterson et al., 2007; Benik et al., 2003; Flanagan et al., 2002a; Flanagan et al., 2002b; Peterson et al., 2002; Roa-Espinosa et al., 1999; Flanagan et al., 1997a; Flanagan et al., 1997b). If a rainfall simulator was not used during a field-scale experiment, then the research was dependent on natural rainfall, a type of channelized flow, or irrigation to generate the required runoff (Hayes et al., 2005; Peterson et al., 2003; Flanagan et al., 2002b; Bjorneberg et al., 2000).

A study conducted by Peterson et al. (2007) used two field test sites for testing new liquid and emulsified PAM formulations for use on agricultural fields. These sites had on average, slopes ranging from 7% to 9%. At both locations, test plots were created by using sheet metal to border the testing area. These enclosed areas had dimensions measuring 2.0 m x 0.75 m. Soil surfaces were raked to a uniform level. Two test plots were created at each site for a total of four sections. At the down-slope end of each test plot, a gutter system was installed to collect runoff and PVC pipes were used to transport and convey the runoff to collection buckets (Peterson et al., 2007). The PAM was applied using a hand sprayer at a rate of 5 kg/ha. Tests were performed at three different times with two replications, at 2-days, 3-weeks, and 10 weeks from the initial PAM application. With the exception of the 2-day tests, the site was exposed to natural precipitation in between experiment times.

Data collection consisted of runoff samples collected every 5 minutes. The samples were dried in an oven for 24 hours and weighed afterwards. Following this, additional runoff samples were taken at 5 minute intervals to determine silt, clay, and sand content. Since this experiment was concerned primarily with agricultural applications, additional runoff samples were taken at 5, 15, and 25 minute intervals for phosphorus analysis (Petersen et al., 2007). Finally, total runoff was collected and measured at the end of each test. Results of the experiment indicated that runoff volumes were reduced 100% at 2-days, 59% at 3-weeks, and 55% at 10-weeks. Sediment loss on test plots also experienced similar reductions of: 100%, 80%, and 74% at their respective time periods of 2-days, 3-weeks, and 10-weeks.

Research by Hayes et al. (2005) also used multiple site locations for setting up test plots. The purpose of this research was to examine the effectiveness of two dry granular PAM products, Soilfix and Siltstop 705, mixed with water to form a liquid solution applied with and without seed and mulching. Recommended application rates of Siltstop 705 and Soilfix consisted of 10.5 kg/ha and 1.5 kg/ha, respectively. In addition to examining theses rates, researchers performed tests to determine the effectiveness of the PAM products at half the recommended rate.

Slope used for experimentation were similar to those found on construction sites (i.e. 20% to 50%). At one test site, plots were constructed with dimensions of 6 m by 1.5 m. These plots were separated by a 15 cm high plastic barrier driven into the soil (Hayes et al. 2005). Additional plastic barriers were placed down-slope to channel the runoff to a drain pipe connected to collection buckets. The other sites varied slightly by plot spacing and the use of different methods for runoff collection.

Data collection consisted of analyzing the runoff in the collection buckets at the end of each storm event. Samples were taken to measure the turbidity and suspended solids. Results collected indicated that the addition of PAM to the seed and mulch provided no significant benefits to volume and sediment reduction. However, researchers acknowledge that steep slopes may require higher application rates than used in this research.

Two studies performed by Flanagan et al. (2002a; 2002b) were conducted using field conditions consisting of 9 test plots measuring 2.96 m wide by 9.14 m long. Slope steepness for plots ranged from 32% to 45% (Flanagan et al., 2002a; Flanagan et al., 2002b). PAM treatments, of Percol 336 with an application rate of 80 kg/ha, were mixed with water to form a liquid spray. One of the PAM mixtures included an addition of gypsum. Runoff was collected with a metal trough which directed all runoff for analysis.

The first study, using simulated rainfall, collected samples at intervals based upon on the rate of runoff and did not exceed 3 minute time intervals. Data of interest included runoff rate, sediment concentration, and sediment yield rate. Following the completion of all rainfall simulations, additional soil samples were taken from the test plots to determine soil surface conditions (Flanagan et al., 2002a). Results for this study found that treatments of PAM reduced runoff and sediment yield 40% and 83%, respectively. PAM treatments with gypsum performed slightly better, with runoff reduced by 52% and sediment yield by 91%.

The second study, using the same experimental setup as the first, was examined under natural rainfall conditions. Test plots were constructed at two locations. Runoff was collected in barrels placed at the end of each test plot. The researchers used multiple methods to collect the runoff, depending on the volume of runoff generated. Since samples were not collected at specific time intervals, data consisted of cumulative amounts of runoff and sediment yield (Flanagan et al., 2002b). Performance of different

PAM treatments were similar to the experiments that used simulated rainfall. The first test location experienced runoff and sediment reductions for PAM and PAM with gypsum treatments of: 33%, 54%, 33%, and 45%, respectively. The second test location also experienced similar reductions of runoff and sediment volume of: 15%, 40%, 28%, and 53%.

Another study conducted by Flanagan et al. (1997a; 1997b) was a two-part project which looked at PAM's effectiveness on field plots using simulated rainfall. Three test sites were constructed for experimentation. The first part of Flanagan's study examined the effect different soil amendments had on infiltration and runoff. One of the treatments was a liquid solution of PAM applied at an application rate of 20 kg/ha. The other treatment consisted of fluidized bed combustion bottom ash (FBCBA). The second part of this research focused on how different treatments affected soil erosion specifically. Test plots were divided to include three, small interrill plots measuring 0.8 m wide x 0.6 m long and three, larger interrill plots measuring 0.8 m wide and 10.7 m long (Flanagan et al., 1997a; Flanagan et al., 1997b). Test slopes ranged from 6% to 9%. Runoff sampling used different size collection containers depending on flow rate generated.

Data collection for the first part of the study focused on measuring the flow rate by timing the leading edge flow velocity with a fluorescent dye (Flanagan et al., 1997a). In addition, cross sectional measurements were taken using a laser scanner. Total runoff was calculated from the generated hydrograph and infiltration rate was measured by taking the difference of runoff rates from measured rainfall rate.

The second part of Flanagan's study also recorded leading edge flow velocity. Sediment samples were collected every 3 minutes and concentration was determined by gravimetric analysis (Flanagan et al., 1997b). Cross sectional measurements were also taken to evaluate any change in the plot elevation. Total runoff and sediment rates were calculated from the flow and sediment discharge curves (Flanagan et al., 1997b). Researchers found that for both studies, PAM was effective at significantly increasing infiltration, while reducing runoff and sediment transport.

Peterson et al. (2002) used 12 testing plots at one site location to examine the effectiveness of dry and liquid PAM applications of 60kg/ha each. Slopes at the site were graded to approximately 17%. Soil depth was raked and leveled by hand to 0.3 m, then roto-tilled afterwards. Plots were also seeded with an unspecified grass mixture (Peterson et al. 2002). Individual test plots were constructed measuring 9.1 m x 3 m and separated with sheet metal. Samples were collected every 3 minutes and discharge rates were measured by collecting runoff at the outlet trough in buckets at an unspecified amount of time (Peterson et al., 2002). The total runoff was calculated from discharge measurements over time and sediment yield was determined from the discharge rate and average sediment concentration. The research concluded the liquid PAM applications were more effective, by reducing runoff and sediment yield with values ranging from 62% to 76% and 93% to 98%, respectively. Dry granular PAM was observed to have almost no benefit during experimentation

The final study using field-scale plots examined was performed by Roa-Espinosa et al (1999). The PAM treatments consisted of: (1) liquid PAM applied to dry soil, (2) dry granular PAM applied to dry soil, (3) liquid PAM with seed and mulch, and (4) liquid PAM applied to wet soil. This study is unique because while the plots were installed outdoors in field conditions, the size of the plots was smaller than any previously conducted research discussed. The study used 15 plots measuring 1 m x 1 m with an unspecified depth on a 10% slope. These smaller plots were easier to set-up and allowed researchers three replications, opposed to a single experiment on a larger scale. Runoff was collected in 1 minute intervals by diverting it into specified collection containers to determine sediment yield (Roa-Espinosa et al., 1999). A representative sample taken from the total collected runoff was oven dried and weighed to determine an average sediment load from each test run. Results from the experiments showed that all soil treatments were effective at reducing sediment yield. The test plots treated with liquid PAM on dry soil reduced sediment yield by 87% and 57%. Plots treated with dry granular PAM on dry soil had an average reduction of sediment yield measuring 34%. The liquid PAM with seed and mulching treatment was determined to perform the best, with an average sediment yield reduction of 93%. Runoff and infiltration were unaffected by the addition of PAM for all replications.

2.2.2.2 Intermediate-Scale Tests

A testing configuration smaller in scale, when compared to field-scale testing, potentially allows for more control in the overall experiment. These controls can include a more manageable setup, and one that is less resource dependent when compared to a field-scale test. In addition, smaller laboratory tests could allow for one particular experiment to be replicated, at a faster rate, ensuring an accurate testing procedure and results.

A study conducted in Iran used seven steel boxes measuring 1.4 m x 1.4 m (Sepaskhah and Bazrafshan-Jahromi, 2006). The metal boxes had a depth of 0.09 m, and can be filled with any type of soil. At the down-slope end of each box, a flume was constructed to funnel runoff to a collection point. The slope of the boxes could be changed to 2.5%, 5.0%, or 7.5%. PAM treatments were applied through the rainfall simulator at applications rates of 1, 2, 4, and 6 kg/ha for the first test and subsequent tests used untreated water. Data collection consisted of measuring the runoff rate per unit area and infiltration rate. Researchers concluded that test plots configured with a steeper slope required higher application rates of PAM to reduce erosion. Experiments indicated that PAM treatments were more effective in reducing erosion, opposed to runoff and infiltration.

Research presented by McLaughlin and Brown (2006) examined the effectiveness of ground cover practices with and without the addition of PAM. Treatments included: (1) PAM on bare soil, (2) straw, (3) wood fiber, (4) straw erosion control blankets (ECB), and (5) mechanically bonded fiber matrix (MBFM). Soil treatments were tested in field and laboratory conditions. The study conducted in the field examined ground cover with and without PAM and its effect in establishing long-term vegetation under natural rainfall. Test plots were constructed on a 4% slope in 1 m x 1 m sections. Laboratory experiments, using a rainfall simulator, included four intermediate-scaled boxes constructed out of wood. Each box measured 1 m wide x 2 m long with an allowable soil depth of 0.09 m. When soil was added, it was leveled by hand and no additional compaction was performed. The rainfall simulator could only be used over two plots, so this allowed researchers to setup the proceeding experiment while the initial one was running. The slope of the boxes could be changed to either 10% or 20%. Small drain holes were drilled along the bottom of the down-slope side to reduce the amount of ponding at the lower end (McLaughlin and Brown, 2006). Runoff was collected with plastic gutters attached to the down-slope end of each plot. These were used to collect runoff volume, turbidity, and suspended solids. Samples were then oven dried to determine the quantity of eroded soil.

Results from the field-scale setup indicated that the performance of the straw, wood fiber, ECB, and MBFM all significantly reduced runoff volume, turbidity, and total sediment loss. However, the addition of PAM provided little or no added benefits, with no effect on establishing vegetation. The intermediate-scaled laboratory test produced similar results, demonstrating that the addition of PAM had no significant result in the performance of the ground cover practices examined. PAM was effective in reducing turbidity for the first and second rain events simulated, but did not consistently improve runoff quality with additional tests (McLaughlin and Brown, 2006).

The last study discussed here that used intermediate-scaled laboratory tests was conducted by Bjorneberg et al (2000). In this research, PAM was tested in conjunction with different methods of applying straw. Six steel test boxes were constructed with dimensions measuring: 1.5 m long, 1.2 m wide and 0.2 m deep. Soil was filtered through a sieve and mixed prior to leveling. This resulted in a slightly compacted surface. At the down-slope side, the depth measured 0.15 m to provide for the installation of a runoff trough to funnel runoff into containers (Bjorneberg et al., 2000). Test plots were hinged to allow for varying slopes from 0 to 15%. Additional drainage tubes were placed to allow any excess water through infiltration to be collected, though later experiments proved this was not necessary. Tests examined the effectiveness of different amounts of straw coverage with and without an application of PAM. PAM was applied at a rate of 2 and 4 kg/ha with an irrigation sprinkler and allowed to dry for 7 to 10 days. After the experiment was conducted, the collected runoff was weighed and examined for any straw. The rest of the runoff was filtered to determine total amount of eroded soil. Researchers observed that PAM treated test plots with straw coverage of 70% reduced runoff by 75% to 80%. PAM treated plots on bare soil only reduced runoff with values ranging from 30% to 50%, which were similar to plots tested with only 30% straw coverage.

2.2.2.3 Procedures and Methods Summary

Many different methods exist for testing the effectiveness of erosion control practices. Along with different procedural steps in the experimental procedure, the physical construction and configuration of experiments varied. Scale is one of these physical components, which are necessary to define during experimental design. Table 2.2 summarizes the different parameters and configurations used in the literature discussed in this section. By choosing to conduct experiments out in the field, conditions experienced will accurately model real-life situations and performance of the treatment will be similar to when it is used for real world applications. However, these setups tend to be large in scale and require additional resources and expenses. Time to construct and install these testing plots is greater and makes it difficult to obtain results which could be easily reproduced. This may affect any future comparison of results with additional experimental or actual treatments used in practice.

Experiments conducted in a laboratory setting offers researchers an extra level of control not found in field-scale testing. Desired soil can be selected depending on research goals and can be easily monitored throughout an experiment. Plot size can vary and usually smaller than what is seen out in the field-scale tests. In addition, the required resources to construct these intermediate-scale setups can be easily acquired and built.

Table 2.2 Summary of Experimental Testing and Procedures

Study	Type	Test Plots	Slope	Length (m)	Width (m)	Depth (m)
Petersen et al. (2007)	Field Test (2)*	4	3% to 9%	2	0.75	UNK
Sepaskhah and Bazrafshan-Jahromi (2006)	Steel Boxes	7	2.5, 5.0, 7.5%	1.4	1.4	0.1
McLaughlin and Brown (2006)	Wood Boxes	2	10% to 20%	2	1	0.1
Hayes et al. (2005)	Field Test (3)*	30	20% to 50%	6	1.5	UNK
Flanagan et al. (2002)a	Field Test	9	32% to 45%	9.14	2.96	UNK
Flanagan et al. (2002)b	Field Test	9	32% to 45%	9.14	2.96	UNK
Peterson et al. (2002)	Field Test	12	17%	9.1	3	0.3
Bjorneberg et al. (2000)	Steel Boxes	6	0% to 15%	1.5	1.2	0.2
Roa-Espinosa et al. (1999)	Field Test	15	10%	1	1	UNK
Flanagan et al. (1997)a	Field Test	6	6% to 9%%	0.6 and 10.7	0.8	0.3
Flanagan et al. (1997)b	Field Test (2)*	6	6% to 9%%	0.6 and 10.7	0.8	0.26

Notes: 'UNK' indicates that the data was not specified in the literature.
'*' indicates number of site locations used

Large-scale field test require grading equipment and experienced operators. Intermediate-scale tests allow researchers to setup and conduct experiments more quickly than when compared to field-scale. This allows for a greater frequency of experiments, which more data can be produced, analyzed, and compared. However, depending on the experimental design, a laboratory setting may not accurately reflect actual conditions found in the field. Care and effort must be used when deciding on setup and procedures used for testing.

Overall, the issue of scale is relevant to the available resources and research goals. Both methods have distinct advantages and disadvantages associated with each. As long as the methods use sound engineering judgment and provide justification, the experiment should result in viable data.

Methods used for an experimental setup are another part of the design process that is heavily dependent on resources and research goals. Generally, experiments pertaining to agricultural purposes used disturbed soil which had little or no compaction. Also, slopes used in such research tended to be mild, not exceeding 10%. These experiments provide valuable insight into similar procedures and methods, which can be adapted and modified to fit needs of research outside the realm of agricultural applications.

2.2.2.4 Summary of Results

While many experiments conducted in previous research vary in procedures, all are interested in the performance of PAM as an erosion control measure. PAM has been documented as a means to reduce runoff through promoting infiltration and reducing sediment yield either by improving flocculation or maintaining soil surface structure.

However, results generated from research provide a widely varying account of the effectiveness of PAM. Table 2.3 and Table 2.4 summarize results presented from the literature reviewed in this section.

The use of PAM as a liquid (i.e. dry PAM/water mixture or emulsified PAM) appears to be the predominant method of application. Most likely this is driven by applications methods contractors use in the field. Typically, the primary goal of any erosion control plan is the long-term establishment of vegetation. Seed mixtures are commonly applied in the field by using a hydro-seeder, so no additional equipment is required to apply a treatment of PAM to a site. However, very little research has been conducted analyzing and comparing the use of dry granular PAM applied directly to the soil surface versus liquid PAM. Only two studies presented examined this comparison (Roa-Espinosa et al., 1999; Peterson et al., 2002). In both cases, PAM was effective in reducing erosion and sedimentation, with liquid PAM performing better than dry PAM. Flanagan et al (2003) concluded that when PAM applied as a liquid spray and allowed to dry will perform better than dry granular PAM at immediately reducing erosion. However, this time to allow for drying may not be feasible, depending on climate conditions. Previous research does not indicate liquid PAM's performance when subjected to rain soon after application.

The severity of slope is another factor that needs to be taken under consideration when examining PAM's effectiveness. Typically, slopes associated with a construction sites are compacted and steeper than slopes found in agricultural settings. Some researchers doubt whether PAM can function effectively on steep slopes, while it was observed in some studies that conditions with steeper slopes required higher application rates of PAM. Table 2.3 illustrates results generated from experiments configured for mild slopes, (i.e. less than 10%). Generally, the application rates used were low when compared to values pertaining to steep slopes (i.e. greater than 10%), as reported in Table 2.4. This can also be observed when comparing studies prepared by McLaughlin and Brown (2006) and Hayes et al. (2005). Both of these studies observed that PAM had no significant effect on soil plots; however, these experiments were conducted with low application rates on steep slopes configurations.

Finally, comparing results from Table 2.3 and Table 2.4, no appreciable difference was observed when comparing an experimental design using simulated versus natural rainfall, or large field-scale versus intermediate-scale setups. The main unifying feature common in all studies presented in this section indicates that experiments were conducted on un-compacted soil, which is atypical to conditions present on construction sites.

Table 2.3 Summary of PAM Treatments Applied to Mild Slopes (i.e. < 10%)

Study	Rainfall	Plot Slope	Application Rate	Application Type	Results
Flanagan et al. (1997a, b)	Simulated	6% to 9%	20 kg/ha	Liquid	Significantly reduced runoff and sediment transport
Bjornberg et al. (2000)	Simulated	2.40%	2 and 4 kg/ha	Liquid	PAM with 70% straw coverage: runoff reduced by 75 to 80% PAM on bare soil: runoff reduced by 30 to 50%
Sepaskhah and Bazrafshan-Jahromi (2006)	Simulated	2.5%, 5.0%, 7.5%	1, 2, 4, and 6 kg/ha	Liquid	Steeper slopes required higher PAM applications. PAM was effective in reducing erosion
Petersen et al. (2007)	Simulated	3% to 9%	5 kg/ha	Liquid	Runoff volume was reduced 100% after 2 days, 59% after 3 weeks, and 55% at 10 weeks. Sediment loss was reduced 100% after 2 days, 80% after 3 weeks, and 74% at 10 weeks.
McLaughlin and Brown (2006)[1]	Natural	4%	19 kg/ha	Liquid[2]	PAM did not provide a significant benefit in most cases
Lentz et al. (2002)	Irrigation	1.50%	1.8 kg/ha	Liquid[3]	Sediment loss reduced by an average of 82%
Peterson et al. (2003)	Channelized	1%	80 kg/ha	Liquid	Sediment reduction ranged from 93 to 98%. PAM was effective in controlling erosion in earth channels, according to cross-section measurements.

Notes: '1' Research examined PAM on field conditions (natural rainfall) and laboratory conditions (simulated rainfall).
'2' PAM treatments: (1) PAM on bare soil, (2) straw with and without PAM, (3) wood fiber with and without PAM, (4) straw erosion control blankets (ECB) with and without PAM, and (5) mechanically bonded fiber matrix (MBFM) with and with PAM.
'3' PAM added to furrow irrigation

Table 2.4 Summary of PAM Treatments Applied to Steep Slopes (i.e. > 10%)

Study	Rainfall	Plot Slope	Application Rate	Application Type	Results
Roa-Espinosa et al. (1999)[1]	Simulated	10%	22.5 kg/ha	Dry and Liquid	All soil treatments significantly reduced sediment yield of test plots. PAM with seed and mulch was most effective.
Flanagan et al. (2002a)[2]	Simulated	32%	80 kg/ha	Liquid	PAM treatment reduced runoff by 40% and sediment yield by 83% PAM & gypsum treatment reduced runoff by 52% and sediment yield by 91%
Peterson et al. (2002)[3]	Simulated	16.6 % (± 3%)	60 kg/ha	Dry and Liquid	Liquid PAM was more effective, reducing runoff by 62 to 76% and sediment yield by 93 to 98%. Dry PAM provided almost no benefit.
McLaughlin and Brown (2006)[4]	Simulated	10% and 20%	19 kg/ha	Liquid[5]	PAM did not provide a significant benefit in most cases
Flanagan et al. (2002b)[2]	Natural	35% and 45%	80 kg/ha	Liquid	PAM reduced runoff by 33% (15%)[6] and sediment yield by 54% (40%)[6] PAM & gypsum reduced runoff by 33% (28%)[6] and sediment yield by 45% (53%)[6]
Hayes et al. (2005)	Natural	20% and 50%	10.5 kg/ha* and 1.5 kg/ha*	Liquid[7]	PAM had no significant result on runoff volume, turbidity, and sediment loss

Notes: ‘1’ Treatments: (1) liquid PAM applied to dry soil, (2) dry granular PAM applied to dry soil, (3) liquid PAM with seed& mulch, and (4) liquid PAM applied to wet soil.
‘2’ PAM treatments: Liquid PAM with and without the addition of gypsum.
‘3’ PAM treatments: (1) liquid PAM and Nutra-Ash, (2) dry granular PAM and Nutra-Ash, and (3) liquid PAM with SoilerLime.
‘4’ PAM treatments: (1) PAM on bare soil, (2) straw with and without PAM, (3) wood fiber with and without PAM, (4) straw erosion control blankets (ECB) with and without PAM, and (5) mechanically bonded fiber matrix (MBFM) with and with PAM.
‘5’ PAM added to furrow irrigation
‘6’ Values in ( ) indicate results from second field location.
‘7’ Two types of PAM used: Soilfix and Siltstop 705. PAM treatments: seed/mulch with and without PAM.
‘*’ PAM was also tested at half this rate

2.3 ANALYSES

This section examines the different ways researchers examined and analyzed data collected from erosion control experiments. This will focus on how researchers used different statistical tests to evaluate the collected data and how conclusions were developed from reported analyses.

2.3.1 Statistical Testing

Statistical testing provides researchers with powerful tools to examine collected data and quantify a particular treatment or experiment to determine its overall effectiveness. Determining if experimental results were statistically significant provides a common and widely accepted method of comparing data. Many different types of statistical test are available and used throughout the research presented. Therefore, care must be taken when choosing which type of analysis should be used to ensure that results are accurately analyzed and reported. This section will examine different methods and techniques used when analyzing data collected from erosion control experiments.

In the study by Sepaskhah and Bazrafshan-Jahromi (2006), to determine if the runoff depth and amount of eroded soil was statistically significant, a Duncan multiple range test with a 5% level of probability was used. This test method uses, "multiple comparisons in which the group means are ranked from smallest to largest, and then the number of steps that two means are apart in this ranking is used to compute a range statistic for each comparison," (Colman, 2001). In addition to using this statistical test, a multiple regression analysis was conducted on soil erosion and slope to determine if there was a relationship between the two results. Similarly, another regression analysis was conducted on the relationship between soil loss and runoff depth (Sepaskhah and Bazrafshan-Jahromi, 2006).

Research conducted by McLaughlin and Brown (2006) reported on whether or not the PAM treatment had a significant effect on the tested parameters. The specific test used to determine significance was not specified. The level of significance was reported to be 5% and sometimes 10% if required. Data tested included runoff amount, eroded soil, turbidity, and grass cover (i.e. as observed in field-scale experiments).

Hayes et al., (2005) used an analysis of variance (ANOVA) to determine if the results were significant. ANOVA is used to compare multiple treatments by assessing equality of several recorded means (Ramsey and Schafer, 2002). This type of statistical test provides researchers a powerful tool to compare multiple treatments, and further analyses can be used to examine individual comparison within multiple treatments. In this research conducted by Hayes et al., (2005) treatment pairs were compared using a Tukey-Kramer test to determine a statistically significant difference between runoff volume, turbidity, and sediment loss.

Experiments performed by Leib et al., (2005) also used ANOVA to test significance between the different treatments by examining the mean separation by using least square difference (LSD). The collected data was transformed before analysis. Level of significance used for testing was 5%. After the ANOVA analysis, results were transformed back to the original units.

In the two part research by Flanagan et al., (2002a; 2002b) statistical analysis was performed on runoff volume and sediment yield using ANOVA procedures. Additional analyses were performed on individual runs, examining cumulative runoff volume, runoff rate, sediment concentration, sediment discharge rate, and total sediment loss. This was performed by examining the mean separation using LSD method. Level of significance selected for testing collected data was 5%. Previous research by Flanagan et al., (1997a, 1997b) also used ANOVA procedures for both parts of the effort. The first part used LSD and a level of significance of 10% on runoff and infiltration rates. The second part of the study used LSD if treatments were found to be significant at the 10% level.

2.3.2 Analyses Summary

Statistical analysis can be a valuable tool to researchers when working with data collected from experiments. By using proven methods to analyze data, the accuracy of experimental results can be validated and compared. In addition to using a widely accepted practice of analyzing data, the results from statistical tests can be easily conveyed when presenting conclusions and determining the effectiveness of different treatments. By quantifying the results through these techniques, researchers can determine which treatments perform the best. However, many differences and preferences exist when it comes to statistical testing.

Some of the literature reviewed for this research reported statistically significant results, without describing which tests or procedures were used in the analysis (McLauglin and Brown, 2006; Bjorneberg et al., 2000). While results of their prospective experiments were presented, other researchers performing similar experiments do not have the ability to compare results, make it difficult to evaluate the procedures used in their experiments, while also making comparisons to research results. Other literature reviewed made no effort to use or report on statistical methods to analyze data (Petersen et al., 2007; Peterson et al., 2003; Lentz et al., 2002; Peterson et al., 2002; Roa-Espinsoa 1999).

2.4 LITERATURE REVIEW SUMMARY

Experimental procedures can differ on a wide array of issues. The two main factors attributed to experimental procedures include available resources and research goals. These effectively control the way an experiment is conducted. Available resources can refer to construction, materials, and necessary labor associated with a project. Smaller research efforts may not have the necessary funds and means to construct a large testing facility. Additionally, goals that the intended research may be interested in examining may require such a setup. So these items can determine how testing will proceed.

In this chapter, researchers examined some of the advantages and disadvantages associated with different types of experimental setups used and the performance of PAM as an erosion control measure. This included the differences in how runoff can be generated and applied to an experiment. Generally this is accomplished through exposing an experiment to natural rainfall or by constructing a rainfall simulator. It was observed that both methods are widely used. It was accepted that a rainfall simulator can effectively provide simulated rainfall, given that the design accurately models natural rainfall conditions.

The other key part of an experiment design and the procedures depends on how an experiment was prepared. This can include the scale and location of an experiment. Intermediate-scale experiments, which can be conducted in laboratory settings, can allow for more controllable conditions. Large-scale experiments conducted in the field provide conditions that accurately mimic those found in practice. The physical construction of test setups also varied and depended on different experimental parameters.

Researchers' opinions on the use and effectiveness of PAM were observed to be widely different. Overall, it is accepted that liquid PAM can be an effective means to control erosion. Many studies indicate that the amount of eroded soil was significantly less when compared to treatments without an application of PAM. The use of liquid PAM appears to be widely accepted as the preferred method of application, while research examining the effect of dry PAM reported that it did not perform as well as when applied in a liquid form. The physical layout of a soil surface also appears to affect how PAM will perform. When steeper slopes were examined, a higher application rate of PAM was required to achieve satisfactory results.

The final part of this chapter examined different analyses used in erosion control experiments. By using statistical tests, results generated can be effectively compared using a unified and widely accepted method of analysis. However, which statistical test depends mainly on the experimental design. Overall, many researchers did not include any form of statistical analysis, and some of the literature reviewed did not specify details involved in the reported statistics. It was also observed that ANOVA procedures to compare multiple treatments were found to be most effective in analyzing experimental data.

Based on the research examined in the literature review, the difference in performance between the various PAM applications methods (i.e. dry or liquid form) have not been thoroughly documented and additional research should be conducted to determine if one application method is superior to the other with varying conditions.

Additionally, existing research efforts investigating the addition of PAM as an erosion and sediment control measure were primarily focused on agricultural purposes. As reported, construction sites are one of the main contributors to NPS pollution, so research focusing on condition representative of that found on construction sites needs to be expanded upon to include testing procedures focusing on steep, compacted slopes. Therefore, the research presented in this report will focus on these areas to contribute additional results on the use and performance of PAM, and its effect in reducing erosion and sedimentation from surface stormwater runoff, similar to that generated on construction sites. This would be accomplished using intermediate-scale tests with a rainfall simulator. This experimental setup was shown to have attractive features that help contribute to quality data generation, which will enable researchers to analyze and determine the effectiveness of PAM.

CHAPTER THREE

INTERMEDIATE-SCALE METHODS AND PROCEDURES

3.1 INTRODUCTION

Upon reviewing previous research, it became apparent that many different techniques, setups, designs, and procedures are available and used for erosion and sediment control experimentation. The research presented in this report is a continuation of research previously conducted; therefore similar ideas and practices were used and modified to appropriately reflect new concepts, designs, and conditions. Therefore, research conducted by Halverson (2006) and McDonald (2007) at Auburn University was used as a general guideline for this research effort. However, potential limitations found in the original designs were identified and addressed for future experimentation. These included areas pertaining to: (1) designing and constructing new intermediate-scale test boxes, (2) designing, constructing, and testing a new rainfall simulator, (3) test preparation procedures, (4) and data collection methods.

3.2 INTERMEDIATE-SCALE TESTING

At the onset of this research it was decided to conduct experiments using an intermediate-scale testing apparatus. This was done to examine the effects of PAM in a more controlled environment, while using methods that were less-resource dependent.

By using intermediate-scale test plots, experiments could be set-up and conducted with relative ease, speed, and accuracy. A goal was established during the experimental design process to develop a means to conduct any erosion and sediment experiment quickly to allow for replications, ultimately resulting in more data for analysis.

The first step that was taken in creating a new experimental design involved development of a dedicated space for this research. In this section, the design and specifications of the newly constructed test facility for intermediate-scale testing will be discussed.

3.2.1 Intermediate-Scale Test Facility

A dedicated space was constructed for this research's intermediate-scale experiments. This space was custom built and contained features specifically tailored for this research. Land was made available by the NCAT test facility located near Opelika, Alabama. The proposed building measured 20 x 30 ft (6.1 x 9.1 m) with two drum roll up doors at opposite ends of the structure, and a concrete slab poured for the building's foundation, as pictured in Figure 3.1(a). Water was supplied by a nearby underground well and fed into the building using two faucets located at the northeast and southeast corners. Electricity was installed and provided indoor lighting and electrical outlets. Jersey barriers were arranged outside the building as a means for storing test soil as pictured in Figure 3.1(b). When soil was stored in these bins, a tarp was used to cover and protect soil stock piles against rainfall and excess moisture.

The facility provided ample space for conducting experiments and could easily be expanded upon. The intermediate-scale test building includes room to store equipment, testing apparatus, and material required throughout the study. Additionally, due to the close proximity to the test track facility, WI-FI internet access is available as well. Figure 3.2(a) and 3.2(b) illustrate the interior of the building and the laboratory setup, including equipment.

(a) Testing Facility Structure **(b) Storage Bins for Soil**

Figure 3.1 Test Facility Exterior.

(a) Facing East Side of Building

(b) Facing West Side of Building

Figure 3.2 Test Facility Interior.

3.3 EXPERIMENTAL DESIGN

After the new building was constructed, researchers were able to focus on elements of a new experimental design. The new design for experiments was derived from research originally conducted by Halverson (2006), where his work focused on testing different configurations of silt fences on an intermediate-scale representation of a highway embankment. As stated earlier, this design was further modified by McDonald (2007) to determine dry granular PAM's effectiveness as an erosion control measure on three intermediate-scale test plots.

However, designs used for both research efforts resulted in experimental setups that were time consuming and labor intensive, due to the size of the testing apparatus. In addition, researchers were not satisfied with the rainfall simulator's overall performance. Therefore, it was decided to address these issues and develop a new experimental design for use at the new testing facility.

3.3.1 Intermediate-Scale Test Plots

The first part of a new experimental methodology was to redesign the test plots. It was decided that the added benefits of intermediate-scale testing allowed for more flexibility and control in conducting experiments. Also, with intermediate-scale test plots, effort required to prepare an experiment would be reduced dramatically. To ensure that a new design would meet these requirements, the smallest acceptable plot size was determined to have an approximate width of 24 inch (61 cm) with and a length of 48 inch (122 cm). These dimensions were approximately half that used previously by McDonald (2007). The previous design allowed for a 6 inch (15 cm) depth for soil. The bottom 3 inches (7.6 cm) was filled with an Expanded Polystyrene (EPS) material. This allowed researchers to reduce the overall load on the supporting structure, in addition to assisting in facilitating infiltration, due to the very high hydraulic conductivity of the EPS material. On top of the EPS layer, a geotextile was installed, and then an additional 3 inches (7.6 cm) of the desired test soil. This whole process was time consuming to set-up and reset for additional experiments. During experimentation, no appreciable infiltration data was collected. Therefore, it was determined that the addition of an EPS material and geotextiles could be removed in favor of a smaller overall depth. The new selected depth allowed for approximately 3 inches (7.6 cm) of compacted soil.

The design and construction of the boxes used were similar to test plots recommended by McLaughlin and Brown (2006), but with smaller dimensions. The specifications and design drawings for the new test plot are illustrated in Figure 3.3.

Two test plots were built for simultaneous experimentation. Plots were constructed from pressurized timber, consisting of a 1/2 inch (1.27 cm) plywood base and two-by-fours to form the perimeter. At the down-slope end, a metal strip with 3/8 inch holes drilled was installed to prevent ponding, as recommended by McLaughlin and Brown (2006). A PVC pipe was cut in half and installed below the metal strip to potentially collect any infiltration. However, it was observed during preliminary testing that any resulting infiltration was insignificant and no additional care was taken to collect this data. Also, at the down-slope end, commercial plastic gutters were fabricated and installed to act as a runoff collection device. Figure 3.4 shows the gutters attached to one of the test boxes. Gutters were installed and angled to promote runoff discharge. A gutter rainfall guard was also attached to prevent any rainfall from interfering with surface runoff volumes, as displayed in Figure 3.5(a).

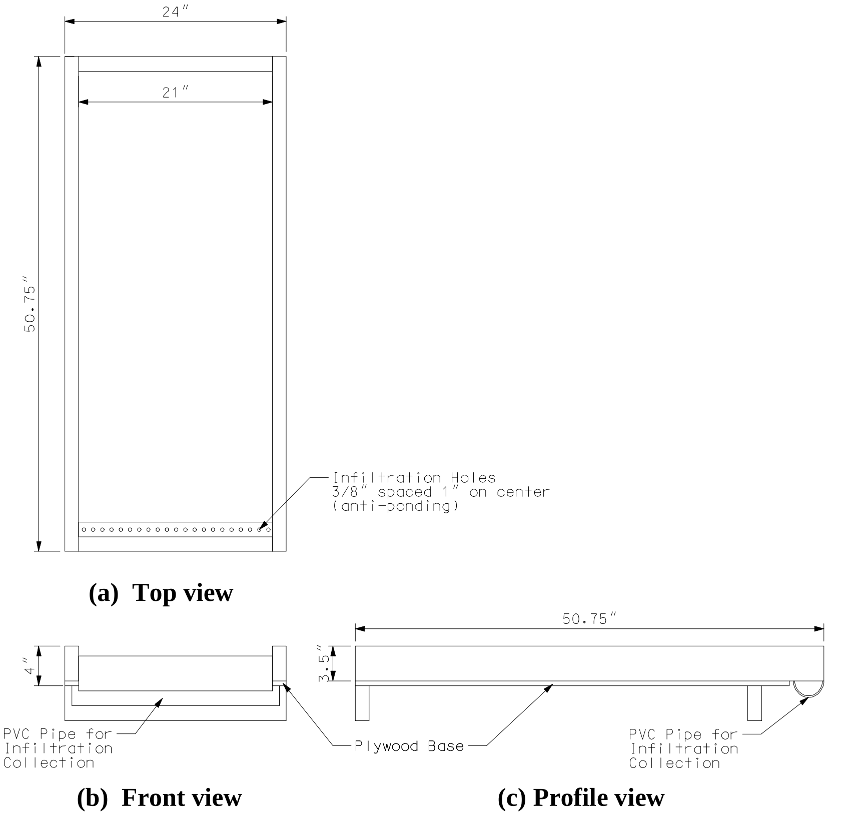


Figure 3.3 Design and Specifications of a Test Box.

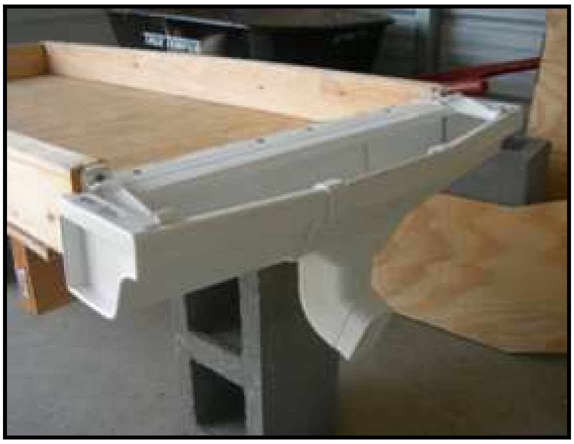


Figure 3.4 Runoff Collection Device.

By using the intermediate-scale test boxes, a greater amount of flexibility was made available, due to the reduction in weight and ease of setup. Two commercial sawhorses were purchased to support the test boxes. These sawhorses are adjustable, allowing a wide range of available slopes for testing. Cinderblocks were used to support the down-slope end and raise the elevation of test boxes to allow for collection buckets to be placed under the gutter discharge point. This testing setup allowed for a test slope of 3:1 to be established. Photos of the completed test plots are displayed in Figure 3.5(a) and 3.5(b).

(a) Constructed Test Boxes with Rain Guards (b) Adjustable Slopes with Saw Horses

Figure 3.5 Constructed Test Boxes used for Experimentation.

This size of these test plots allowed for a more manageable setup, where a single person could lift and adjust an empty box, and only required two people to lift a fully loaded box, ready for experimentation. These boxes helped reduced the time needed for set-up and clean-up, when compared to previous experiments. This allowed more experiments to be conducted, increasing the amount of data available for analysis.

3.3.2 Rainfall Simulator

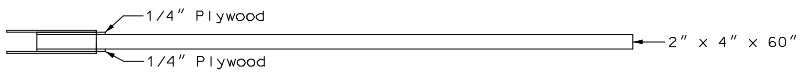
The rainfall simulator used by Halverson (2006) and McDonald (2007) produced a large spray area to ensure coverage over the entire experiment. This was achieved by using ¾ in. (1.9 cm) schedule 40 PVC pipes and consisted of six 1/8HH-3.6SQ FullJet™ spray nozzles and an F-405 Series In-Line Flow meter. However, by using this design, the six nozzles created areas in which rainfall overlapped, resulting in areas receiving concentrated amounts of rainfall. Also, researchers observed that once flow was shut off after the conclusion of a test, water remaining in the system would continue to fall on test plots. To address these issues, a new rainfall simulator was designed for use in the intermediate-scale test building.

The issue of overlapping sprays was an area of great concern for producing uniform rainfall distribution. By allowing certain areas to receive greater amounts of rainfall, the authenticity of the collected results could be affected. Therefore, one of the goals for a new rainfall simulator design was to eliminate the possibility of overlapping spray areas. To achieve this goal, one nozzle would be used in the design, eliminating any possibility of overlap. A one nozzle rainfall simulator would allow for a more uniform spray area and no significant areas of concentrated rainfall would fall on the test plots.

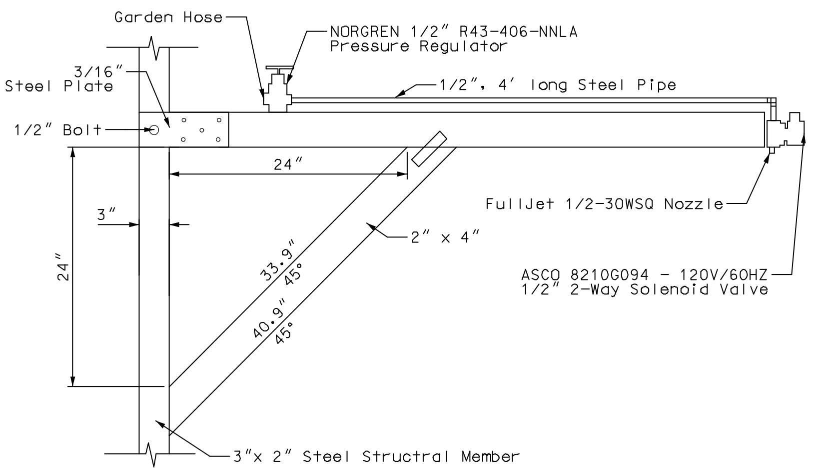
Another area in the previous rainfall simulator design was related to water flow. Researchers observed that rate of water flow varied and would not remain constant throughout the duration of an experiment. Steps were taken to help control water flow by including a pressure regulator into a new design. By having a pressure regulator, the inflow of water could be kept at a constant pressure, allowing researchers to have greater control over rainfall. This includes the ability to change the rain regime and test different storm events.

The third and final change made in the design was to address the issue of water remaining in the system once the simulator was shut off. As stated earlier, water would continue to fall from nozzles onto test plots after the simulator was turned off. This additional water was undesirable and was identified as an area which could be improved upon. To solve this problem, a solenoid valve was introduced into the design. This valve, when shut off, instantaneously closes; ensuring that the flow of water will cease at the conclusion of an experiment.

With these key issues from the original design identified, a new rainfall simulator was designed using similar features recommended by McLaughlin and Brown (2006). Drawings for the new design are shown in Figure 3.6.



(a) Plan View



(b) Profile View

Figure 3.6 Rainfall Simulator Design.

The construction of the rainfall simulator, as indicated in Figure 3.6, consists of two-by-fours, a ½ inch (1.27 cm) diameter steel pipe, support braces, a garden hose, and electrical wiring for the solenoid valve. The rainfall simulator was attached to steel support members in the building's structure using a ½ inch (1.27 cm) bolt. The overall rainfall simulator extended 5 ft (1.5 m) from the building wall. The maximum allowable height (as restricted by the building's ceiling) was 10 ft (3 meters) from floor level. Multiple holes were drilled into the support member to allow for an adjustable height, with a lowest allowable height of 6 feet (1.8 meters) from floor level. A hose was attached to the pressure regulator down to a faucet in the northeast corner. The pressure regulator installed was a Norgren™ R43-406-NNLA with ½ inch (1.27 cm) port sizes. Attached to the pressure regulator was a gauge to observe the operating water pressure. This allowed for any necessary adjustment to be made during operation to ensure a constant flow was achieved. Four feet (1.2 m) of ½ inch (1.27 cm) steel piping connected to the pressure regulator ran along the length of the simulator into the solenoid valve. An ASCO™ 2-way 8210 series solenoid valve was installed to control water shutoff. This valve, when de-energized, remained closed. Care was taken to ensure the electrical wiring for the solenoid was water tight, which lead to a nearby wall switch. Connected directly into the solenoid valve was a FullJet™ ½HH - 30WSQ nozzle, with a wide angle uniform square spray area, and medium to large drop size distribution, similar to natural rainfall. Detailed specifications for the pressure regulator, solenoid valve, nozzle, and raindrop sizes can be seen in Appendix A. Figure 3.7 illustrates the constructed rainfall simulator as installed in the testing facility.

Figure 3.7 Illustration of Constructed Rainfall Simulator.

With the new rainfall simulator complete, additional tests were conducted to determine the overall performance of this new design. These test examined the nozzle manufacturer's claim of uniformity and determining a rain regime best suited for this research.

To determine and analyze rainfall uniformity, an 8 ft x 8 ft (2.4 m x 2.4 m) grid was placed beneath the simulator. This area was approximately the total spray area generated by the rainfall simulator. At 1 ft (0.3 m) intervals, using intersecting gridlines, marks were placed on the slab and 1 quart (946 ml) containers were placed at these locations to collect rainfall, as pictured in Figure 3.8(a). The uniformity of rainfall distribution was collected during three trial runs at three different operating pressures of 5, 10, and 20 psi for a total duration of 10 minutes. The average recorded volumes (in ml) for the three trials performed at 10 psi can be seen in Figure 3.8(b).

(a) Collection Cups on 8' x 8' Grid **(b) Average Volume in Collection Cups at 10 psi**

Figure 3.8 Rainfall Distribution (in ml) Verifying Uniformity.

The chart in Figure 3.8(b) is color-coded to coincide with volume of rainfall, with red indicating higher volumes and blue indicating lower volumes. The squares in gray color were grid marks with no cups placed on them, due to the limited number of cups available for use. The internal square, denoted by the four corners, C3, G3, C7, and G7, was representative of the location of two test plots with an area of 16 ft^2 (1.5 m^2) as if they were placed under the rainfall simulator during an experiment.

To check uniformity, the Christian Uniformity Coefficient, shown as Equation 1, was used (ASAE Standards, 2000). This equation determines a value that quantifies rainfall distribution uniformity as a percentage. The calculated values using Equation 1 for the rainfall simulator in this study are shown in Table 3.1. Generally, a calculated uniformity coefficient ranging from 80% to 100% is considered an acceptable amount for quantifying a rainfall spray area as uniform.

$$CU_c = 100 \times \left[1 - \frac{\sum_{i=1}^{n} v_i - \bar{v}}{\sum_{j=1}^{n} v_i} \right] \tag{1}$$

where,

CU_c = Christian Uniformity Coefficient,
n = number of collectors,
v_i = volume of water in the ith collector, and
$\bar{v}$ = mean volume of water in all collectors.

Table 3.1 Christian Uniformity Coefficients for Rainfall Simulator

Trial	**Entire 8' x 8' Spray Area**	**Test Plot Area**
	5 psi	
1	63%	87%
2	67%	88%
3	67%	88%
Average	***66%***	***88%***
	10 psi	
1	76%	84%
2	76%	88%
3	76%	85%
Average	***76%***	***86%***
	20 psi	
1	73%	83%
2	74%	85%
3	73%	84%
Average	***73%***	***84%***

Note: 'Test Plot Area' is the 16 ft^2 area located directly under rainfall simulator nozzle.

Table 3.1 displays the calculated Christian Uniformity Coefficient for each of the trial runs, including averages. Uniformity of rainfall was examined over the entire spray area, in addition to previously mentioned interior area that was representative of the test plots location. Overall, uniformity for the entire spray area was generally unacceptable at each of the different operating pressures, with values ranging from 63% to 76%. The pattern of spray distribution can be observed in Figure 3.8(b), as recorded volumes on the spray-area-border were less when compared to amounts collected towards the center. However, uniformity of rainfall where testing plots would be placed was much higher, as also seen in Figure 3.8 (b) and Table 3.1. The Christian Uniformity Coefficient for this area was calculated and ranged from 83% to 88%, which was deemed as an acceptable amount of uniform distribution for simulating rainfall during experimentation. Therefore, rain falling specifically on the test plots was determined to be uniform and suitable for experimentation.

The next step in analyzing the rainfall simulator was to determine the rate of water outflow. In the manufacturer specifications for the FullJet™ nozzle, capacity of outflow, in gallons per minute, was given as a function of internal water pressure. These rates were verified by researchers and determined to be consistent with what was provided by the nozzle manufacturer. Flow rate was translated as rainfall intensity to determine potential rain regimes. Capacities in gallons per minute were converted into rainfall intensity by using unit conversions and a spray area, with dimensions of 8 ft x 8 ft (2.4 m x 2.4 m), to obtain rainfall intensities in inches per hour. These different calculated rainfall intensities were plotted as a function of different operating pressures and can be seen in Figure 3.9 below.

It was observed that the rate of water exiting the nozzle had a linear relationship to water pressure. A regression line was determined and plotted as seen in Figure 3.9. The regression line equation was used to determine any future rainfall intensities. Researchers recommended that pressures during experimentation not exceed 30 psi, due to the limited range of the pressure gauge attached to the pressure regulator, which had a maximum observable pressure of 30 psi. With this graph, resulting rainfall intensities and operating pressures required could be used to select a rain regime for experimentation.

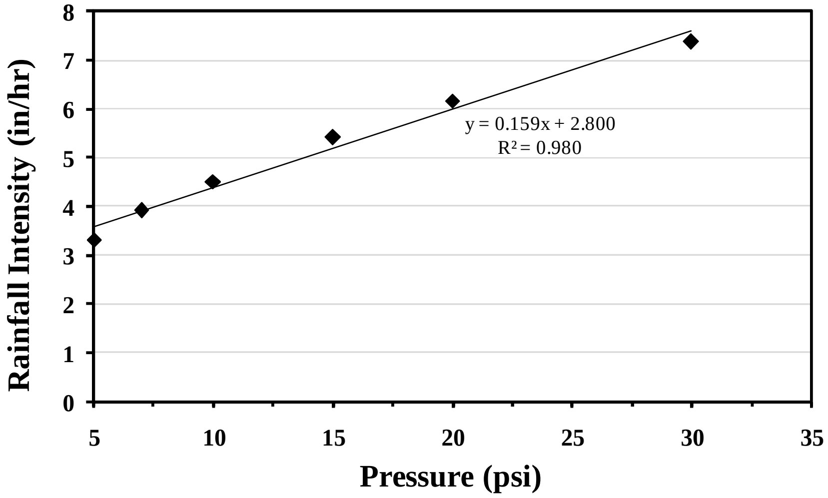


Figure 3.9 Rainfall Intensity (in/hr) as a Function of Rainfall Simulator's Operating Pressure (psi).

3.3.3 Rain Regime

During the literature review, it was observed that rainfall regimes varied. Therefore, for this research, a rainfall regime was selected based off the stormwater inspection guidelines provided by the Alabama Department of Transportation (ALDOT). These guidelines state that an inspection of any erosion BMP will occur within 72 hours of a 'qualifying event', where ALDOT identifies a 'qualifying event' as 0.75 inches (1.9 cm) of rain accumulation within a 24 hour period (ALDOT, 2004). This 0.75 inches was used as a baseline for the selected rainfall regime simulated during experimentation. Therefore, these inspection requirements provide an amount of rainfall that should be achieved during an experiment to provide data which is representative of a qualifying event experienced in the field. Table 3.2(a) shows the potential rainfall intensities generated from the rainfall simulator with respective water pressure, and calculates total accumulated rainfall based on corresponding rainfall durations.

Since 0.75 inches was selected as the minimum amount of rainfall required, researchers selected an operating pressure of 10 psi, which generates an intensity of 4.39 in/hr. A total duration of 15 minutes would produce an amount of rainfall approximately 1.10 inches, which is above the established baseline of 0.75 inch and deemed acceptable for experimentation. Details for this rain regime are illustrated in bold in Table 3.2(a).

In addition to using ALDOT's inspection guidelines, researchers examined rainfall intensity-duration-frequency (IDF) curves from Technical Paper #25, for Montgomery, Alabama (USDC, 1955). IDF curves used for this research are included in Appendix B. These curves relate a rainfall intensity, in inches per hour, with a given rain duration, to determine a return period (i.e. storm event), in years. Table 3.2(b) shows the relationship between these different storm events from the IDF curves and corresponding intensities generated by the rainfall simulator with respective durations. The rain regime for an individual 15 minute test would be representative of a 2-year, 15-min storm event, as illustrated in bold in Table 3.2(b). In ASWCC's handbook on erosion and sediment control BMPs, many of the different technologies are designed to withstand specific storm events. While the guidebook does not provide a specific design storm for chemical stabilization (i.e. PAM), a 2-year, 24 hour storm is commonly used in many of the BMPs outlined (ASWCC, 2003). This storm event is a relatively common occurrence and is used in the design and selection of many different technologies currently used for erosion and sediment control. Therefore, research conducted with these rainfall parameters would be similar to those an erosion control product or BMP would be exposed to in actual practice.

Using the Rainfall Frequency Charts presented in Technical Paper #40, included in Appendix B, it was observed that a 2 year, 24 hour rain event for mid-Alabama would produce a cumulative rainfall amount ranging from 4 to 4.5 inches of rainfall (USDC, 1961). The selected intensity of 4.4 in/hr would need to last for one hour to adequately model this specific storm event. Therefore, the final rain regime used for experimentation would consist of four, 15 minute events, representative of a 2-yr, 15-min event. These four events would be required to achieve the desired 2-yr, 24-hr storm event and will permit researchers to examine the long-term effectiveness of PAM treatments. A period of no rainfall would be observed to allow researches time to collect data in between events. This period of would last for a duration of 15 minutes.

Table 3.2 Rain Regime Table for Different Intensities and Storm Durations

(a) Total Accumulated Rainfall Based Off Intensity and Duration

Pressure (psi)	Intensity (in/hr)	Total Accumulated Rainfall (in)						
		5 min	10 min	15 min	20 min	30 min	40 min	60 min
5	3.60	0.30	0.60	0.90	1.20	1.80	2.40	3.60
10	***4.39***	0.37	0.73	***1.10***	1.46	2.20	2.93	4.39
15	5.19	0.43	0.86	1.30	1.73	2.59	3.46	5.19
20	5.98	0.50	1.00	1.50	1.99	2.99	3.99	5.98
25	6.78	0.56	1.13	1.69	2.26	3.39	4.52	6.78
30	7.57	0.63	1.26	1.89	2.52	3.79	5.05	7.57

(b) Representative 24-Hour Storm Events Based Off IDF Curves for Montgomery, AL

Pressure (psi)	Intensity (in/hr)	Storm Events						
		5 min	10 min	15 min	20 min	30 min	40 min	60 min
5	3.60	--	--	2-yr	2-yr	5-yr	10-yr	25-yr
10	***4.39***	--	2-yr	***2-yr***	5-yr	10-yr	50-yr	100-yr
15	5.19	2-yr	2-yr	5-yr	10-yr	50-yr	100-yr	100-yr
20	5.98	2-yr	5-yr	10-yr	25-yr	100-yr	100-yr	100-yr
25	6.78	5-yr	25-yr	50-yr	100-yr	100-yr	100-yr	100-yr
30	7.57	25-yr	100-yr	100-yr	100-yr	100-yr	100-yr	100-yr

3.4 EXPERIMENTAL PROCEDURES

Experimental procedures and methods used in previous experiments were examined and modified where improvements could be implemented. Modifications from previous research procedures included: (1) detailed analyses of test soil, (2) preparation methods for conducting compaction on test plots, (3) general procedural changes pertaining to new test boxes and experiment preparation, and (4) data collection methods.

3.4.1 Soil Analysis

Soil used for this research was provided by a local grading contractor from a construction site near the NCAT test track in Opelika, Alabama (32°33'5" N, 85°20'28" W). A sample of this material was sent to the Auburn University Soil Testing Laboratory to determine soil composition. Table 3.3 shows the percent composition and United States Department of Agricultural (USDA) textural classification of the soil sample used for this research.

Table 3.3 Percent Composition and Classification of Experimental Soil

% Sand	% Silt	% Clay	Classification
58.6	12.5	28.9	Sandy Clay Loam

The test soil was found to be composed primarily of sand, with smaller amounts of clay and silt. In addition to identifying soil composition, particle distribution was determined using a sieve analysis. Figure 3.10 illustrates distribution of particles and researchers determined that the test soil was well-graded.

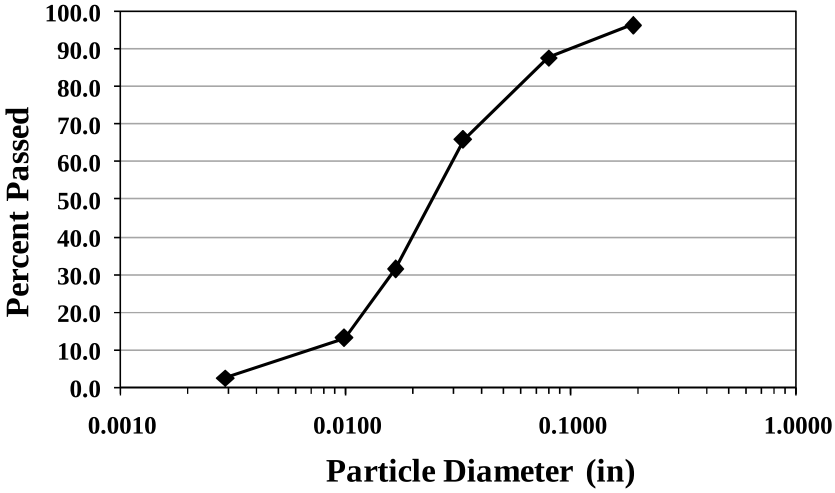


Figure 3.10 Particle Size Distribution for Experimental Soil.

3.4.2 Compaction Analysis

Following tests to classify and identify soil characteristics, additional information pertaining to compaction was analyzed. For this research, test plots were designed to model similar characteristics of a typical highway embankment. The main characteristics of interest were 3:1 compacted fill slopes and how this configuration affects the performance of PAM. Previous research conducted by Halverson (2006) and McDonald (2007) used a metal roller to compact test soils to a compaction rate of 90% of the maximum density. However, to reach a higher level of compaction required by ALDOT for fill slopes, a new method of compaction was considered. ALDOT specifies in its *Standard Specification for Highway Construction* (2002) that in-place density requirements for highway embankments must be compacted to 95%. The different method examined here used hand-tamps dropped on the test plots to achieve the required compaction rate.

To determine the number of drops required to compact the soil using hand-tamps, multiple compaction tests were conducted. A modified Proctor test, as specified in American Society for Testing and Materials (ASTM) D1557, was used to generate a Proctor curve relating moisture content (MC) with dry unit weight, as seen below in Figure 3.11.

The chart in Figure 3.11 shows specific moisture contents required to obtain different dry unit weights for the tested material. The optimum moisture content (OMC) was determined by locating the maximum dry unit weight on the Proctor curve, which is 114 pcf (1826.1 kg/m^3), and would be achieved with a MC of 15%. The dashed-line at 108 pcf (1730 kg/m^3) denotes the minimum acceptable dry unit weight to achieve 95% compaction. Since compaction would be accomplished with hand-tamps, procedures stated in ASTM D1557 specifications were modified for a new mold custom built for the hand-tamps, as pictured in Figure 3.12(a) and 3.12 (b).

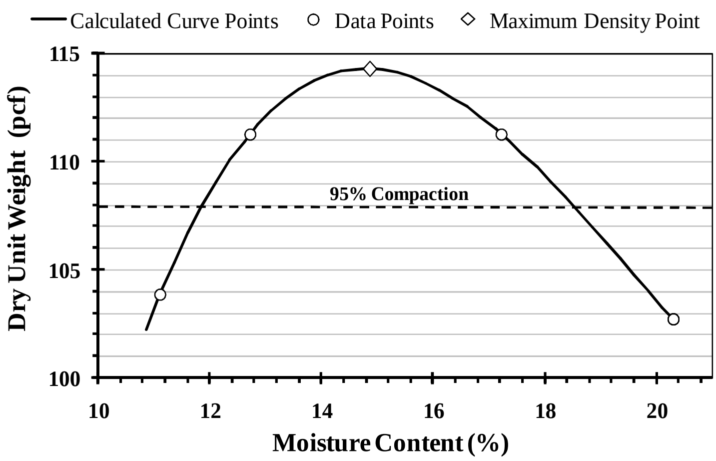


Figure 3.11 Proctor Curve for Experimental Soil.

(a) Hand-tamp with Mold (b) Hand-tamp Compacting Soil in Mold

Figure 3.12 Determining Required Compaction Rate with Hand-tamp.

The footprint of the hand-tamps used measured 10 in. x 10 in. (25.4 cm x 25.4 cm), so the mold was constructed to contain soil for that area (approximately 12 in. x 12 in.). The sides of the mold were constructed so the top inch of excess soil from compaction could be leveled off. This would provide a 1 inch (2.5 cm) depth of compacted soil with a known volume. This known volume of compacted soil was used to determine a corresponding unit weight pertaining to an amount of compaction generated with the hand-tamps.

Soil was compacted with five different setups using a hand-tamp, dropped at approximately 12 inches above the soil surface, at the required OMC of 15%. These different setups corresponded to a hand-tamp dropped 10, 20, 30, 50, and 60 times. After the corresponding number of drops, a dry unit weight was calculated and plotted as a function of hand-tamp drops, as seen in Figure 3.13.

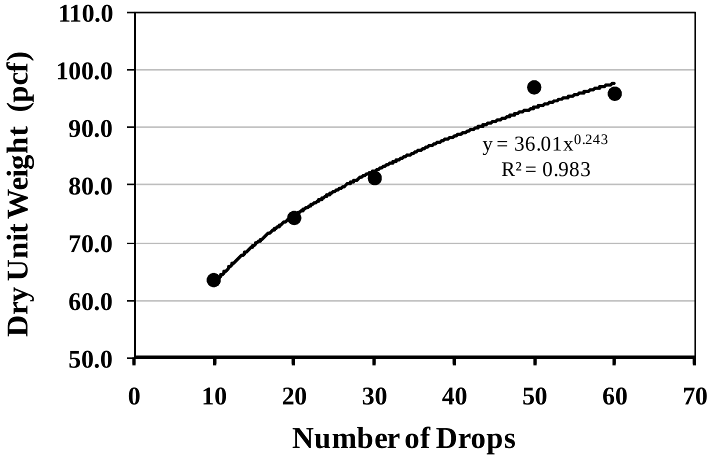


Figure 3.13 Compaction of Soil using Hand-tamp.

A regression line was plotted as illustrated in Figure 3.13. A power function was selected to reflect the nature of compacting soil. Soil will reach a point where it can no longer be compacted, no matter how much energy is applied. Therefore, the regression line would level off at this point. Using this equation, the number of drops required to obtain different unit weights was calculated and shown in Table 3.4. To obtain a 95% compaction rate, at least 90 drops of a hand-tamp would be necessary to reach a unit weight around 108 pcf (1730 kg/m^3).

Table 3.4 Calculated Dry Unit Weight (pcf) and Required Number of Drops

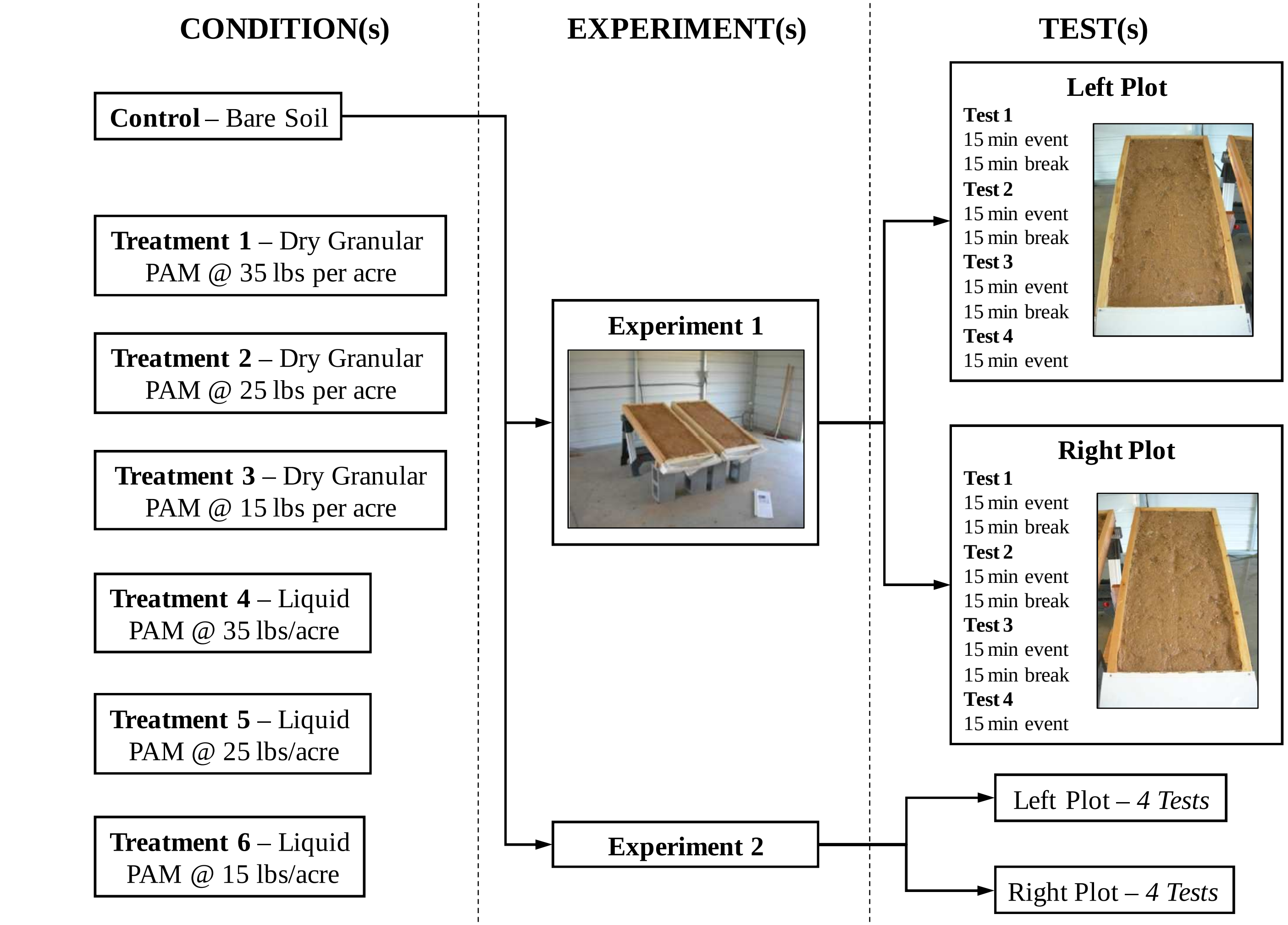
Number of Drops	Dry Unit Weight (pcf)
10	63.1
20	74.7
30	82.5
40	88.5
50	93.4
60	97.7
70	101.4
80	104.8
90	***107.8***
100	110.6

3.4.3 Polymer Selection

To determine which formulation of PAM was to be used, additional tests were conducted on soil samples prior to experimentation. These tests determine the optimum mixture of PAM and recommended application rate. Therefore, a sample of the sandy clay soil was sent to Applied Polymer Systems (APS) in Woodstock, GA. APS conducted analyses on the soil sample, recommended a PAM formulation and application rate, and supplied the PAM for experiments. APS recommended using the 712 Silt Stop powder, applied at an application rate ranging from 25 to 35 lbs/acre. Application guidelines for PAM were available from APS and were used for this research (APS, 2006). For this study, different application rates of PAM at 35 lbs/acre, 25 lbs/acre, and 15 lbs/acre, in both a dry and liquid form were examined to analyze differences in overall effectiveness with different application rates as an erosion control measure. Both treatment methods (i.e. dry and liquid) would be tested under similar conditions, focusing on the immediate effectiveness of each product after its initial application. Therefore, the liquid PAM applications would not be given time to dry prior to the start of an experiment.

3.4.4 Experiment Organization

Figure 3.14 illustrates a flowchart which describes the overall experimental plan for this research. The flowchart shows the terminology and organization used to identify each experimental setup. This research examined six different treatment options and compared results to a control setup, containing bare soil (i.e. conditions). The six treatments options (i.e. experiments) included three different application rates of dry and liquid PAM, (i.e. 15 lbs/acre, 25 lbs/acre, 35 lbs/acre) respectively. Within each treatment option, two experiments were conducted as a means to check reproducibility between setups. Each experiment contained two test plots, identified by its random placement under the rainfall simulator (i.e. 'left' or 'right' position). These locations were randomly assigned using a coin flip, which produced an exact, 50/50 distribution of test boxes to the left and right positions. To obtain the desired amount of rain, as indicated in Section 3.3.3, four 'tests' were simulated within an experiment. Between each test, there was a 15 minute break between storm events. This rain regime also allows researchers to examine the long-term effectiveness of PAM tested under various rainfall events over an extended period of time.



Note: 14 Total Experiments, 28 Replicates, 56 Tests

Figure 3.14 Flowchart of Experimental Organization.

3.4.5 Test Plot Preparation

For each experimental setup, test plot preparation consisted of five parts: (1) determine existing OMC of stockpile, (2) soil compaction, (3) treatment application, (4) plot placement under rainfall simulator, and (5) saturate test plots.

To reach a desired level of compaction, test soil must be near the recommended moisture content as determined in Section 3.4.2. Twenty-four hours before an experiment, moisture content for the soil was checked to determine if additional water was required. When the moisture content was lower than the required amount, the necessary ratio of test soil and water were weighed and measured, as seen in Figure 3.15(a). Soil and water were thoroughly mixed in a wheelbarrow, and added into a test box, as seen in Figure 3.15(b).

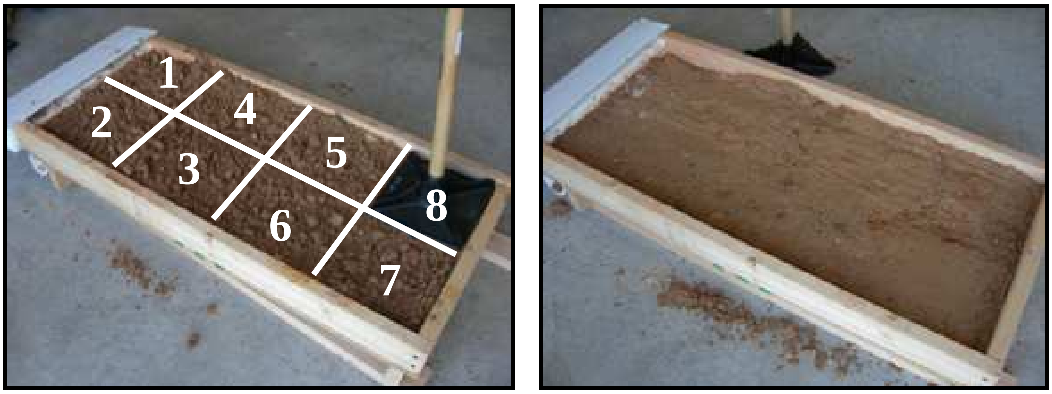
(a) Preparing Soil for an OMC of 15%

(b) Soil and Water Thoroughly Mixed

Figure 3.15 Obtaining OMC for Experimentation.

Approximately 2 inches of soil was placed in a box, because it was observed that when compacted, the depth of un-compacted soil would be approximately halved when compacted. It was also determined that two, 5 gallon buckets, as seen in Figure 3.15(a), would be sufficient to achieve this un-compacted amount for one layer. Therefore, this amount of un-compacted soil would be reduced to a target depth of 1 inch when compacted.

To compact one layer of soil, a hand tamp was used to compact 8 subsections, as illustrated in Figure 3.16(a). To achieve a 95% compaction rate, one of these subsection required 90 drops of a hand-tamp. This was performed over all 8 subsections to compact approximately a 1 inch layer of soil, as seen in Figure 3.16 (b). This entire process was repeated one more time to fill a box with approximately 2 inches of compacted material.



(a) 8 Sections to Compact One Layer **(b) First Layer Compacted**

Figure 3.16 Using Hand Tamp to Compact 1 inch of Test Soil.

After compaction, the test plots could be treated with the different PAM applications required for experimentation. The two methods of PAM application analyzed for this research was (1) dry, granular PAM applied directly to the plots and (2) liquid PAM; prepared using granular PAM mixed with water and applied with a sprayer. Both types of applications were examined using different recommended rates of 35, 25, and 15 lbs/acre.

The necessary amount of PAM required for all experiments was converted to experimental scale. Table 3.5(a) and 3.5(b) show the application rates determined for intermediate-scale experiments. Note that in Table 3.5(b), the water corresponds with the necessary amount to mix with dry granular PAM to create liquid PAM for treatments. The recommended amount of water required for mixing with PAM to achieve the proper water to PAM ratio was provided by APS.

Table 3.5 PAM Application Rates

(a) Application Rates for Dry PAM

Dry Rate[1] (lbs/acre)	Dry Rate[2] (grams/plot)
35	2.80
25	2.00
15	1.20

(b) Application Rates for Liquid PAM

Dry Rate[1] (lbs/acre)	Water[1] (gal/acre)	Dry Rate[2] (grams/plot)	Water[2] (gal/plot)
35	3000	2.80	0.53
25	2143	2.00	0.38
15	1286	1.20	0.23

Notes: 1. Field Scale | 2. Intermediate Scale

Application of the dry granular PAM was accomplished by utilizing a salt shaker, as shown in Figure 3.17(a). PAM was applied uniformly to both test plots, verified through observation. Figure 3.17(b) illustrates the uniform coverage of dry PAM as it was applied to a test plot.

(a) 712 Silt Stop and Salt Shaker **(b) Dry PAM Applied on Test Plot**

Figure 3.17 Application of Dry Granular PAM.

The process to apply liquid PAM required the use of a Maruyama MS074 backpack sprayer with a built in agitator. Specifications for the backpack sprayer can been seen in Appendix C, included in this report. This type of backpack sprayer was necessary because the dry PAM needed to be introduced slowly and mixed thoroughly with water prior to application. Without an agitator, the mixture would become too viscous and clog a traditional sprayer. Therefore, care was taken to ensure that dry granular PAM was added slowly to the water. The mixture of dry PAM and water was allowed to mix for approximately 30 minutes prior to application. Figure 3.18(a), 3.18(b), and 3.18(c) demonstrate this process for preparing liquid PAM for experimentation.

(a) Adding Water to Sprayer

(b) Slowly adding Dry PAM

(c) Observing Mixing

Figure 3.18 Preparing Liquid PAM Mixture for Application.

The backpack sprayer was used to uniformly apply the liquid PAM, coating both test plots simultaneously. Care was taken to control the application of PAM, so the sprayer was set to apply a consistent amount of liquid PAM and was applied equally to both plots until all the mixture was completely used. Figure 3.19(a), 3.19(b), and 3.19(c) show the backpack sprayer applying liquid PAM to two test plots prior to experimentation. PAM was applied outdoors to keep the liquid PAM off the concrete slab, due to potential safety hazards with slippery conditions.

(a) Backpack Sprayer used for Liquid PAM Application

(b) Spraying Liquid PAM on Plot

(c) Close-up of Spray Nozzle

Figure 3.19 Application of Liquid PAM.

Once both test plots were treated with a PAM application, they were moved to a location under the rainfall simulator. A test plot location was randomly assigned using a coin-flip and placed under the simulator to control for any potential bias. Therefore, test plots were classified as either the 'left' position or 'right' position, as shown in Figure 3.20.

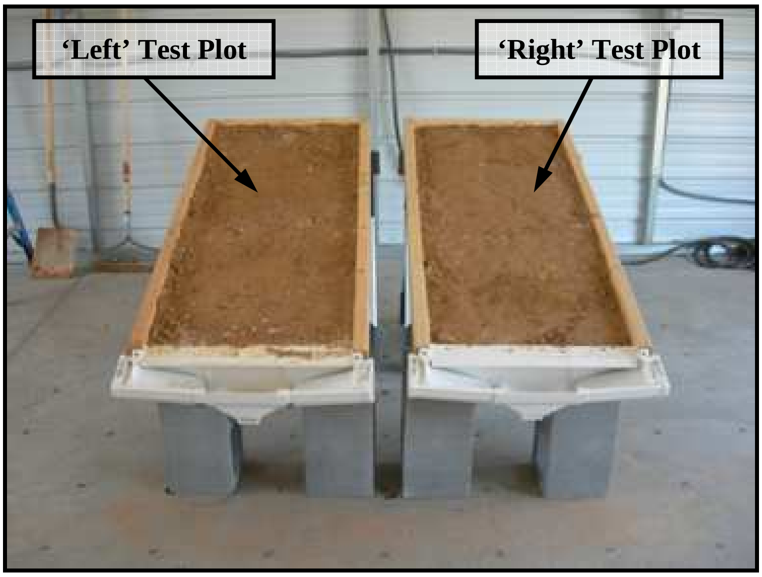


Figure 3.20 Plots Placed in 'Left' and 'Right' Position.

With test plots setup and placed under the rainfall simulator, a brief saturation period was conducted to facilitate the start of runoff prior to experimentation. The rainfall simulator was set to the desired properties as discussed in Section 3.3.3 and started. Plots were briefly exposed to rainfall until the runoff was initiated. Plot preparation at this point was completed and experiments could commence.

3.4.6 Data Collection

Data collection for this study was similar to previous conducted research by Halverson (2006) and McDonald (2007), with slight modifications to reflect changes made in the experimental design. However, improvements were made in recording turbidity from runoff samples. Additional information was also collected, which was not examined from previous research (i.e. runoff mass and particle sizes). Photographs of each test plot were taken to document a visual condition prior to an experiment and at the end of each of the four tests. In addition, the entire experiment duration was recorded with a video camera, which allowed for time-lapse footage of the erosion process to be documented.

The primary concern during data collection pertained to runoff generated from test plots during rainfall events. Runoff samples were collected every minute during experimentation in clear, five quart buckets with volume markings denoted on the side of each. Volume and mass for these buckets were recorded for each 'left' and 'right' test plot, as illustrated in Figure 3.21. Instantaneous turbidity was recorded using an ANALITE NEP160 turbidity meter with a ANALITE NEP 260 probe, as seen in Figure 3.22. This probe was capable of measuring turbidity levels from 0 to 4,000 NTU. Detailed specifications for the meter and probe can be found in Appendix C. Prior to recording initial turbidity, collected samples were stirred to represent turbidity of the surface runoff as it was leaving the test plots. This new turbidity meter allowed researchers a direct means to test water samples for turbidity during an ongoing experiment, reducing overall time involved with experimentation and data collection. Instantaneous turbidity was recorded at minute intervals during each test run. Along with instantaneous turbidity, the meter and probe were used to collect and record turbidity over time, which illustrated the rate of particle settling. At the 5 and 10 minute interval for each of the four tests on each plot, samples were collected in one quart cups and researchers recorded turbidity over time. An example of this process is illustrated in Figure 3.22, where the probe was suspended in the runoff sample, and allowed to collect data over a set period of time. This period of time was set at 10 minutes for the 'control' experiments, and 3 minutes for subsequent PAM treated experiments, due to the difference in length of time required for particles to settle out between the control and treated experiments.

Figure 3.21 Recording Volume and Mass of Surface Runoff.

Figure 3.22 ANALITE NEP 160 Turbidity Meter and Probe.

Next, surface runoff samples were poured into Hayward single-length filter bags with one micron sized pores, as pictured in Figure 3.23. This was done every 3 minutes, for a total of 5 bags per test, totaling 40 bags for an entire experiment. At the conclusion of an experiment, these sediment-laden filter bags were placed in an oven at 160^o F (71.1^o C) and dried for 24 hours. These dried bags were weighed to determine the amount of eroded soil from each test plot contained within each bag. Dried soil samples from each bag were collected and combined for sieve analysis to determine particle size of the surface runoff, as illustrated in Figure 3.24.

Figure 3.23 Hayward Filter Bags with Sediment-Laden Water.

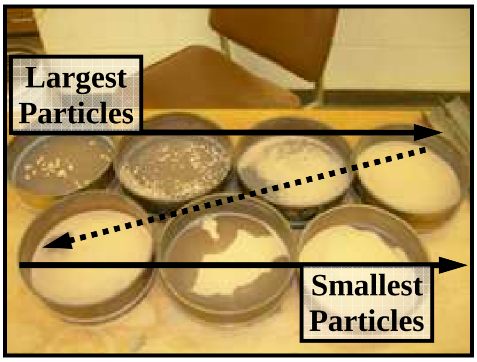


Figure 3.24 Soil Particle Distribution and Sieves.

By following the above mentioned experimental procedures for data collection, a large sample size of data was produced. Table 3.6 illustrates the totals of data collected during experimentation. For runoff observations, in which mass and volume were recorded, a total of 1,680 observations were recorded (e.g. 7 conditions × 4 test plots × 4 tests × 15 observations per test = 1,680 total recorded measurements). The ‘conditions’ parameter, as shown, represents the multiple treatments examined (i.e. ‘control’, ‘dry PAM 35’, ‘dry PAM 25’, etc) and ‘observations per test’ represent measurements recorded for every minute during a 15 minute test. For data pertaining to soil loss, samples were recorded every 3 minutes, resulting in 5 observations per test plot. This produced a total of 560 measurements for analysis. Therefore, using these new experimental procedures, more experiments were conducted, which produced more data for researchers to examine and analyze.

Table 3.6 Breakdown of Collected Data Totals

Conditions	Test Plots	Tests	Observations per Test	Runoff Observations[1]	Turbidity Observations[1]	Soil Loss Observations[2]
7	4	4	15	1,680	1,680	560

Notes: 1. Observations were recorded every minute
2. Observations were recorded every 3 minutes

3.4.7 Statistical Analyses

One-way analysis of variance (ANOVA) was the primary statistical method used to analyze experimental data presented in this research. Typically, ANOVA is used with testing three of more independent groups of data, where a standard t-test is generally used for comparing two independent groups. This is attributed to the fact that if a t-test is performed on more than two independent groups, there is a chance of incorrectly rejecting a null hypothesis or failing to accept the null hypothesis (i.e. Type I and II errors). A 5% level of significance indicates that there is a 95% chance of correctly accepting a null hypothesis. If more than two groups were tested, than the probability of correctly accepting the null hypothesis decreases. This decrease is a function of the number of groups being tested (e.g. if five groups are tested using a standard t-test with a 5% level of significance, the probability of correctly accepting the null hypothesis is approximately $[0.95]^5$ or 0.77). ANOVA procedures compensate for this effect and multiple independent groups can be tested equally without the possibility of compounding these errors. Most statistical software packages contain tools to conduct an ANOVA analysis, due to the complex mathematical computations required to analyze a large number of groups. The one-way ANOVA tool provided by Microsoft's Excel™ 2007 was used for this research effort.

However, ANOVA analysis alone is not sufficient to determine statistical significance between individual pairs. ANOVA procedures only provide the capability to determine if all tested means are equal. A typical null and alternative hypothesis used during this research for ANOVA analysis is illustrated in Equation 3 and 4, respectively.

$$H_o: \mu_0 = \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_6 = \mu_7 \quad (3)$$

$$H_a: \text{all means are different} \quad (4)$$

where,

H_o = null hypothesis

H_a = alternative hypothesis

μ_i = mean values of each data set 'i',

i = independent groups [i.e. (0) control, (1) dry 35, (2) dry 25, etc]

The null and alternative hypothesis statements for ANOVA are not sufficient to discern statistical significant difference between individual pairs. Therefore, additional ad hoc tests needed to be performed on different combinational pairs of groups. These test that examine multiple means incorporate measures to assist in reducing the risks associated with Type I error, as outlined above. For this research, the Tukey-Kramer procedure for multiple comparisons was selected for analysis, since comparisons were conducted on all pair-wise differences between means.

To determine if statistical significance was observed using Tukey-Kramer procedures, a confidence interval (CI) was calculated using the following equations:

$$CI_{95\%} = (\mu_i - \mu_j) \pm Tukey\,Kramer\,multiplier \times s_p \sqrt{\left(\frac{1}{n_i} + \frac{1}{n_j}\right)} \qquad (5)$$

where,

$CI_{95\%}$ = 95% confidence interval,

μ_i - μ_j = difference of means for 'i' and 'j' groups,

s_p = pooled standard deviation, and

$n_{i,j}$ = sample sizes of 'i' and 'j' groups

The pooled standard deviation as shown in Equation 5 can be derived from taking the square-root of the Mean Square Error (MSE), which is calculated during creation of an ANOVA table. A Tukey-Kramer multiplier can be determined using Equation 6:

$$Tukey\ Kramer\ multiplier = \frac{q_{a,n-a,\alpha}}{\sqrt{2}} \qquad (6)$$

where,

q = upper percentile for a studentized range distribution,

a = total number of groups,

n = sample size, and

α = level of significance (5%)

To determine if the two test groups are statistically significant, the calculated confidence interval are examined and if zero is contained within the upper and lower bounds of the interval, than the two groups are not statistically significant.

3.5 SUMMARY

In total, fourteen experiments were conducted, examining the effectiveness of two different treatment options, with varying application rates, to a bare soil condition. A new facility was built to house this research, which provided researchers the necessary equipment and space for experimentation. Experiments were designed using methods and procedures from previous research as a general guideline. Modifications were made where researchers felt that certain areas needed improvements. One of these areas was designing and constructing a new testing apparatus used to contain experimental soil. These newly designed test plots allowed for an experimental setup that required less time to prepare, allowing researchers the ability to conduct more experiments and collect more data than the previous research could feasibly produce. Another area that was redesigned was the rainfall simulator. A new simulator was designed with new components which produced controllable rainfall events with a uniform spray area.

Procedures were developed to reflect differences made in the new experimental design. Soil was compacted using hand-tamps, which provide the necessary energy to effectively compact the test soil to a rate of 95%. New equipment was used during data collection to assist with reducing the amount of time needed for each experiment. This included a turbidity meter and probe which could be used to collected turbidity instantaneously during an experiment. Additional data was collected from experiments, which included runoff mass and particle size distribution of surface runoff.

These new experimental designs and procedures allowed researchers to develop the means to uniformly setup, conduct, and analyze erosion control BMPs with laboratory conditions using intermediate-scale plot sizes. This new design reduced the overall time and the amount of effort required for conducting an experiment with this setup which produces a high quality data set for conducting an ANOVA analysis to determine if results were statistically significant.

CHAPTER FOUR

INTERMEDIATE-SCALE EXPERIMENTS RESULTS AND DISCUSSION

4.1 INTRODUCTION

Intermediate-scale experiments provided means to perform multiple tests with fewer resources, when compared to field-scale experiments, and also generated a large amount of data for analysis. This chapter will present the results generated from experiments and the statistical tests used for analyses pertaining to the performance of PAM as an erosion and sediment control measure.

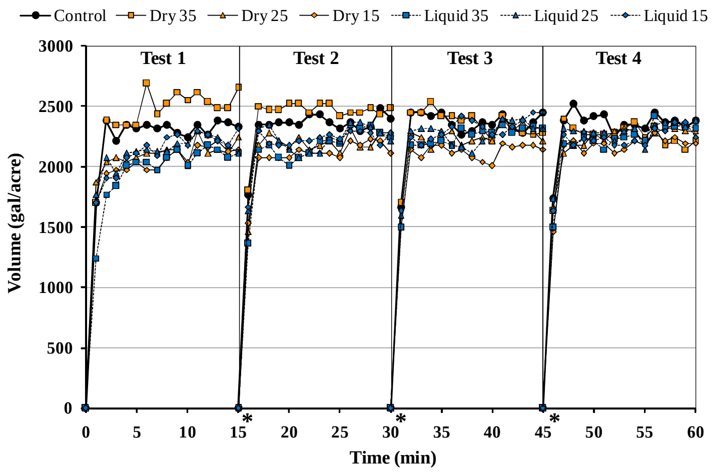
4.2 EXPERIMENTAL RESULTS

Data collection methods and features, as outlined in Section 3.4.6, provided researchers with an abundant amount of raw data. The data collected and recorded includes: (1) surface runoff volume, (2) surface runoff mass, (3) initial turbidity, (4) runoff samples (turbidity versus time) and, (5) amount of soil eroded from test plots. Raw data collected from each experiment is included in Appendix D. Data from replicated test plots were compared to determine if any anomalies were present and an overall average was calculated for further analysis. The raw data was scaled to represent practical field units for the purpose of reporting in subsequent sections.

4.2.1 Surface Runoff

Surface runoff generated from test plots was collected at 1 minute intervals during an experiment's 60 minute total duration. Volume and weight for each sample were measured and recorded. Overall averages of runoff volume for the control and six PAM treatments are illustrated in Figure 4.1

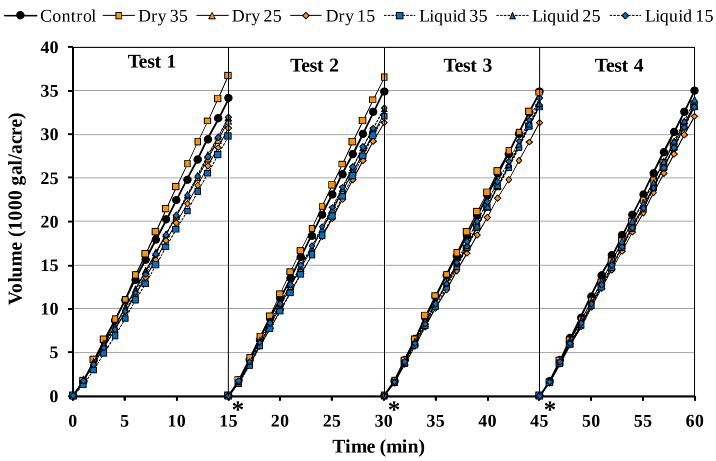
Upon visual inspection, Figure 4.1 demonstrates no observable difference between different treatments tested. Specifically, no increase or decrease was discerned in the amount of surface runoff generated. The higher amount of runoff reported in the dry PAM at 35 lbs/acre was attributed to a slightly higher operating pressure of the rainfall simulator, rather than any effect the treatment had on the amount of runoff generated.



Note: '*' denotes 15 minute break in between tests

Figure 4.1 Average Surface Runoff vs. Time.

Figure 4.2 illustrates the cumulative amount of average surface runoff for each of the four tests (i.e. Test 1, Test 2, Test 3, and Test 4). As seen earlier with Figure 4.1, the addition of PAM appears to have no substantial effect in the total amount of runoff accumulated, which ranged from 30,000 to 36,000 gal/acre. These figures show that similarities in data confirm the researchers' experimental design goals by rapidly generating reproducible results.



Note: '*' denotes 15 minute break in between tests

Figure 4.2 Average Cumulative Surface Runoff vs. Time.

Specific values for surface runoff for the dry and liquid PAM treatments are shown below in Table 4.1 and Table 4.2, respectively. Both tables illustrate the calculated average of runoff for each 15 minute test interval and each test's corresponding cumulative amount. Average runoff and standard deviation were calculated from a total sample size of 60 measurements per test (e.g. 4 test plots × 15 min per test = 60 total samples).

Table 4.1 Average Surface and Cumulative Runoff for Each Test [*Dry PAM*]

Condition	Runoff [a] (gal/acre)	Standard Deviation [b] (gal/acre)	Percent Reduction [c]	Cumulative Runoff [d] (gal/acre)
		Test 1		
Control	2279.0	236.9	-	34184.4
Dry 35	2448.0	328.9	-7.4%	36719.7
Dry 25	2102.0	135.6	7.8%	31530.0
Dry 15	2044.1	182.9	10.3%	30662.2
		Test 2		
Control	2331.1	236.6	-	34967.1
Dry 35	2432.1	289.8	-4.3%	36481.5
Dry 25	2158.7	251.0	7.4%	32380.7
Dry 15	2088.4	188.6	10.4%	31325.8
		Test 3		
Control	2326.6	243.8	-	34899.0
Dry 35	2324.3	263.4	0.1%	34865.0
Dry 25	2215.4	212.5	4.8%	33231.5
Dry 15	2087.3	198.0	10.3%	31308.8
		Test 4		
Control	2335.7	241.2	-	35035.2
Dry 35	2227.9	195.7	4.6%	33418.7
Dry 25	2215.4	197.9	5.1%	33231.5
Dry 15	2141.7	231.2	8.3%	32125.5

Notes: 'a' Average surface runoff vs. time for each test
'b' Standard deviation of surface average runoff vs. time
'c' Denotes values normalized by control condition
'd' Average cumulative surface runoff for each 15 min. test

Table 4.2 Average Surface and Cumulative Runoff for Each Test [*Liquid PAM*]

Condition	Runoff [a] (gal/acre)	Standard Deviation [b] (gal/acre)	Percent Reduction [c]	Cumulative Runoff [d] (gal/acre)
		Test 1		
Control	2279.0	236.9	-	34184.4
Liquid 35	1984.0	264.9	12.9%	29760.3
Liquid 25	2127.0	194.4	6.7%	31904.3
Liquid 15	2128.1	194.4	6.6%	31921.3
		Test 2		
Control	2331.1	236.6	-	34967.1
Liquid 35	2140.6	251.4	8.2%	32108.5
Liquid 25	2197.3	197.8	5.7%	32959.3
Liquid 15	2200.7	191.6	5.6%	33010.3
		Test 3		
Control	2326.6	243.8	-	34967.1
Liquid 35	2212.0	221.2	4.9%	33180.5
Liquid 25	2237.0	220.4	3.9%	33554.8
Liquid 15	2276.7	217.2	2.1%	34150.4
		Test 4		
Control	2335.7	241.2	-	34967.1
Liquid 35	2210.9	222.6	5.3%	33163.5
Liquid 25	2264.2	215.5	3.1%	33963.2
Liquid 15	2206.4	205.3	5.5%	33095.4

Notes: 'a' Average surface runoff vs. time for each test
'b' Standard deviation of surface average runoff vs. time
'c' Denotes values normalized by control condition
'd' Average cumulative surface runoff for each 15 min. test

Percent reductions, as seen Table 4.1 and Table 4.2, were normalized with the control condition for comparison. Negative values, as observed with the 35 lb/acre dry PAM treatment, indicate an increase in recorded runoff. The largest reduction of runoff occurred during test 1 with the 35 lbs/acre application of liquid PAM at 12.9%. Conversely, dry PAM applied at 35 lbs/acre for test 1 had a recorded increase of 7.4% when compared to the control.

4.2.1.1 Statistical Analysis: Surface Runoff

To determine if there was a statistically significant difference between calculated averages for control vs. treatment surface runoff, an ANOVA table was generated for each test (e.g. test 1, test 2). These ANOVA tables are included in Appendix E within this report. An ANOVA analysis showed that test 1, test 2, and test 3 rejected the null hypothesis, indicated that differences between control and treatments existed. Test 4 ANOVA analyses determined that the null hypothesis should be accepted, resulting in no differences occurred between all test groups. Tukey-Kramer confidence intervals were calculated using the Equations 5 and 6, outlined in Section 3.4.7, to determine any specific significant differences between conditions tested, as illustrated in Table 4.3, Table 4.4, Table 4.5, and Table 4.6.

Table 4.3 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 1*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	169.0	-22.9	361.0	No
Control vs. Dry 25	**234.8**	**42.9**	**426.8**	**Yes**
Control vs. Dry 15	177.0	-15.0	368.9	No
Control vs. Liquid 35	**294.9**	**103.0**	**486.9**	**Yes**
Control vs. Liquid 25	150.9	-41.1	342.8	No
Control vs. Liquid 15	152.0	-39.9	343.9	No
Dry 35 vs. Dry 25	**403.8**	**211.9**	**595.8**	**Yes**
Dry 35 vs. Dry 15	**346.0**	**154.0**	**537.9**	**Yes**
Dry 35 vs. Liquid 35	**464.0**	**272.0**	**655.9**	**Yes**
Dry 35 vs. Liquid 25	**319.9**	**128.0**	**511.8**	**Yes**
Dry 35 vs. Liquid 15	**321.0**	**129.1**	**513.0**	**Yes**
Dry 25 vs. Dry 15	57.9	-134.1	249.8	No
Dry 25 vs. Liquid 35	60.1	-131.8	252.1	No
Dry 25 vs. Liquid 25	83.9	-108.0	275.9	No
Dry 25 vs. Liquid 15	82.8	-109.1	274.7	No
Dry 15 vs. Liquid 35	118.0	-74.0	309.9	No
Dry 15 vs. Liquid 25	26.1	-165.8	218.0	No
Dry 15 vs. Liquid 15	25.0	-167.0	216.9	No
Liquid 35 vs. Liquid 25	144.1	-47.9	336.0	No
Liquid 35 vs. Liquid 15	142.9	-49.0	334.9	No
Liquid 25 vs. Liquid 15	1.1	-190.8	193.1	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.4 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 2*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	101.0	-103.5	305.4	No
Control vs. Dry 25	**242.8**	**38.3**	**447.2**	**Yes**
Control vs. Dry 15	172.4	-32.0	376.8	No
Control vs. Liquid 35	190.6	-13.8	395.0	No
Control vs. Liquid 25	130.5	-74.0	334.9	No
Control vs. Liquid 15	133.9	-70.6	338.3	No
Dry 35 vs. Dry 25	**343.7**	**139.3**	**548.1**	**Yes**
Dry 35 vs. Dry 15	**273.4**	**69.0**	**477.8**	**Yes**
Dry 35 vs. Liquid 35	**291.5**	**87.1**	**495.9**	**Yes**
Dry 35 vs. Liquid 25	**231.4**	**27.0**	**435.8**	**Yes**
Dry 35 vs. Liquid 15	**234.8**	**30.4**	**439.2**	**Yes**
Dry 25 vs. Dry 15	70.3	-134.1	274.7	No
Dry 25 vs. Liquid 35	52.2	-152.2	256.6	No
Dry 25 vs. Liquid 25	112.3	-92.1	316.7	No
Dry 25 vs. Liquid 15	108.9	-95.5	313.3	No
Dry 15 vs. Liquid 35	18.1	-186.3	222.6	No
Dry 15 vs. Liquid 25	42.0	-162.4	246.4	No
Dry 15 vs. Liquid 15	38.6	-165.8	243.0	No
Liquid 35 vs. Liquid 25	60.1	-144.3	264.5	No
Liquid 35 vs. Liquid 15	56.7	-147.7	261.1	No
Liquid 25 vs. Liquid 15	3.4	-201.0	207.8	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.5 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	2.3	-209.7	214.3	No
Control vs. Dry 25	**239.4**	**27.3**	**451.4**	**Yes**
Control vs. Dry 15	111.2	-100.8	323.2	No
Control vs. Liquid 35	114.6	-97.4	326.6	No
Control vs. Liquid 25	49.9	-162.1	261.9	No
Control vs. Liquid 15	89.6	-122.4	301.6	No
Dry 35 vs. Dry 25	**237.1**	**25.1**	**449.1**	**Yes**
Dry 35 vs. Dry 15	108.9	-103.1	320.9	No
Dry 35 vs. Liquid 35	112.3	-99.7	324.3	No
Dry 35 vs. Liquid 25	47.6	-164.4	259.7	No
Dry 35 vs. Liquid 15	87.3	-124.7	299.4	No
Dry 25 vs. Dry 15	128.2	-83.8	340.2	No
Dry 25 vs. Liquid 35	124.8	-87.2	336.8	No
Dry 25 vs. Liquid 25	189.4	-22.6	401.5	No
Dry 25 vs. Liquid 15	149.7	-62.3	361.8	No
Dry 15 vs. Liquid 35	3.4	-208.6	215.4	No
Dry 15 vs. Liquid 25	61.3	-150.8	273.3	No
Dry 15 vs. Liquid 15	21.6	-190.5	233.6	No
Liquid 35 vs. Liquid 25	64.7	-147.4	276.7	No
Liquid 35 vs. Liquid 15	25.0	-187.1	237.0	No
Liquid 25 vs. Liquid 15	39.7	-172.3	251.7	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.6 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 4*]

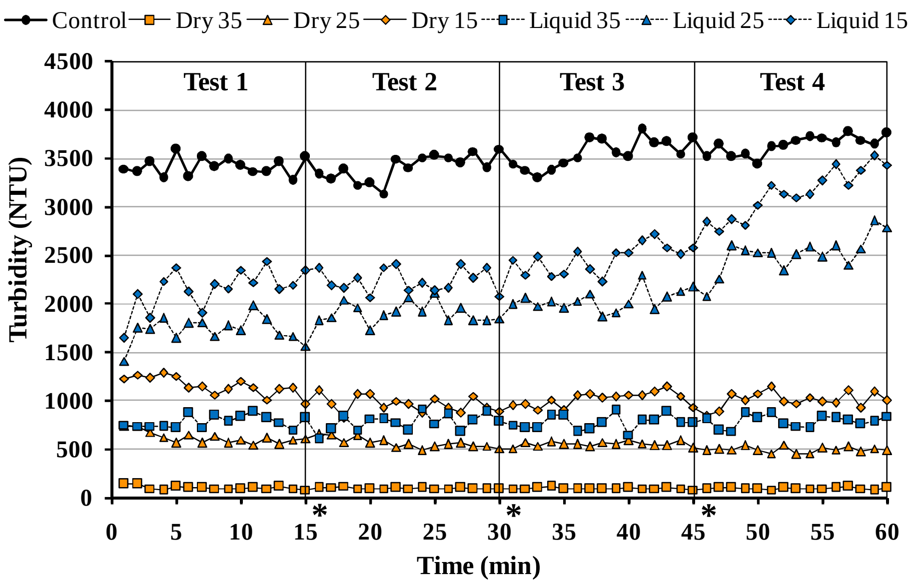
Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	107.8	-90.8	306.4	No
Control vs. Dry 25	194.0	-4.6	392.6	No
Control vs. Dry 15	120.2	-78.4	318.9	No
Control vs. Liquid 35	124.8	-73.8	323.4	No
Control vs. Liquid 25	129.3	-69.3	327.9	No
Control vs. Liquid 15	71.5	-127.1	270.1	No
Dry 35 vs. Dry 25	86.2	-112.4	284.8	No
Dry 35 vs. Dry 15	12.5	-186.1	211.1	No
Dry 35 vs. Liquid 35	17.0	-181.6	215.6	No
Dry 35 vs. Liquid 25	21.6	-177.1	220.2	No
Dry 35 vs. Liquid 15	36.3	-162.3	234.9	No
Dry 25 vs. Dry 15	73.7	-124.9	272.3	No
Dry 25 vs. Liquid 35	69.2	-129.4	267.8	No
Dry 25 vs. Liquid 25	64.7	-134.0	263.3	No
Dry 25 vs. Liquid 15	122.5	-76.1	321.1	No
Dry 15 vs. Liquid 35	4.5	-194.1	203.2	No
Dry 15 vs. Liquid 25	9.1	-189.5	207.7	No
Dry 15 vs. Liquid 15	48.8	-149.8	247.4	No
Liquid 35 vs. Liquid 25	4.5	-194.1	203.2	No
Liquid 35 vs. Liquid 15	53.3	-145.3	251.9	No
Liquid 25 vs. Liquid 15	57.9	-140.8	256.5	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Many of the observed differences within tests 1, 2, and 3 occurred with comparisons made to dry PAM at 35 lbs/acre. The Tukey-Kramer results for test 4, shown in Table 4.6, found no statistical difference between any combinations of groups. Overall, no statistical significant results were observed pertaining to PAM treatments reducing the amount of runoff generated on the control. While dry PAM at 35 lbs/acre appeared to be performing poorly at first, no other treatments experienced a similar effect. Other PAM applications (with the exception of liquid 35) experience no significant difference when compared to the control condition as well. When different PAM applications were compared to each other, no significant results were observed. Therefore, the addition of PAM, in either a dry or liquid form, at different application rates, had no appreciable effect on surface runoff volume.

4.2.2 Initial Turbidity

Turbidity measurements were recorded at 1 minute intervals from thoroughly stirred runoff samples, collected in 5 qt buckets. This provided researchers with a total of 1,680 turbidity measurements. These measurements were identified as an initial turbidity reading for surface runoff, recorded from 1 minute intervals samples from each condition's data was averaged together, as illustrated in Figure 4.3. Distribution of initial turbidity was observed to be consistent, with dry PAM at 35 lbs/acre performing the best. Throughout the duration of an experiment, dry PAM at 35 lbs/acre was able to reduce turbidity levels and maintain low readings. The dry PAM granular was exposed to water, at which point the PAM molecules were 'activated'. As PAM was slowly introduced into the runoff, the activated PAM molecules bonded with the suspended soil particles present in the stormwater. This process promotes particles to flocculate and settle out as PAM and soil particles become larger. As PAM application rates decreased, initial turbidity measurements increased. This trend continued throughout all PAM treatments observed. Liquid PAM at 25 and 15 lbs/acre experienced a specific increase approximately at 40 minutes into the total experiment duration, with a greater increase occurring for test 4. This increase of initial turbidity was identified as the point at which these PAM treatments were no longer effective at reducing turbidity, as the PAM treatments were being effectively washed away by the runoff. The PAM molecules washed away were still capable of reducing sedimentation, but not as effectively as dry PAM treatments



Note: '*' denotes 15 minute break in between tests

Figure 4.3 Average Initial Turbidity of Surface Runoff vs. Time.

Table 4.7 and Table 4.8 show average turbidity measurements, standard deviation of the average turbidity, and a percent reduction, normalized for the control condition. As seen here, dry PAM at 35 lbs/acre performed the best with a reduction of approximately 97% for all tests. The increase of turbidity can also be observed in Table 4.8, as the percent reduction decreases from 49.4 % to 30.9 % and 36.9% to 32.1% for liquid PAM 25 and 15 lbs/acre, respectively. A slight reduction of turbidity occurs with all three applications of the dry PAM treatments over the duration of all four tests.

Table 4.7 Average Initial Turbidity Results for Surface Runoff [*Dry PAM*]

Condition	Average Turbidity [a] (NTU)	Standard Deviation [b] (NTU)	Percent Reduction [c]
		Test 1	
Control	3414.7	513.6	-
Dry 35	103.4	28.9	97.0%
Dry 25	620.0	113.8	81.8%
Dry 15	1153.5	171.2	66.2%
		Test 2	
Control	3405.4	395.6	-
Dry 35	99.0	14.7	97.1%
Dry 25	563.8	110.3	83.4%
Dry 15	967.0	198.4	71.6%
		Test 3	
Control	3553.6	304.3	-
Dry 35	96.1	15.7	97.3%
Dry 25	553.8	85.4	84.4%
Dry 15	1018.1	156.0	71.4%
		Test 4	
Control	3636.6	233.5	-
Dry 35	95.5	15.2	97.4%
Dry 25	496.1	54.3	86.4%
Dry 15	1008.7	132.6	72.3%

Notes: ‘a’ Average of initial turbidity vs. time for each test
‘b’ Standard deviation for average initial turbidity vs. time
‘c’ Denotes values normalized by control condition

Table 4.8 Average Initial Turbidity Results for Surface Runoff [*Liquid PAM*]

Condition	Average Turbidity [a] (NTU)	Standard Deviation [b] (NTU)	Percent Reduction [c]
		Test 1	
Control	3414.7	513.6	-
Liquid 35	784.8	167.3	77.0%
Liquid 25	1726.4	262.6	49.4%
Liquid 15	2153.1	417.3	36.9%
		Test 2	
Control	3405.4	395.6	-
Liquid 35	776.7	176.0	77.2%
Liquid 25	1907.8	281.0	44.0%
Liquid 15	2245.4	279.6	34.1%
		Test 3	
Control	3553.6	304.3	-
Liquid 35	775.5	187.4	78.2%
Liquid 25	2036.2	279.0	42.7%
Liquid 15	2240.9	274.3	36.9%
		Test 4	
Control	3636.6	233.5	-
Liquid 35	789.6	145.1	78.3%
Liquid 25	2513.3	300.5	30.9%
Liquid 15	2470.8	282.9	32.1%

Notes: 'a' Average of initial turbidity vs. time for each test
'b' Standard deviation for average initial turbidity vs. time
'c' Denotes values normalized by control condition

4.2.2.1 Statistical Analysis: Initial Turbidity

Differences observed between the control and treatments for the surface runoff's initial turbidity measurements indicated that PAM treatments were having an effect on the amount of sediment contained in the runoff. To verify this observation and determine if this difference was statistically significant, ANOVA tables were created (Appendix E) and Tukey-Kramer tests were conducted to determine statistical significance between individual pairs of groups, as illustrated in Table 4.9, Table 4.10, Table 4.11, and Table 4.12.

As expected, these tables demonstrate that the initial turbidity averages had statistically significant differences between all possible pairs tested. Therefore, it can be observed that the addition of PAM had a significant effect on its ability to reduce initial turbidity from surface runoff generated from test plots. Also, statistically significant differences were observed between individual PAM treatments, which indicate that different application rates were statistically significantly different when compared. Examining the mean differences, reported in Table 4.9, Table 4.10, Table 4.11, and Table 4.12, it can be seen which treatment was more effective. Dry PAM applied as 35 lbs/acre performed the best out of the tested treatments in reducing initial turbidity for the bare soil control during all 4 tests. Dry PAM 35 also clearly performed well when compared to other treatments and respective applications rates. Even though it was observed that the effectiveness of liquid PAM 25 and 15 lbs/acre began to diminish during test 4, reductions in initial turbidity were still observed to be statistically significant.

Table 4.9 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 1*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3311.3	3187.5	3435.1	Yes
Control vs. Dry 25	2261.2	2137.5	2385.0	Yes
Control vs. Dry 15	2794.7	2670.9	2918.4	Yes
Control vs. Liquid 35	2629.9	2506.2	2753.7	Yes
Control vs. Liquid 25	1261.6	1137.8	1385.3	Yes
Control vs. Liquid 15	1688.3	1564.6	1812.1	Yes
Dry 35 vs. Dry 25	1050.1	926.3	1173.8	Yes
Dry 35 vs. Dry 15	516.6	392.9	640.4	Yes
Dry 35 vs. Liquid 35	681.4	557.6	805.1	Yes
Dry 35 vs. Liquid 25	2049.7	1926.0	2173.5	Yes
Dry 35 vs. Liquid 15	1623.0	1499.2	1746.7	Yes
Dry 25 vs. Dry 15	533.4	409.7	657.2	Yes
Dry 25 vs. Liquid 35	368.7	244.9	492.5	Yes
Dry 25 vs. Liquid 25	999.7	875.9	1123.4	Yes
Dry 25 vs. Liquid 15	572.9	449.1	696.7	Yes
Dry 15 vs. Liquid 35	164.7	41.0	288.5	Yes
Dry 15 vs. Liquid 25	1533.1	1409.3	1656.9	Yes
Dry 15 vs. Liquid 15	1106.3	982.6	1230.1	Yes
Liquid 35 vs. Liquid 25	1368.4	1244.6	1492.1	Yes
Liquid 35 vs. Liquid 15	941.6	817.8	1065.4	Yes
Liquid 25 vs. Liquid 15	426.8	303.0	550.5	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.10 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 2*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3306.4	3203.1	3409.8	Yes
Control vs. Dry 25	2438.4	2335.1	2541.8	Yes
Control vs. Dry 15	2841.6	2738.2	2944.9	Yes
Control vs. Liquid 35	2628.7	2525.3	2732.0	Yes
Control vs. Liquid 25	1164.5	1061.1	1267.8	Yes
Control vs. Liquid 15	1497.6	1394.2	1600.9	Yes
Dry 35 vs. Dry 25	868.0	764.6	971.4	Yes
Dry 35 vs. Dry 15	464.9	361.5	568.2	Yes
Dry 35 vs. Liquid 35	677.8	574.4	781.1	Yes
Dry 35 vs. Liquid 25	2141.9	2038.6	2245.3	Yes
Dry 35 vs. Liquid 15	1808.8	1705.5	1912.2	Yes
Dry 25 vs. Dry 15	403.2	299.8	506.5	Yes
Dry 25 vs. Liquid 35	190.3	86.9	293.6	Yes
Dry 25 vs. Liquid 25	1273.9	1170.6	1377.3	Yes
Dry 25 vs. Liquid 15	940.8	837.5	1044.2	Yes
Dry 15 vs. Liquid 35	212.9	109.5	316.3	Yes
Dry 15 vs. Liquid 25	1677.1	1573.7	1780.4	Yes
Dry 15 vs. Liquid 15	1344.0	1240.6	1447.3	Yes
Liquid 35 vs. Liquid 25	1464.2	1360.8	1567.5	Yes
Liquid 35 vs. Liquid 15	1131.1	1027.7	1234.4	Yes
Liquid 25 vs. Liquid 15	333.1	229.7	436.5	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.11 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3457.5	3350.2	3564.8	Yes
Control vs. Dry 25	2535.6	2428.2	2642.9	Yes
Control vs. Dry 15	2999.9	2892.6	3107.2	Yes
Control vs. Liquid 35	2778.2	2670.9	2885.5	Yes
Control vs. Liquid 25	1082.8	975.5	1190.1	Yes
Control vs. Liquid 15	1517.4	1410.1	1624.7	Yes
Dry 35 vs. Dry 25	921.9	814.6	1029.2	Yes
Dry 35 vs. Dry 15	457.6	350.3	564.9	Yes
Dry 35 vs. Liquid 35	679.3	572.0	786.6	Yes
Dry 35 vs. Liquid 25	2374.7	2267.4	2482.0	Yes
Dry 35 vs. Liquid 15	1940.1	1832.8	2047.4	Yes
Dry 25 vs. Dry 15	464.3	357.0	571.6	Yes
Dry 25 vs. Liquid 35	242.6	135.3	349.9	Yes
Dry 25 vs. Liquid 25	1452.7	1345.4	1560.0	Yes
Dry 25 vs. Liquid 15	1018.2	910.8	1125.5	Yes
Dry 15 vs. Liquid 35	221.7	114.4	329.0	Yes
Dry 15 vs. Liquid 25	1917.1	1809.8	2024.4	Yes
Dry 15 vs. Liquid 15	1482.5	1375.2	1589.8	Yes
Liquid 35 vs. Liquid 25	1695.4	1588.0	1802.7	Yes
Liquid 35 vs. Liquid 15	1260.8	1153.5	1368.1	Yes
Liquid 25 vs. Liquid 15	434.6	327.3	541.9	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.12 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 4*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3541.1	3397.7	3684.5	Yes
Control vs. Dry 25	2627.9	2484.5	2771.3	Yes
Control vs. Dry 15	3140.5	2997.1	3283.9	Yes
Control vs. Liquid 35	2847.0	2703.6	2990.4	Yes
Control vs. Liquid 25	492.0	348.6	635.4	Yes
Control vs. Liquid 15	1123.3	979.9	1266.7	Yes
Dry 35 vs. Dry 25	913.2	769.8	1056.6	Yes
Dry 35 vs. Dry 15	400.6	257.2	544.0	Yes
Dry 35 vs. Liquid 35	694.1	550.7	837.5	Yes
Dry 35 vs. Liquid 25	3049.1	2905.7	3192.5	Yes
Dry 35 vs. Liquid 15	2417.8	2274.4	2561.2	Yes
Dry 25 vs. Dry 15	512.6	369.2	656.0	Yes
Dry 25 vs. Liquid 35	219.1	75.7	362.5	Yes
Dry 25 vs. Liquid 25	2136.0	1992.6	2279.4	Yes
Dry 25 vs. Liquid 15	1504.6	1361.2	1648.0	Yes
Dry 15 vs. Liquid 35	293.5	150.1	436.9	Yes
Dry 15 vs. Liquid 25	2648.6	2505.1	2792.0	Yes
Dry 15 vs. Liquid 15	2017.2	1873.8	2160.6	Yes
Liquid 35 vs. Liquid 25	2355.1	2211.6	2498.5	Yes
Liquid 35 vs. Liquid 15	1723.7	1580.3	1867.1	Yes
Liquid 25 vs. Liquid 15	631.4	488.0	774.8	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

4.2.3 Turbidity vs. Time

In 2008, the EPA began the process of introducing effluent limits on construction runoff. These limitations propose that stormwater runoff must contain a turbidity level less than or equal to 13 NTUs (U.S. EPA, 2008b). However, while these limitations are currently being subjected to review, a potential exists for a required turbidity level. Therefore, for the purposes of this research, runoff samples were examined to determine whether PAM treatments could achieve EPA's proposed effluent limitation of 13 NTUs.

Samples were collected during each of the four tests at predetermined times of 5 and 10 minutes to observe turbidity over time. This was accomplished for each test plot, providing researchers with 224 runoff samples (e.g. 7 conditions × 4 test plots × 4 tests x 2 samples = 224 runoff samples) to measure and record turbidity over time. This collected data was representative of time require for suspended soil particles in the runoff to settle out. This collected data for turbidity versus time can be observed in Figure 4.4.

The time selected to observe turbidity over time was originally 10 minutes, with measurements occurring at 1 minute intervals, producing a curve that shows turbidity slowly decreasing over time. However, examining PAM-treated samples; the decrease in recorded turbidity was nearly instantaneous. Therefore, the observational time was reduced to approximately 3 minutes; with readings measured every 10 seconds to better capture the speed at which particles were settling. As illustrated in Figure 4.4, sediment in PAM treatments was capable of settling out much more quickly than the control. By the end of the 10 minute observational period, recorded turbidity for the control had not decreased to 500 NTUs. Only dry PAM applied at 35 and 25 lbs/acre were capable of obtaining EPA’s effluent limit of 13 NTU within the observed time period. Dry PAM 35 obtained 13 NTUs within 20 seconds and dry PAM 25 in 3 minutes and 20 seconds.

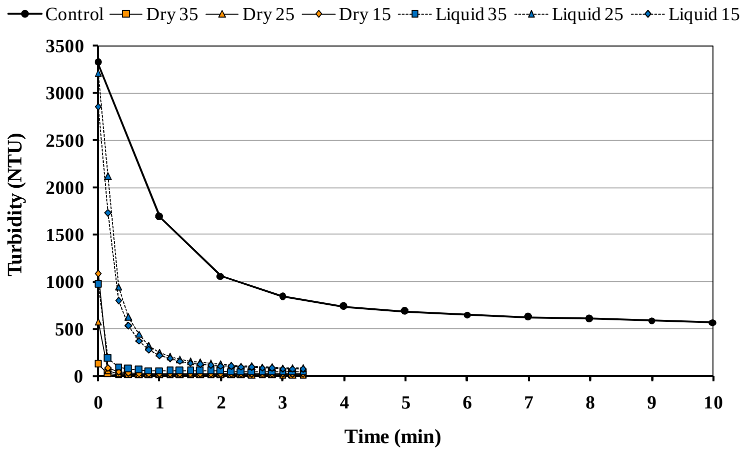
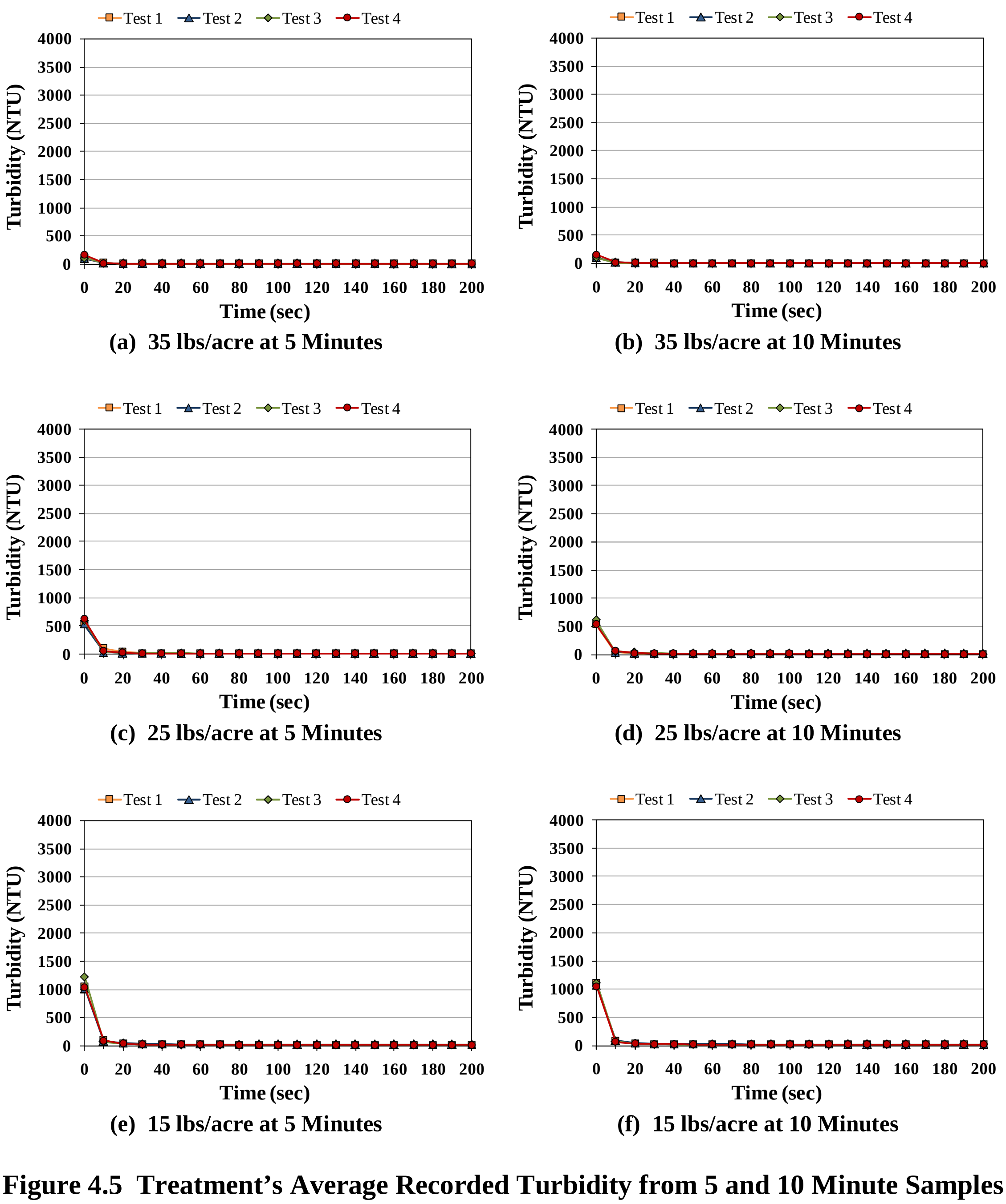


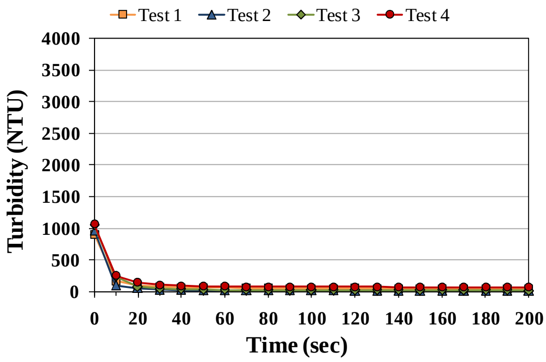
Figure 4.4 Average Recorded Turbidity for All Samples vs. Time.

Further investigations were conducted on turbidity versus time measurements to determine relative performance between treatments and respective application rates. Data for each treatment and application were graphed for their respective collection times of 5 and 10 minutes. Figure 4.5 and Figure 4.6 illustrate these results for dry and liquid PAM treatments, respectively. It was observed in Figure 4.5 that dry PAM treatments initial turbidity readings perform consistently throughout an experiment’s duration, dince all four test produce graphs with similar shapes.

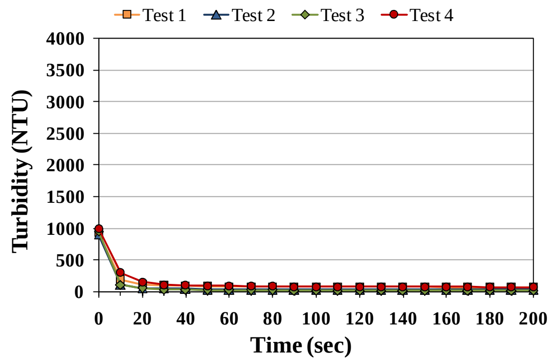


(a) 35 lbs/acre at 5 Minutes
(b) 35 lbs/acre at 10 Minutes
(c) 25 lbs/acre at 5 Minutes
(d) 25 lbs/acre at 10 Minutes
(e) 15 lbs/acre at 5 Minutes
(f) 15 lbs/acre at 10 Minutes

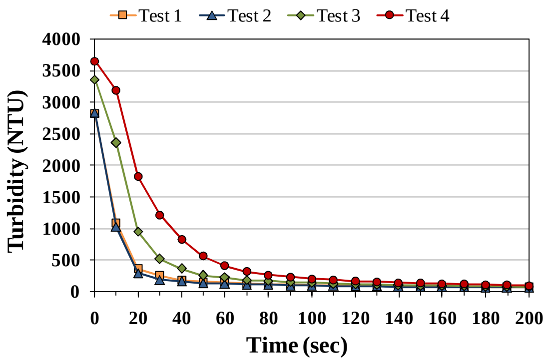
Figure 4.5 Treatment's Average Recorded Turbidity from 5 and 10 Minute Samples [*Dry PAM*].



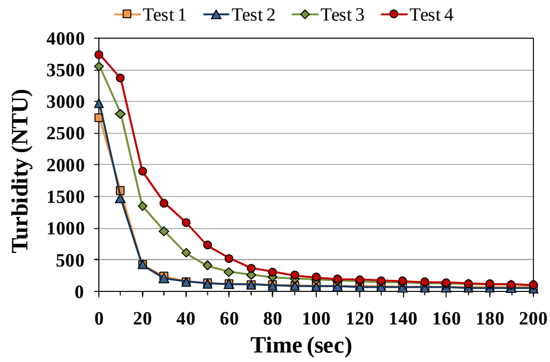
(a) 35 lbs/acre at 5 Minutes



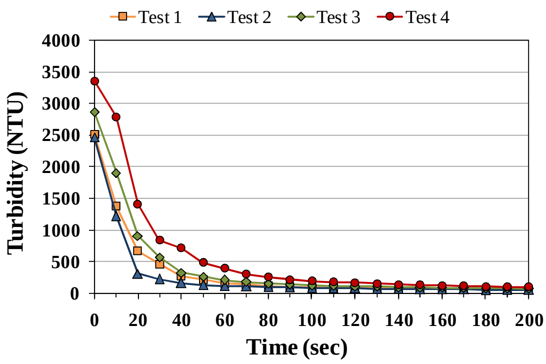
(b) 35 lbs/acre at 10 Minutes



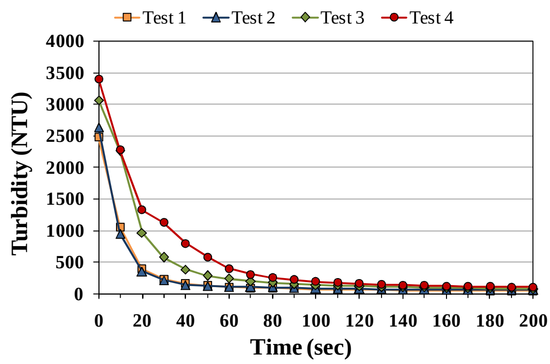
(c) 25 lbs/acre at 5 Minutes



(d) 25 lbs/acre at 10 Minutes



(e) 15 lbs/acre at 5 Minutes



(f) 15 lbs/acre at 10 Minutes

Figure 4.6 Treatment's Average Recorded Turbidity from 5 and 10 Minute Samples [*Liquid PAM*].

Figure 4.6 illustrates that turbidity over time increased for liquid PAM treatments through an experiments individual rainfall events (i.e. test 1 through 4), as a function of application rate. Specifically, both liquid PAM 25 and 15 lbs/acre, as observed in Figure 4.6 (c) through 4.6(f), experienced an increase of turbidity measurements during test 3 and test 4 for both treatments. This is indicative that the performance of liquid PAM at these application rates was not as effective as reducing turbidity levels as seen with dry PAM treatments. This also confirms the previous observation that liquid PAM 25 and 15's effectiveness had begun to diminish during test 3 and test 4 when examining initial turbidity readings. While recorded turbidity levels were still lower than the control condition, the data shows that higher application rates of PAM were more effective in reducing settling time of sediment particles in surface runoff as a function of time.

Table 4.13 illustrates turbidity measurements taken at 200 seconds, averaged from all four tests. These measurements were the final data point collected while observing turbidity versus time. It can be seen that final measurements for dry PAM at 35 lbs/acre reached low turbidity levels around 10 NTUs. Dry PAM 25 and 15 lbs/acre also reached low levels, around 15 and 20 NTUs, respectively. These values show how effective dry PAM was at reducing sedimentation during experimentation. Liquid PAM treatments, while still capable of reducing turbidity levels, were higher than observed with dry PAM treatments, indicating that liquid PAM was not as effective at controlling sedimentation.

Table 4.13 Summary of Turbidity vs. Time Measurements

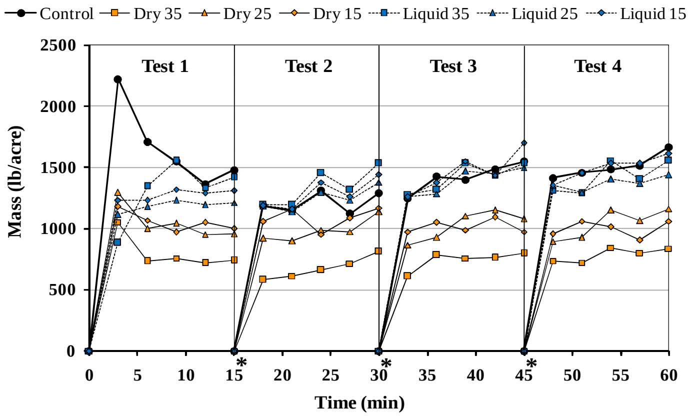
Condition	Turbidity (NTU)[1]	
	5 min	10 min
Dry 35	10.2	9.2
Dry 25	15.2	14.7
Dry 15	21.8	20.1
Liquid 35	40.4	51.5
Liquid 25	78.3	84.2
Liquid 15	77.0	73.7

Note: 1. Turbidity measurement at 200 sec.

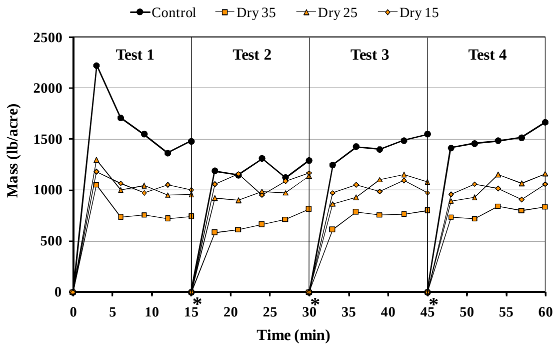
This observed difference between the performances of dry PAM compared to liquid PAM was attributed to how the dry granules of PAM slowly dissolve during experimentation. These dry granules of PAM were activated once water (i.e. rainfall and surface runoff) was applied to the test plots. As the rainfall passed over the granules, the dry PAM treatment was slowly and consistently introduced into the runoff. The liquid PAM treatments were sprayed on and 'distributed' to the soil and were washed away more quickly. This was observed specifically during test 3 and 4 of the liquid PAM treatment at 25 and 15 lbs/acre. This effect was magnified since this research examined the 'worse-case scenario' and did not allow liquid PAM treatments time to dry after the initial application. Therefore, the dry PAM provided long-term protection and enabled the dry PAM treatments to perform better than the liquid PAM treatments at these conditions. Liquid PAM that is formed through mixing dry granular with water becomes activated at this point. Once applied on the soil, the PAM molecules will bond with the soil surface and provided a protective layer. However, the effectiveness of this protective layer is dependent on two factors: (1) uniform coverage and (2) time allotted for drying. Therefore, since this research focused on a 'worse-case scenario' for liquid PAM, (i.e. no time was allotted for drying), the uniform coverage of the spray area was the main controlling factor in the performance of liquid PAM. Appendix F in this report covers additional experiments that examined the effect of liquid PAM that was allowed to dry for 48 hours in comparison to the other PAM treatments presented in this chapter.

4.2.4 Soil Loss

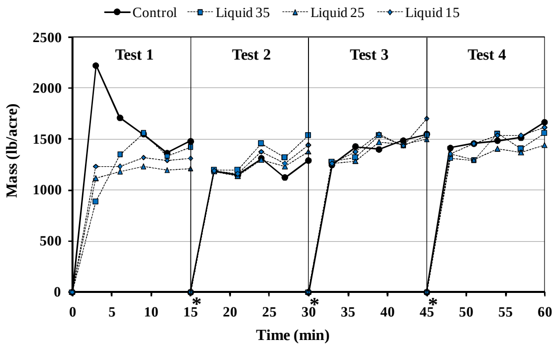
Soil samples, which were representative of the amount of eroded soil from each test plot, were collected from surface runoff every three minutes for a total of 560 observations (e.g. 7 conditions × 4 test plots × 4 tests × 5 observations per test = 560 total recorded measurements)for all experiments conducted. Samples were oven dried and weighed to determine a soil loss for each experimental setup. Figure 4.7(a) illustrates the average values of eroded soil during an experiment's duration. The control condition and dry PAM applications experienced an initial surge of sediment contained within the runoff. Following this surge, eroded soil levels achieved a steady state and remained relatively constant throughout the four tests. It was observed that dry PAM treatments consistently produced levels of sediment that were less than the bare soil. The application rate of 35 lbs/acre performed better than the 25 and 15 lbs/acre treatments at reducing the amount of eroded soil from the plots. All three liquid PAM treatments produced levels of eroded soil that were less than the bare soil control, but only during test 1. Subsequent tests showed that the liquid PAM treatments had similar soil losses when compared to the control. However, liquid PAM treatments were not capable of producing less eroded soil than dry PAM treatments. Figure 4.7(b) and 4.7(c) display the amount of eroded soil for both the dry and liquid PAM treatments, respectively.



(a) Dry and Liquid PAM Treatments vs. Control



(b) Dry PAM Treatments

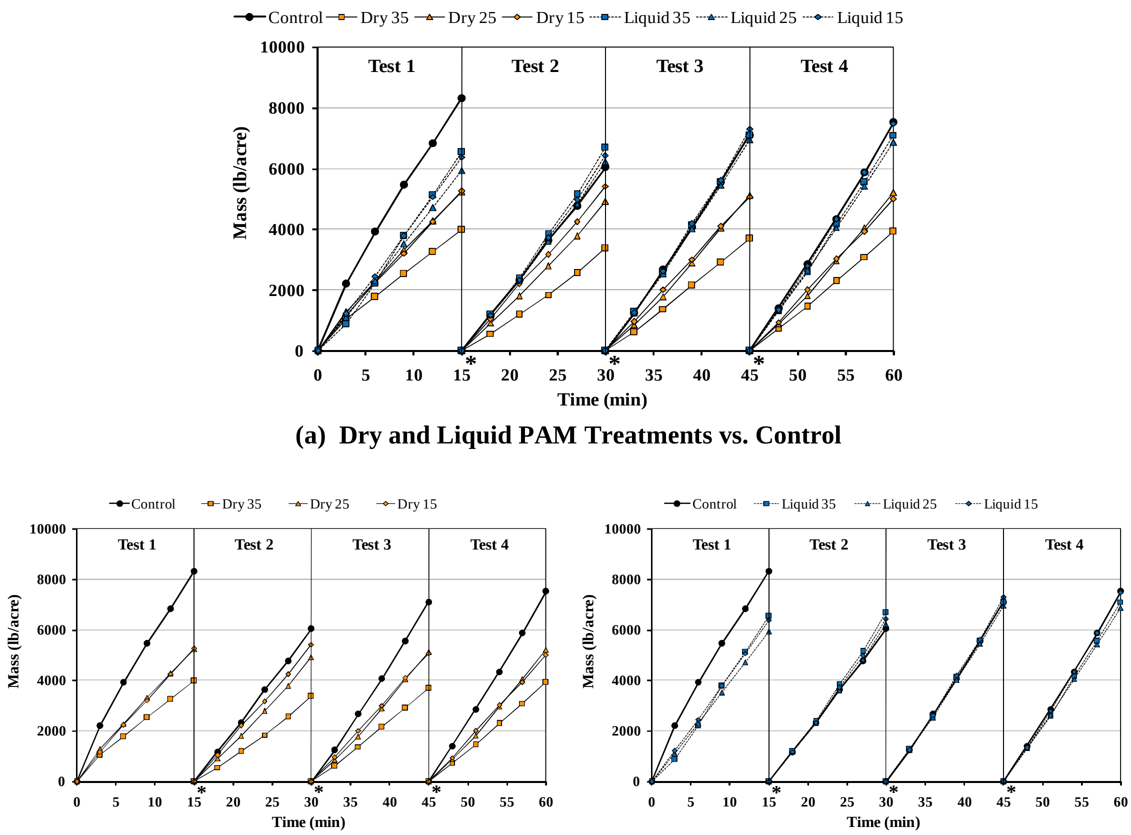


(b) Liquid PAM Treatments

Note: **'*'** denotes 15 minute break in between tests [*applies to all figures*]

Figure 4.7 Average Soil Loss versus Time.

Figure 4.8 illustrates the cumulative amount of eroded soil during each 15 minute rain event. Dry PAM applied at 35 lbs/acre produced less total sediment for each test when compared to all other treatments. All three of the different application rates of dry PAM remained constant during an experiment, maintaining a relatively consistent level of protection. The effectiveness of liquid PAM treatments during test 1 can be observed in Figure 4.8. However, subsequent tests show that the liquid PAM treatments produced quantities of eroded soil comparative to that of the control, bringing into question the effectiveness of liquid PAM's long term potential.



(a) Dry and Liquid PAM Treatments vs. Control

(b) Dry PAM Treatments

(b) Liquid PAM Treatments

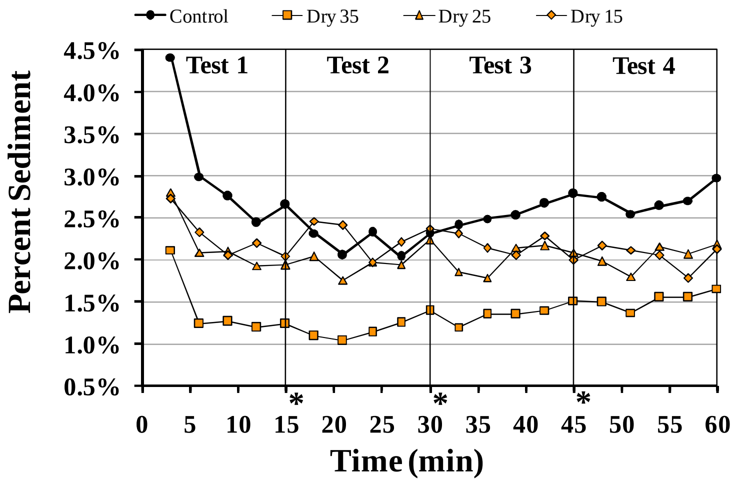
Note: '*' denotes 15 minute break in between tests [*applies to all figures*]

Figure 4.8 Average Cumulative Soil Loss vs. Time.

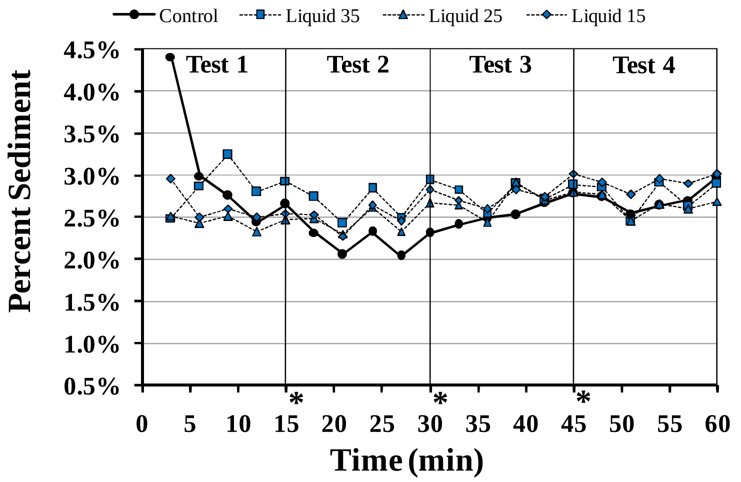
Table 4.14 and Table 4.15 contain the specific values of average soil loss and cumulative soil loss for dry and liquid PAM treatments, respectively. The dry PAM treatments, at 35 lbs/acre, produced on average, less eroded soil at around 700 to 900 lbs/acre for each test. Lower application rates for dry PAM had higher amounts of eroded soil measuring around 1,000 lbs/acre. Liquid PAM treatments saw a higher amount of soil loss, with all treatments producing amounts of soil measuring from around 1,200 to 1,500 lbs/acre.

Dry PAM 35 lbs/acre performed the best among of all PAM treatments by reducing soil loss by about 50% for all tests. Other application rates of dry PAM were capable of reducing soil loss with measurements ranging from 10 to 30% reductions. Liquid PAM treatments saw a similar reduction of soil loss, but only during test 1 (i.e. first 15 min). Tests 2 through 4 showed that liquid PAM treatments had no effect on the amount of eroded soil produced. As was seen with turbidity results, these differences in the amount of eroded soil was attributed to the effectiveness of the dry granules being slowly and consistently dissolved and introduced into the runoff providing long-term performance when compared to liquid PAM treatments.

To further analyze the effect PAM treatments had at reducing erosion, the average recorded amount of eroded soil was compared with its corresponding runoff sample to generate ‘percent sediment’, as illustrated in Figure 4.9(a) and (b) for dry and liquid PAM treatments, respectively. This percent sediment shows the amount of sediment contained within a runoff sample during the overall experiment duration when compared to the bare soil condition. The initial surge of sediment is illustrated in these figures, and reaches a steady state around 6 minutes during the first test. As already stated, dry PAM at 35 lbs/acre was observed to perform the best, with collected runoff samples that contained around 1 to 1.5% of sediment. Dry PAM 25 and 15 lbs/acre had sediment levels ranging from 1.75 to 2.25% sediment, which was still observed to be less than recorded with the control. However, liquid PAM treatments appeared to have no effect at reducing the percent of sediment contained within the runoff, with values consistent with the control.



(a) Dry PAM Treatment



(b) Liquid PAM Treatments

Note: '*****' denotes 15 minute break in between tests [*applies to all figures*]

Figure 4.9 Average Percent Sediment in Surface Runoff vs. Time.

Table 4.14 Average Soil Loss due to Surface Runoff [*Dry PAM*]

Condition	Soil Loss [a] (lbs/acre)	Standard Deviation [b] (lbs/acre)	Percent Reduction [c]
	Test 1		
Control	1663.8	693.8	-
Dry 35	798.9	293.5	52.0%
Dry 25	1048.6	300.6	37.0%
Dry 15	1052.8	102.0	36.7%
	Test 2		
Control	1210.6	189.7	-
Dry 35	674.6	262.9	44.3%
Dry 25	982.5	175.0	18.8%
Dry 15	1084.0	149.7	10.5%
	Test 3		
Control	1420.7	236.3	-
Dry 35	740.6	308.2	47.9%
Dry 25	1024.5	206.1	27.9%
Dry 15	1014.9	117.1	28.6%
	Test 4		
Control	1506.5	194.0	-
Dry 35	787.5	334.6	47.7%
Dry 25	1039.6	204.8	31.0%
Dry 15	998.7	92.3	33.7%

Notes: 'a' Average of eroded soil vs. time for each test
'b' Standard deviation for average soil loss vs. time
'c' Denotes values normalized by control condition

Table 4.15 Average Soil Loss due to Surface Runoff [*Liquid PAM*]

Condition	Soil Loss [a] (lbs/acre)	Standard Deviation [b] (lbs/acre)	Percent Reduction [c]
	Test 1		
Control	1663.8	693.8	-
Liquid 35	1307.2	377.5	21.4%
Liquid 25	1185.4	230.8	28.8%
Liquid 15	1276.6	178.0	23.3%
	Test 2		
Control	1210.6	189.7	-
Liquid 35	1337.9	322.9	-10.5%
Liquid 25	1243.6	172.7	-2.7%
Liquid 15	1284.4	145.9	-6.1%
	Test 3		
Control	1420.7	236.3	-
Liquid 35	1419.5	256.0	0.1%
Liquid 25	1390.7	172.0	2.1%
Liquid 15	1463.3	205.8	-3.0%
	Test 4		
Control	1506.5	194.0	-
Liquid 35	1421.9	233.5	5.6%
Liquid 25	1372.7	147.8	8.9%
Liquid 15	1496.9	185.4	0.6%

Notes: 'a' Average of eroded soil vs. time for each test
'b' Standard deviation for average soil loss vs. time
'c' Denotes values normalized by control condition

4.2.4.1 Statistical Analysis: Soil Loss

Continuing the statistical analyses used throughout this research, ANOVA procedures with a Tukey-Kramer multiple comparisons were used for the recorded amounts of soil loss. Statistically significant results are reported in bold in Table 4.16 through Table 4.19.

During test 1, only dry PAM at 35 lbs/acre produced statistically significant results when compared in comparison to the control, as illustrated in Table 4.16. In addition to being statistically significant to the control, dry PAM at 35 lbs/acre was determined to be significant when compared to all three applications of liquid PAM. This indicates that dry PAM at 35 lbs/acre outperformed liquid treatments for test 1. As experimental duration increases through tests 2, 3, and 4, dry PAM at 25 and 15 lbs/acre are observed to be statistically significant. This delay in effectiveness observed with dry PAM 25 and 15 could be attributed to a longer required time for treatments to reach necessary levels of PAM concentrations capable of reducing soil loss and sedimentation. Test plots treated with 35 lbs/acre of PAM had higher amounts of PAM applied, resulting in more product available for reducing erosion and sedimentation. Therefore, lower application rates of PAM required more time to become active and provide a level of effectiveness. Differences were also observed between the lower rates of dry PAM when compared to the liquid PAM treatments in later tests, indicating that even the lower rates of dry PAM were capable of outperforming liquid PAM. For all test conducted, no statistical significance between liquid PAM treatments and the bare soil condition was observed with respect to soil loss.

Table 4.16 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 1*]

Comparison	μ_i - μ_j	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**386.5**	**127.1**	**386.5**	**Yes**
Control vs. Dry 25	132.6	-126.8	132.6	No
Control vs. Dry 15	136.8	-122.6	136.8	No
Control vs. Liquid 35	121.8	-137.6	121.8	No
Control vs. Liquid 25	91.2	-168.2	91.2	No
Control vs. Liquid 15	0.0	-259.5	0.0	No
Dry 35 vs. Dry 25	253.9	-5.6	253.9	No
Dry 35 vs. Dry 15	249.7	-9.8	249.7	No
Dry 35 vs. Liquid 35	**508.4**	**248.9**	**508.4**	**Yes**
Dry 35 vs. Liquid 25	**477.8**	**218.3**	**477.8**	**Yes**
Dry 35 vs. Liquid 15	**386.5**	**127.1**	**386.5**	**Yes**
Dry 25 vs. Dry 15	4.2	-255.3	4.2	No
Dry 25 vs. Liquid 35	254.5	-5.0	254.5	No
Dry 25 vs. Liquid 25	223.9	-35.6	223.9	No
Dry 25 vs. Liquid 15	132.6	-126.8	132.6	No
Dry 15 vs. Liquid 35	258.7	-0.8	258.7	No
Dry 15 vs. Liquid 25	228.1	-31.4	228.1	No
Dry 15 vs. Liquid 15	136.8	-122.6	136.8	No
Liquid 35 vs. Liquid 25	30.6	-228.8	30.6	No
Liquid 35 vs. Liquid 15	121.8	-137.6	121.8	No
Liquid 25 vs. Liquid 15	91.2	-168.2	91.2	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.17 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 2*]

Comparison	μ_i - μ_j	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**569.0**	**352.7**	**569.0**	**Yes**
Control vs. Dry 25	159.7	-56.7	159.7	No
Control vs. Dry 15	**261.1**	**44.8**	**261.1**	**Yes**
Control vs. Liquid 35	94.2	-122.1	94.2	No
Control vs. Liquid 25	40.8	-175.5	40.8	No
Control vs. Liquid 15	0.0	-216.3	0.0	No
Dry 35 vs. Dry 25	**409.3**	**193.0**	**409.3**	**Yes**
Dry 35 vs. Dry 15	**307.9**	**91.6**	**307.9**	**Yes**
Dry 35 vs. Liquid 35	**663.2**	**446.9**	**663.2**	**Yes**
Dry 35 vs. Liquid 25	**609.8**	**393.5**	**609.8**	**Yes**
Dry 35 vs. Liquid 15	**569.0**	**352.7**	**569.0**	**Yes**
Dry 25 vs. Dry 15	101.4	-114.9	101.4	No
Dry 25 vs. Liquid 35	**253.9**	**37.5**	**253.9**	**Yes**
Dry 25 vs. Liquid 25	200.5	-15.9	200.5	No
Dry 25 vs. Liquid 15	159.7	-56.7	159.7	No
Dry 15 vs. Liquid 35	**355.3**	**139.0**	**355.3**	**Yes**
Dry 15 vs. Liquid 25	**301.9**	**85.6**	**301.9**	**Yes**
Dry 15 vs. Liquid 15	**261.1**	**44.8**	**261.1**	**Yes**
Liquid 35 vs. Liquid 25	53.4	-162.9	53.4	No
Liquid 35 vs. Liquid 15	94.2	-122.1	94.2	No
Liquid 25 vs. Liquid 15	40.8	-175.5	40.8	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

Table 4.18 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**650.0**	**421.6**	**650.0**	**Yes**
Control vs. Dry 25	**375.7**	**147.3**	**375.7**	**Yes**
Control vs. Dry 15	**366.1**	**137.7**	**366.1**	**Yes**
Control vs. Liquid 35	28.8	-199.6	28.8	No
Control vs. Liquid 25	72.6	-155.8	72.6	No
Control vs. Liquid 15	0.0	-228.5	0.0	No
Dry 35 vs. Dry 25	**274.3**	**45.8**	**274.3**	**Yes**
Dry 35 vs. Dry 15	**283.9**	**55.4**	**283.9**	**Yes**
Dry 35 vs. Liquid 35	**678.8**	**450.4**	**678.8**	**Yes**
Dry 35 vs. Liquid 25	**722.6**	**494.2**	**722.6**	**Yes**
Dry 35 vs. Liquid 15	**650.0**	**421.6**	**650.0**	**Yes**
Dry 25 vs. Dry 15	9.6	-218.8	9.6	No
Dry 25 vs. Liquid 35	**404.5**	**176.1**	**404.5**	**Yes**
Dry 25 vs. Liquid 25	**448.4**	**219.9**	**448.4**	**Yes**
Dry 25 vs. Liquid 15	**375.7**	**147.3**	**375.7**	**Yes**
Dry 15 vs. Liquid 35	**394.9**	**166.5**	**394.9**	**Yes**
Dry 15 vs. Liquid 25	**438.7**	**210.3**	**438.7**	**Yes**
Dry 15 vs. Liquid 15	**366.1**	**137.7**	**366.1**	**Yes**
Liquid 35 vs. Liquid 25	43.8	-184.6	43.8	No
Liquid 35 vs. Liquid 15	28.8	-199.6	28.8	No
Liquid 25 vs. Liquid 15	72.6	-155.8	72.6	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

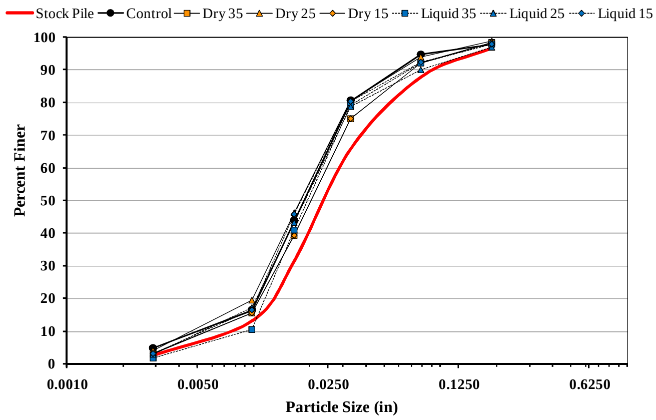
Table 4.19 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 4*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**585.2**	**406.8**	**585.2**	**Yes**
Control vs. Dry 25	**373.9**	**195.6**	**373.9**	**Yes**
Control vs. Dry 15	**333.1**	**154.7**	**333.1**	**Yes**
Control vs. Liquid 35	49.2	-129.2	49.2	No
Control vs. Liquid 25	124.2	-54.1	124.2	No
Control vs. Liquid 15	0.0	-178.4	0.0	No
Dry 35 vs. Dry 25	**211.3**	**32.9**	**211.3**	**Yes**
Dry 35 vs. Dry 15	**252.1**	**73.7**	**252.1**	**Yes**
Dry 35 vs. Liquid 35	**634.4**	**456.0**	**634.4**	**Yes**
Dry 35 vs. Liquid 25	**709.4**	**531.1**	**709.4**	**Yes**
Dry 35 vs. Liquid 15	**585.2**	**406.8**	**585.2**	**Yes**
Dry 25 vs. Dry 15	40.8	-137.6	40.8	No
Dry 25 vs. Liquid 35	**423.1**	**244.8**	**423.1**	**Yes**
Dry 25 vs. Liquid 25	**498.2**	**319.8**	**498.2**	**Yes**
Dry 25 vs. Liquid 15	**373.9**	**195.6**	**373.9**	**Yes**
Dry 15 vs. Liquid 35	**382.3**	**204.0**	**382.3**	**Yes**
Dry 15 vs. Liquid 25	**457.4**	**279.0**	**457.4**	**Yes**
Dry 15 vs. Liquid 15	**333.1**	**154.7**	**333.1**	**Yes**
Liquid 35 vs. Liquid 25	75.0	-103.3	75.0	No
Liquid 35 vs. Liquid 15	49.2	-129.2	49.2	No
Liquid 25 vs. Liquid 15	124.2	-54.1	124.2	No

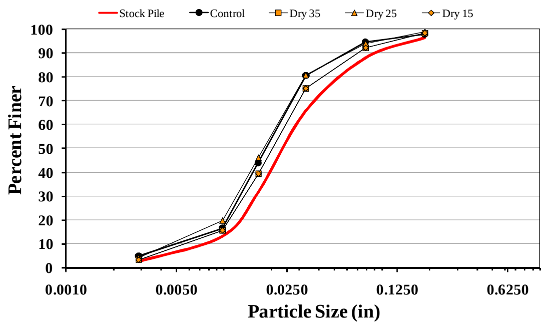
Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.26

4.2.5 Soil Particle Size

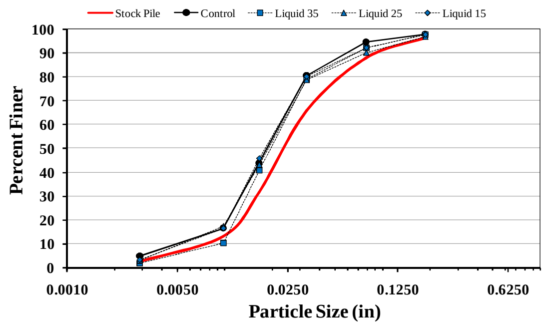
As stated in Section 3.4.1, a particle size analysis was conducted on the soil prior to experimentation. These recorded data were used during the analysis and identification procedures, in addition to comparison with soil particles transported during runoff. This allowed researchers to observe any differences in particle size between the initial soil and soil transported by runoff. Therefore, samples of soil contained within the runoff were taken and resulting particle sizes were determined. These samples of runoff soil were obtained from the oven dried soil used for determining quantities of eroded soil. Figure 4.10(a) illustrates particle size distribution for the initial soil, prior to experimentation (i.e. stock pile soil), and soil contained in the runoff generated during testing. Figure 4.10(b) and 4.10(c) show particles sizes that were determined for dry and liquid PAM treatments, respectively. As seen in Figure 4.10, soil contained within the runoff was smaller in size when compared to the stock pile soil. This was expected, because smaller particles could be more easily detached and transported by runoff. However, there was no appreciable difference observed between PAM treatments and resulting particle sizes, as all recorded particle distributions produced similar values and curves.



(a) Dry and Liquid PAM Treatments vs. Control and Stock Pile Soil



(b) Dry PAM Treatments



(b) Liquid PAM Treatments

Figure 4.10 Average Particle Size Distribution of Stock Pile Soil and Surface Runoff.

4.2.6 Initial Turbidity vs. Soil Loss

To determine if any relationship existed between the average recorded initial turbidity and average measured soil loss, values were plotted together, as demonstrated in Figure 4.11. Initially, it appears that turbidity and soil loss may be linearly related, but distinct groupings of data pertaining to individual treatments were observed. The control condition, with high levels and turbidity and large amounts of eroded soil appear together on the right side of the graph. Conversely, dry PAM at 35 lbs/acre, with recorded low turbidity levels and low soil loss appear on the left. This relationship could be used as a method to determine which treatment was most effective at reducing turbidity and soil loss. Therefore, it was observed that dry PAM at 35 lbs/acre was the most effective treatments for reducing erosion and sedimentation. Other application rates and treatments can be seen in their respective group in relationship to turbidity and soil loss.

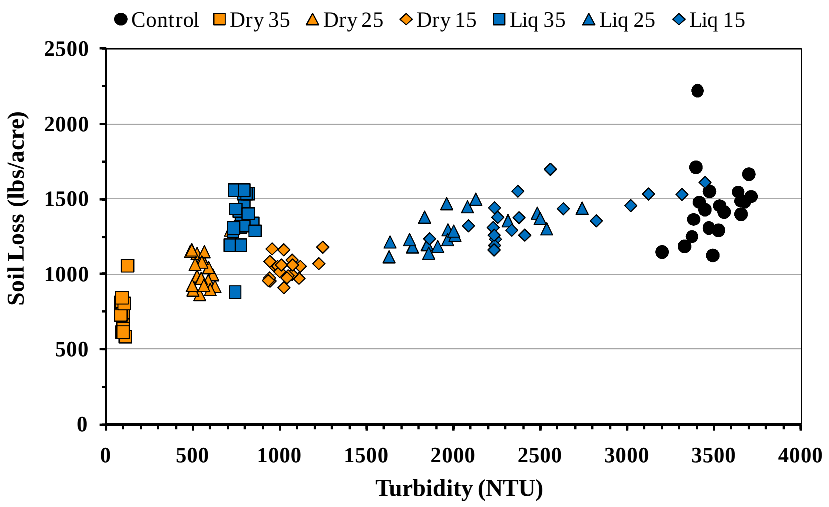


Figure 4.11 Average Initial Turbidity vs. Average Eroded Soil.

4.3 SUMMARY

Data collected from experimentation provided researchers information that was used to evaluate which PAM treatments and application rates were most effective at reducing erosion and sedimentation for this particular test soil. Data that were collected included: (1) surface runoff, (2) initial turbidity, (3) turbidity versus time, (4) soil loss, and (5) particle size distribution. ANOVA procedures were conducted on the data to assist in determining the effect different treatments had and if any statistical significant results were observed.

Runoff samples were collected every minute for all four rain events simulated. These samples were measured to determine volume of surface runoff generated by the rainfall. A total of 1,680 runoff samples were collected and measured during all 14 experiments. Following an ANOVA analysis, it was determined that PAM treatment had no significant results on the amount of runoff generated.

An initial turbidity reading was measured from each of runoff sample collected every minute. Samples were stirred to reflect a condition of runoff as it immediately left a test plot. This produced a total of 1,680 measurements for initial turbidity. When this data was observed, dry PAM at 35 lbs/acre performed the best in reducing turbidity, with calculated reduction of 97% from the control. Initial turbidity readings were observed to increase as the PAM treatment's application rates decreased. Liquid PAM applied at 25 and 15 lbs/acres noticed increases in turbidity during test 4, indicating these treatments were losing their effectiveness.

In addition to recording an initial turbidity, samples were collected from each test at 5 and 10 minutes to measure turbidity over time. This provided researchers with data that showed how treatments performed in reducing turbidity over time. All PAM treatments were observed to reduce the time required for turbidity to decrease when compared to the control, which after 10 minutes had turbidity levels recorded around 500 NTUs. As seen with the initial turbidity recordings, liquid PAM 25 and 15 lbs/acre effectiveness over time also began to decline during test 3 and test 4.

Soil samples were collected every 3 minutes from surface runoff to determine an amount of eroded soil from the test plots. Runoff was filtered and oven dried for 24 hours to show soil loss from each test plot. A total of 560 samples were collected and weighed to determine the eroded soils. Researchers observed that dry PAM at 35 lbs/acre was most effective at reducing soil loss, by 50%. Liquid PAM treatments were only capable of reducing soil loss during the first test, with PAM in subsequent tests performing similarly to the control.

The soil samples which were collected to determine eroded soil were also analyzed to determine particle size distribution. This was compared with previous analyses conducting during the soil classification procedures. Researchers observed that surface runoff contained soil particles that all had similar distributions, which were recorded to be smaller than the stock pile soil, which was recorded earlier. Additionally, no observable difference in particle size distributions existed between PAM treatments when compared to each other.

Overall, it was observed that dry PAM at the recommended application rate of 35 lbs/acre performed the best for reducing erosion and sedimentation. This was observed when analyzing recorded turbidity measurements and the weight of eroded soil transported from each test plots by the surface runoff.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Research presented in this report focused on evaluating the effectiveness of anionic polyacrylamide (PAM) as a temporary erosion control measure. Experiments were established to simulate conditions representative of a typical compacted highway embankments with a fill slope of 3:1. The first task of this research focused on examining the previous experimental procedures established previously by Halverson (2006) and McDonald (2007) and making necessary modifications to improve methods for conducting erosion control experiments. These changes reflected researchers' goal to: (1) design and develop a testing apparatus that will allow for an efficient experimental setup and to achieve reproducible results, (2) design and construct a rainfall simulator that can model realistic rainfall events, and (3) develop a unified testing methodology to obtain reproducible results for the comparison of all possible experiments pertaining to erosion and sediment control best management practices (BMPs).

The second component of this research uses the unified test procedures developed to evaluate the effectiveness of anionic PAM as an erosion control measure. Specific objectives established were to use the newly developed testing procedures to: (1) test various application rates of dry and liquid PAM as an erosion control measure on 3:1 slopes and (2) compare experimental results to provide product recommendations for use of PAM on highway construction sites.

5.2 INTERMEDIATE-SCALE METHODS AND PROCEDURES

A new facility was constructed at the National Center for Asphalt Technology (NCAT) Test Facility for conducting research on erosion and sediment control BMPs. A set of new intermediate-scale test boxes were constructed to streamline the original process that can enable researchers to setup and conduct experiments faster. Overall size of each test plot was reduced and measured approximately 2 ft (0.61 m) wide, 4 ft (1.2 m) long, and a depth of 2 in (5.08 cm) compacted test soil.

Runoff was generated using a newly developed rainfall simulator, designed to address deficiencies identified in previous research. Improvements include: (1) eliminating overlapping spray areas, (2) maintaining a constant water pressure, and (3) developing a more efficient method to shutoff simulated rainfall. Overlapping spray areas were eliminated through designing a one-nozzle rainfall simulator with a uniform spray area. Uniformity was verified using the Christian Uniformity Coefficient and determined that the area consisting of two test plots achieved a uniformity ranging between 84% and 88%. Water pressure within the rainfall simulator was controlled using a pressure regulator, which allowed researchers to simulate different rain events, depending on the internal pressure achieved. Finally, a solenoid valve was added to the design, so water flow in the system could be stopped, preventing any additional water falling on test plots at the conclusion of a test.

The rainfall simulator was set-up to simulate a storm event common to Alabama and was divided into four separate 'tests', which produced approximately 1.10 in. of rainfall, individually. This amount of rainfall coincides with the Alabama Department of Transportation's (ALDOT) inspection guidelines that state that any erosion and sediment control device shall be inspected following an accumulated amount of rainfall measuring 0.75 in. In between each rain event, 15 minute breaks were observed for data collection. The selected rain regime allowed researches to analyze the long-term effectiveness of PAM using a 2-year, 24 hour storm event that produced total rainfall amount of 4.4 in. as experienced in Montgomery, AL.

Additional modifications in experiment preparation included a new method to compact test soil to the required rate of 95%, as established by ALDOT standard specifications. It was determined that using hand-tamps on the test soil, with an OMC of 15%, would achieve the required rate of compaction for the test soil. A turbidity meter was used to record turbidity and could be used during experimentation, rather than collecting samples and measuring turbidity at a later date. The data collected for this research included the mass of surface runoff and particle size distribution for each experiment.

Procedures developed for intermediate-scale experiments allowed researchers to conduct a greater number of experiments and produce large quantities of data for analysis. One control and six different PAM treatments (i.e. dry and liquid PAM at 35, 25, and 15 lbs/acre) conditions were examined. Each one of these experiments was replicated to provide the means for evaluating the effectiveness of experimental procedures by examining the results for reproducible data and validating these new experimental procedures.

5.3 DRY AND LIQUID PAM EROSION CONTROL

Fourteen experiments were conducted to examine two different PAM treatment methods at three application rates (i.e. 35, 25, and 15 lbs/acre). PAM treated test plots were compared with a bare soil control condition. Data that was collected from these experiments included: (1) surface runoff volume and mass, (2) initial turbidity, (3) turbidity versus time, (4) soil loss, and (5) particle size distribution.

An initial turbidity reading was measured from each of runoff sample that was collected every minute. Samples were stirred to reflect a condition of runoff as if it had immediately left a test plot. It was observed that dry PAM at 35 lbs/acre performed the best in reducing turbidity, with a calculated reduction of 97% from the control. Initial turbidity readings were observed to increase as the PAM treatment's application rates decreased. At a point between test 3 and test 4 (i.e. 40 minutes into an experiment), liquid PAM applied at 25 and 15 lbs/acre began to lose its effectiveness in reducing initial turbidity levels.

Additional samples were collected from each test at 5 and 10 minutes to measure turbidity over time. All PAM treatments were observed to reduce the time required for turbidity to decrease when compared to the control, which after 10 minutes had turbidity levels recorded around 500 NTUs. As seen with the initial turbidity recordings, liquid PAM 25 and 15 lbs/acre effectiveness over time also began to wear off during test 3 and test 4. Dry PAM at 35 lbs/acre reached EPA's proposed effluent turbidity requirement of

13 NTU within 20 seconds of measurements. Dry PAM at 25 lbs/acre also reached this limit at 3 minutes, 20 seconds.

Runoff was filtered and oven dried for 24 hours to quantify soil loss from each test plot, every 3 minutes. Researchers observed that dry PAM at 35 lbs/acre was effective in reducing soil loss by 50%. Dry PAM at 25 and 15 lbs/acre, on average, reduced soil loss by 28.7% and 27.4%, respectively. Liquid PAM treatments were only capable of reducing soil loss during the first test, with subsequent tests performing poorly with results similar to the control. This indicates that liquid PAM was incapable of performing consistently over a long period.

The soil samples collected were analyzed to determine their particle size distribution. Researchers observed that all the surface runoff had similar distributions, which contained smaller particle sizes when compared to the stock pile soil distribution. Additionally, no observable difference in particle size distributions occurred between PAM treatments when compared to each other.

The results from this research suggest that dry granular PAM could perform as an effective erosion and sediment control technology, when applied at the recommended application rate. PAM formulations are very site specific and laboratory test must be conducted to determine which formula of PAM will perform the best for a given construction site. These additional tests are usually provided at no additional cost and will provide contractors with the correct type of PAM product for use, with the recommended application rates required. However, PAM is rarely used alone and this research has shown that long-term exposure to rainfall will inhibits the product's effectiveness over time. By using PAM in conjunction with other erosion and sediment control technologies (i.e. erosion control blankets, mulching, etc) would provide the most ideal protection against NPS pollution.

Test plots treated with dry PAM in this research demonstrated that the amount of erosion could be significantly reduced from construction sites with 3:1 compacted file slopes. However, liquid PAM applied did not perform as well when compared to dry PAM. Liquid PAM will only performed effective when the spray coverage is 100% uniform. So the effectiveness of liquid PAM applications is dependent on the quality of applications. Evaluating the turbidity results indicated that both PAM treated test plots were effective in reducing sedimentation in the runoff, with dry PAM at the recommended rate performing the best. This was attributed to how dry PAM granules perform over long periods of time and the way PAM is introduced slowly and consistently into the runoff.

5.4 RECOMMENDED FUTURE RESEARCH

Results presented in this report show that PAM can perform as an effective means in reducing erosion and sedimentation caused by sediment laden runoff. However, PAM is rarely ever used on its own and is more commonly used in conjunction with additional erosion and sediment control BMPs. Therefore, further research should be conducted to examine how the addition of PAM could potential improve existing technologies, such as erosion control blankets (ECBs).

Also, the work conducted during this research effort represents intermediate-scale test plots. It would be beneficial if the performance of PAM was documented under field-scale conditions to validate the intermediate-scale procedures discussed. Also, field-scale experiments could provide additional results to develop recommendations for actual practice. Large-scale test plots could also be used to further the research conducted on ECBs, with and without the addition of PAM. With advantages of conducting experiments at both scales (i.e. intermediate and field), any erosion and sediment control technology could be analyzed thoroughly and performance recommendations could be made for use in practice.

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APPENDICES

Appendix A: Manufacturer's Specifications for Rainfall Simulator Components

Appendix B: Rainfall Intensity-Duration-Frequency Curves for Alabama.

Appendix C: Manufacturer's Specifications for Equipment used during Experimentation

Appendix D: Experimental Results

Appendix E: ANOVA Tables

Appendix F: Further Research on Liquid PAM

APPENDIX A

MANUFACTURER’S SPECIFICATIONS FOR

RAINFALL SIMULATOR COMPONENTS

R43

Water and Compressed Air Service Pressure Regulator 1/4", 3/8" and 1/2" Port Sizes

- Non-relieving models
- Brass body, corrosion resistant construction
- Balanced valve minimizes effects of inlet pressure variations on outlet pressure
- T-bar adjustment standard, nonrising knob adjustment optional
- Full flow gauge ports can be used as auxiliary outlets
- Panel mounting nut standard
- Can be disassembled without the use of tools or removal from the air or water line.

Ordering Information. Models listed have T-handle adjustment, 5 to 125 psig (0.3 to 8.5 bar) outlet pressure adjustment range*, and PTF threads. A gauge is not included.

Port	Model	Flow† U.S. gpm (lpm)	Weight lb (kg)
1/4"	R43-201-NNLA	6 (23)	2.4 (1.09)
3/8"	R43-301-NNLA	6 (23)	2.4 (1.09)
1/2"	R43-406-NNLA	9 (34)	2.4 (1.09)

Alternative Models

R43 - ★★★ - ★★★★

Port Size	Substitute
1/4"	2
3/8"	3
1/2"	4

Adjustment	Substitute
Knob	00
T-handle with 1/4" and 3/8" ports	01
T-handle with 1/2" ports	06

Diaphragm	Substitute
Non relieving	N

Threads	Substitute
PTF	A
ISO Rc taper	B
ISO G parallel	G

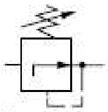
Outlet Pressure Adjustment Range*	Substitute
5 to 50 psig (0.3 to 3.5 bar)	E
5 to 125 psig (0.3 to 8.6 bar)	L
15 to 250 psig (1 to 17 bar)	S

Gauges	Substitute
With	G
Without	N

* Outlet pressure can be adjusted to pressures in excess of, and less than, those specified. Do not use these units to control pressures outside of the specified ranges.

† Typical flow with 150 psig (10 bar) inlet pressure, 90 psig (6.3 bar) set pressure and 15 psig (1 bar) droop from set.

ISO Symbols



Non relieving

See Section ALE-25 for Accessories

Pressure Regulator

ASCO RedHat

Pilot Operated
General Service Solenoid Valves
Brass or Stainless Steel Bodies
3/8" to 2 1/2" NPT

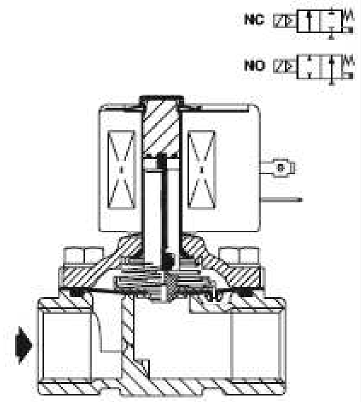
2/2 SERIES 8210 2-WAY

Features

- Wide range of pressure ratings, sizes, and resilient materials provide long service life and low internal leakage
- High Flow Valves for liquid, corrosive, and air/inert gas service
- Industrial applications include:
  - Car wash
  - Laundry equipment
  - Air compressors
  - Industrial water control
  - Pumps

Construction

Valve Parts in Contact with Fluids		
Body	Brass	304 Stainless Steel
Seals and Discs	NBR or PTFE	
Disc-Holder	PA	
Core Tube	305 Stainless Steel	
Core and Plugnut	430F Stainless Steel	
Springs	302 Stainless Steel	
Shading Coil	Copper	Silver



Electrical

Standard Coil and Class of Insulation	Watt Rating and Power Consumption				Spare Coil Part Number			
	DC	AC			General Purpose		Explosionproof	
	DC Watts	Watts	VA Holding	VA Inrush	AC	DC	AC	DC
F	-	6.1	16	40	238210	-	238214	-
F	11.6	10.1	25	70	238610	238710	238614	238714
F	16.8	16.1	35	180	272610	97617	272614	97617
F	-	17.1	40	93	238610	-	238614	-
F	-	20	43	240	99257	-	99257	-
F	-	20.1	48	240	272610	-	272614	-
H	30.6	-	-	-	-	74073	-	74073
H	40.6	-	-	-	-	238910	-	238914

Standard Voltages: 24, 120, 240, 480 volts AC, 60 Hz (or 110, 220 volts AC, 50 Hz). 6, 12, 24, 120, 240 volts DC. Must be specified when ordering. Other voltages available when required.

Nominal Ambient Temp. Ranges

RedHat II/ RedHat AC: 32°F to 125°F (0°C to 52°C)

RedHat II DC: 32°F to 104°F (0°C to 40°C)
RedHat DC: 32°F to 77°F (0°C to 25°C) (104°F/40°C occasionally)

Refer to Engineering Section for details.

Solenoid Enclosures

Standard: RedHat II - Watertight, Types 1, 2, 3, 3S, 4, and 4X; RedHat - Type I.

Optional: RedHat II - Explosionproof and Watertight, Types 3, 3S, 4, 4X, 6, 6P, 7, and 9; Red-Hat - Explosionproof and Watertight, Types 3, 4, 4X, 7, and 9.

(To order, add prefix "EF" to catalog number, except Catalog Numbers 8210B057, 8210B058, and 8210B059, which are not available with Explosionproof enclosures.)

See Optional Features Section for other available options.

Approvals

CSA certified. RedHat II meets applicable CE directives.

Refer to Engineering Section for details.

Solenoid Valve (a)

Specifications (English units)

Pipe Size (Ins.)	Orifice Size (Ins.)	Cv Flow Factor	Operating Pressure Differential (psi) Min.	Max. AC Air-Inert Gas	Max. AC Water	Max. AC Light Oil @ 300 SSU	Max. DC Air-Inert Gas	Max. DC Water	Max. DC Light Oil @ 300 SSU	Max. Fluid Temp. °F AC	Max. Fluid Temp. °F DC	Brass Body Catalog Number	Brass Body Const. Ref. ④	Brass Body UL ⑤ Listing	Stainless Steel Body Catalog Number	Stainless Steel Body Const. Ref. ④	Stainless Steel Body UL ⑤ Listing	Watt Rating/ Class of Coil Insulation ⑦ AC	Watt Rating/ Class of Coil Insulation ⑦ DC
NORMALLY CLOSED (Closed when de-energized), NBR or PTFE ② Sealing																			
3/8	3/8	1.5	①	150	125	-	40	40	-	180	150	8210G073 ③	1P	●	8210G036 ③	1P	●	6.1/F	11.6/F
3/8	5/8	3	0	150	150	-	40	40	-	180	150	8210G093	5D	○	-	-	-	10.1/F	11.6/F
3/8	5/8	3	5	200	150	135	125	100	100	180	150	8210G001	6D	○	-	-	-	6.1/F	11.6/F
3/8	5/8	3	5	300	300	300	-	-	-	175	-	8210G006	5D	○	-	-	-	17.1/F	-
1/2	7/16	2.2	①	150	125	-	40	40	-	180	150	8210G015 ③	2P	●	8210G037 ③	2P	●	6.1/F	11.6/F
1/2	5/8	4	0	150	150	-	40	40	-	180	150	8210G094	5D	○	-	-	-	10.1/F	11.6/F
1/2	5/8	4	0	150	150	125	40	40	-	175	150	-	-	-	8210G087	7D	●	17.1/F	11.6/F
1/2	5/8	4	5	200	150	135	125	100	100	180	150	8210G002	6D	○	-	-	-	6.1/F	11.6/F
1/2	5/8	4	5	300	300	300	-	-	-	175	-	8210G007	5D	○	-	-	-	17.1/F	-
1/2	3/4	4	5	-	300	-	-	300	-	180	125	8210G227	5D	○	-	-	-	17.1/F	40.6/H
3/4	5/8	4.5	0	150	150	125	40	40	-	175	150	-	-	-	8210G088	7D	●	17.1/F	11.6/F
3/4	3/4	5	5	125	125	125	100	90	75	180	150	8210G009	9D	○	-	-	-	6.1/F	11.6/F
3/4	3/4	5	0	150	150	-	40	40	-	180	150	8210G095	8D	○	-	-	-	10.1/F	11.6/F
3/4	3/4	6.5	5	250	150	100	125	125	125	180	150	8210G003	11D	○	-	-	-	6.1/F	11.6/F
3/4	3/4	6	0	-	-	-	200	180	180	-	77	8210B026 ② ‡	10P	-	-	-	-	-	30.6/H
3/4	3/4	6	0	350	300	200	-	-	-	200	-	8210G026 ② ‡	40P	●	-	-	-	16.1F	-
1	1	13	0	-	-	-	100	100	80	-	77	8210B054 ‡	31D	-	8210D089	15D	-	-	30.6/H
1	1	13	0	150	125	125	-	-	-	180	-	8210G054	41D	●	8210G089	45D	●	16.1/F	-
1	1	13	5	150	150	100	125	125	125	180	150	8210G004	12D	○	-	-	-	6.1/F	11.6/F
1	1	13.5	0	300	225	115	-	-	-	200	-	8210G027 ‡	42P	●	-	-	-	20.1/F	-
1	1	13.5	10	300	300	300	-	-	-	175	-	8210G078 ②	13P	-	-	-	-	17.1/F	-
1 1/4	1 1/8	15	0	-	-	-	100	100	80	-	77	8210B055 ‡	32D	-	-	-	-	-	30.6/H
1 1/4	1 1/8	15	0	150	125	125	-	-	-	180	-	8210G055	43D	●	-	-	-	16.1/F	-
1 1/4	1 1/8	15	5	150	150	100	125	125	125	180	150	8210G008	16D	○	-	-	-	6.1/F	11.6/F
1 1/2	1 1/4	22.5	0	-	-	-	100	100	80	-	77	8210B056 ‡	33D	-	-	-	-	-	30.6/H
1 1/2	1 1/4	22.5	0	150	125	125	-	-	-	180	-	8210G056	44D	●	-	-	-	16.1/F	-
1 1/2	1 1/4	22.5	5	150	150	100	125	125	125	180	150	8210G022	18D	●	-	-	-	6.1/F	11.6/F
2	1 3/4	43	5	150	125	90	50	50	50	180	150	8210G100	20P	●	-	-	-	6.1/F	11.6/F
2 1/2	1 3/4	45	5	150	125	90	50	50	50	180	150	8210G101	21P	●	-	-	-	6.1/F	11.6/F
NORMALLY OPEN (Open when de-energized), NBR Sealing (PA Disc-Holder, except as noted)																			
3/8	5/8	3	0	150	150	125	125	125	80	180	150	8210G033	23D	●	-	-	-	10.1/F	11.6/F
3/8	5/8	3	5	250	200	200	250	200	200	180	180	8210G011 ⑧ ⑨	39D	●	-	-	-	10.1/F	11.6/F
1/2	5/8	4	0	150	150	125	125	125	80	180	150	8210G034	23D	●	-	-	-	10.1/F	11.6/F
1/2	5/8	3	0	150	150	100	125	125	80	180	150	-	-	-	8210G030	37D	●	10.1/F	11.6/F
1/2	5/8	4	5	250	200	200	250	200	200	180	180	8210G012 ⑧ ⑨	39D	●	-	-	-	10.1/F	11.6/F
3/4	3/4	5.5	0	150	150	125	125	125	80	180	150	8210G035	25D	●	-	-	-	10.1/F	11.6/F
3/4	5/8	3	0	150	150	100	125	125	80	180	150	-	-	-	8210G038	38D	●	10.1/F	11.6/F
3/4	3/4	6.5	5	-	-	-	250	200	200	-	180	8210D013	24D	●	-	-	-	-	16.8/F
3/4	3/4	6.5	5	250	200	200	-	-	-	180	-	8210G013	46D	●	-	-	-	16.1/F	-
1	1	13	0	125	125	125	-	-	-	180	-	8210B057 ⑨ ⑩	34D	●	-	-	-	20/F	-
1	1	13	5	-	-	-	125	125	125	-	180	8210D014	26D	●	-	-	-	-	16.8/F
1	1	13	5	150	150	125	-	-	-	180	-	8210G014	47D	●	-	-	-	16.1/F	-
1 1/4	1 1/8	15	0	125	125	125	-	-	-	180	-	8210B058 ⑨ ⑩	35D	●	-	-	-	20/F	-
1 1/4	1 1/8	15	5	-	-	-	125	125	125	-	180	8210D018	28D	●	-	-	-	-	16.8/F
1 1/4	1 1/8	15	5	150	150	125	-	-	-	180	-	8210G018	48D	●	-	-	-	16.1/F	-
1 1/2	1 1/4	22.5	0	125	125	125	-	-	-	180	-	8210B059 ⑨ ⑩	36D	●	-	-	-	20/F	-
1 1/2	1 1/4	22.5	5	-	-	-	125	125	125	-	180	8210D032	29D	●	-	-	-	-	16.8/F
1 1/2	1 1/4	22.5	5	150	150	125	-	-	-	180	-	8210G032	49D	●	-	-	-	16.1/F	-
2	1 3/4	43	5	-	-	-	125	125	125	-	150	8210 103	30P	●	-	-	-	-	16.8/F
2	1 3/4	43	5	125	125	125	-	-	-	180	-	8210G103	50P	●	-	-	-	16.1/F	-
2 1/2	1 3/4	45	5	-	-	-	125	125	125	-	150	8210 104	27P	●	-	-	-	-	16.8/F
2 1/2	1 3/4	45	5	125	125	125	-	-	-	180	-	8210G104	51P	●	-			16.1/F	-

① 5 psi on Air; 1 psi on Water.
② Valve provided with PTFE main disc.
③ Valve includes Ultem (G.E. trademark) piston.
④ Letter "D" denotes diaphragm construction; "P" denotes piston construction.
⑤ ○ Safety Shutoff Valve; ● General Purpose Valve.
Refer to Engineering Section (Approvals) for details.
⑥ Valves not available with Explosionproof enclosures.
⑦ On 50 hertz service, the watt rating for the 6.1/F solenoid is 8.1 watts.
⑧ AC construction also has PA seating.
⑨ No disc-holder.
⑩ Stainless steel disc-holder.
‡ Must have solenoid mounted vertical and upright.

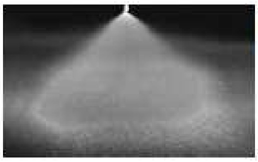
Solenoid Valve (b)

B

FULL CONE NOZZLES

FullJet® Spray Nozzles • Wide Angle Square Spray

Small Capacity



HH-WSQ

One-piece body
1/4"-1/2" NPT or BSPT (M)

DESIGN FEATURES

Wide angle square spray FullJet nozzles feature a solid cone-shaped spray pattern with a square impact area and spray angles of 93° to 110°.

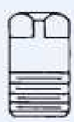
Their uniform spray distribution of medium to large drops is the result of the unique FullJet nozzle vane design, exacting internal proportions, and precision machining. The nozzles are ideal for installations requiring uniform coverage of rectangular and/or square areas.

PERFORMANCE DATA

Nozzle Inlet Conn. NPT or BSPT (M)	Capacity Size	Orifice Dia. Nom.	Max. Free Passage Dia.*	Capacity (gallons per minute)									Spray Angle		
				5 psi	7 psi	10 psi	15 psi	20 psi	30 psi	40 psi	60 psi	80 psi	5 psi	10 psi	80 psi
1/4	14WSQ	.141"	.063"	1.0	1.2	1.4	1.7	1.9	2.3	2.6	3.1	3.5	99°	101°	93°
3/8	17WSQ	.156"	.063"	1.3	1.5	1.7	2.0	2.3	2.8	3.1	3.7	4.2	99°	101°	93°
	20WSQ	.172"	.094"	1.5	1.7	2.0	2.4	2.7	3.2	3.7	4.4	5.0	104°	110°	94°
	24WSQ	.188"	.094"	1.8	2.1	2.4	2.9	3.3	3.9	4.4	5.3	6.0	104°	110°	94°
	27WSQ	.203"	.109"	2.0	2.3	2.7	3.2	3.7	4.4	5.0	5.9	6.7	104°	110°	98°
1/2	30WSQ	.219"	.109"	2.2	2.6	3.0	3.6	4.1	4.9	5.5	6.6	7.5	104°	110°	102°
	35WSQ	.234"	.125"	2.6	3.0	3.5	4.2	4.8	5.7	6.4	7.7	8.7	104°	110°	102°
	40WSQ	.250"	.125"	3.0	3.4	4.0	4.8	5.4	6.5	7.4	8.8	10.0	104°	110°	102°
	45WSQ	.250"	.141"	3.3	3.9	4.5	5.4	6.1	7.3	8.3	9.9	11.2	104°	110°	102°
	50WSQ	.266"	.156"	3.7	4.3	5.0	6.0	6.8	8.1	9.2	11.0	12.5	104°	110°	102°

* Foreign matter with maximum diameter as listed can pass through nozzle without clogging.

DIMENSIONS & WEIGHTS

HH-WSQ	Nozzle Inlet Conn. NPT or BSPT (M)	Length	Dia.	Net Weight
	1/4	29/32"	17/32"	1/2 oz.
	3/8	1-3/16"	21/32"	1 oz.
	1/2	1-3/8"	13/16"	1-1/2 oz.

Based on largest/heaviest version of each type.

ORDERING INFO

STANDARD SPRAY NOZZLE

1/4 HH – SS 14WSQ

1/4 = Inlet Conn.; HH = Nozzle Type; SS = Material Code; 14WSQ = Capacity Size

MATERIALS

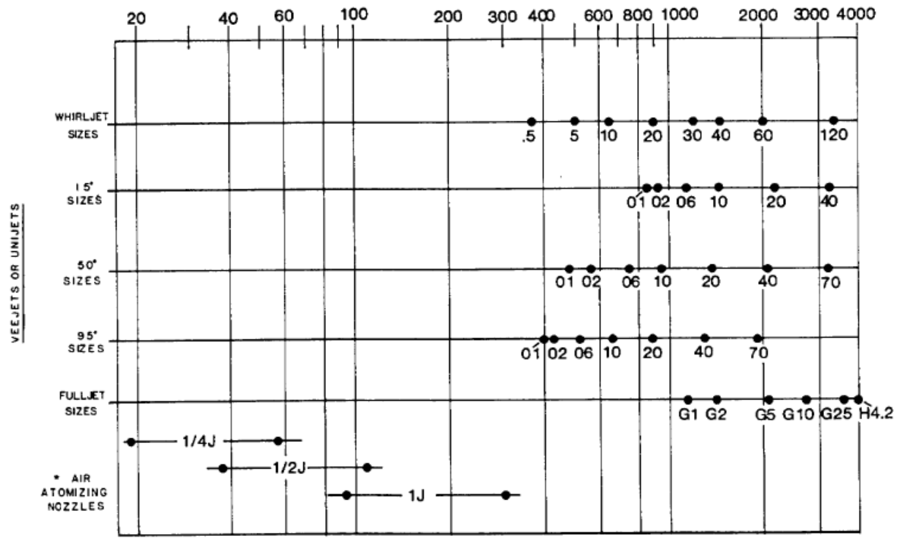
Material	Material Code	Nozzle Type HH-WSQ
Brass	(none)	•
Mild Steel	I	•
303 Stainless Steel	SS	•
316 Stainless Steel	316SS	•
Polyvinyl Chloride	PVC	•

Other materials available upon request.

Rainfall Simulator Nozzle

ESTIMATED M.V.D. PARTICLE SIZE-(MICRONS)-FOR STANDARD SSCO NOZZLES

(Nozzles spraying water at 10 PSIG at room temperature under laboratory conditions)



PARTICLE SIZE RANGE (MICRONS) MEDIAN VOLUME	COMPARATIVE SUBJECT IN PARTICLE SIZE	TIME FOR PARTICLE TO FALL 10 FEET (SECONDS)
5000 to 2000	Heavy Rain	0.85 0.9
2000 to 1000	Intense Rain	0.9 1.1
1000 to 500	Moderate Rain	1.1 1.6
500 to 100	Light Rain	1.6 11
100 to 50	Misty Rain	11 40
50 to 10	Wet Fog	40 1020
10 to 2.0	Dry Fog	1020 25400
1.0 to .01	Fumes	Suspended** in air
.01 to .001	Smoke	Suspended** in air
Below .001	Molecular Dimensions	-

M.V.D. particle size data is based on volumetric measurements where 50% of the liquid sprayed is in drops smaller than the given number and 50% of the liquid is in drops larger than the given number.

EXAMPLE: To determine the approximate M.V.D. of a 5010 Veejet Nozzle:

1. Find 50°--series line for Veejets.
2. Locate--10 position in row of dots.
3. Read the particle diameter directly from the scale above.

Answer: 940 Microns (approx.)

*Air Atomizing Nozzle particle size ranges shown are generalized only. for more specific information, please write Wheaton.

Data is based on spraying water under laboratory conditions using Spraying Systems Co. Imaging Particle Analyzer.

One Micron = 1/25400 of an inch
25.4 Microns = .001" (one thousandth of an inch)
1000 Microns = 1 millimeter

**Below 0.1 microns, particles are suspended in air due to molecular shock (Brownian Motion)

DESCRIPTION

COMPARATIVE PARTICLE SIZE DATA FOR SSCO SPRAY NOZZLES AND RAIN DROP PARTICLE SIZE TAB. (10 P.S.I.)

SPRAYING SYSTEMS CO.
Engineers and Manufacturers
NORTH AVENUE AT SCHMALE ROAD WHEATON, ILL.

DR. BY K.S. | DATE 10/29/81 | DWG. NO. 13911-2

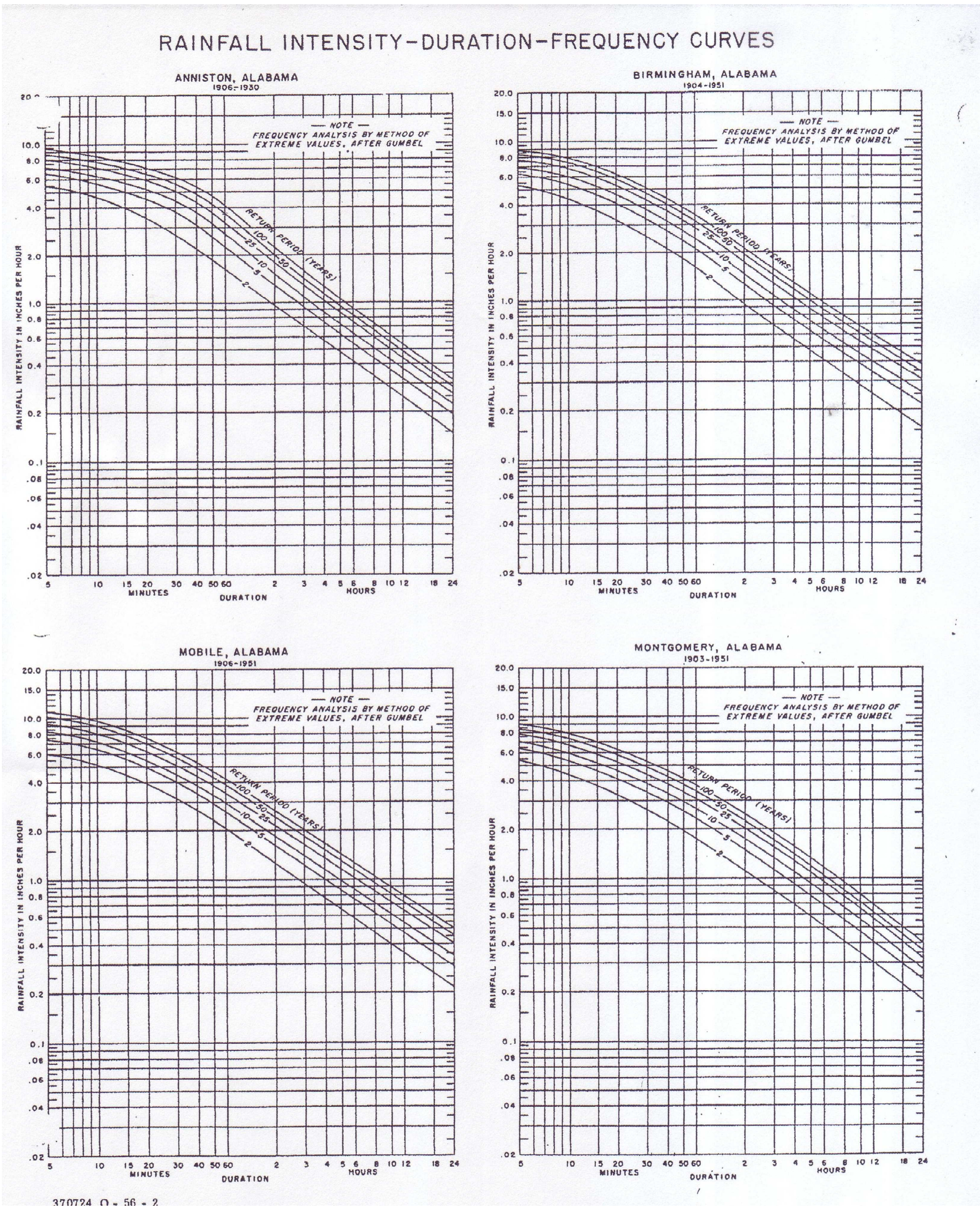
S-B

Raindrop Sizes

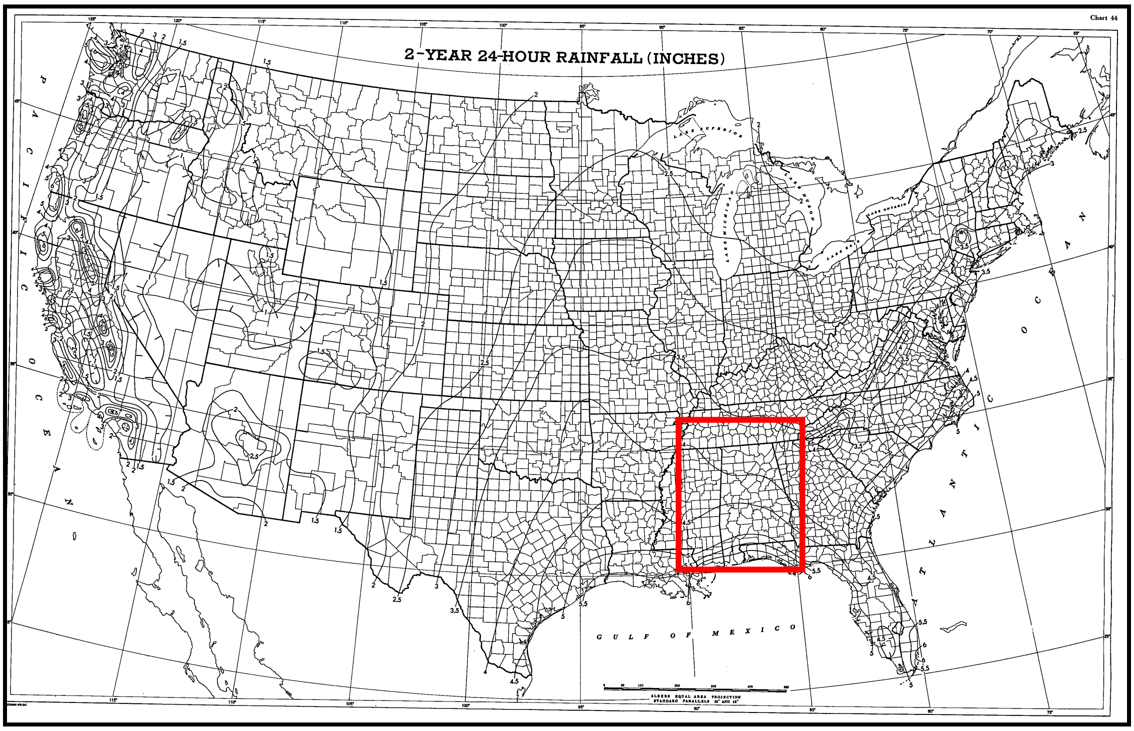
APPENDIX B

RAINFALL INTENSITY-DURATION-FREQUENCY CURVES

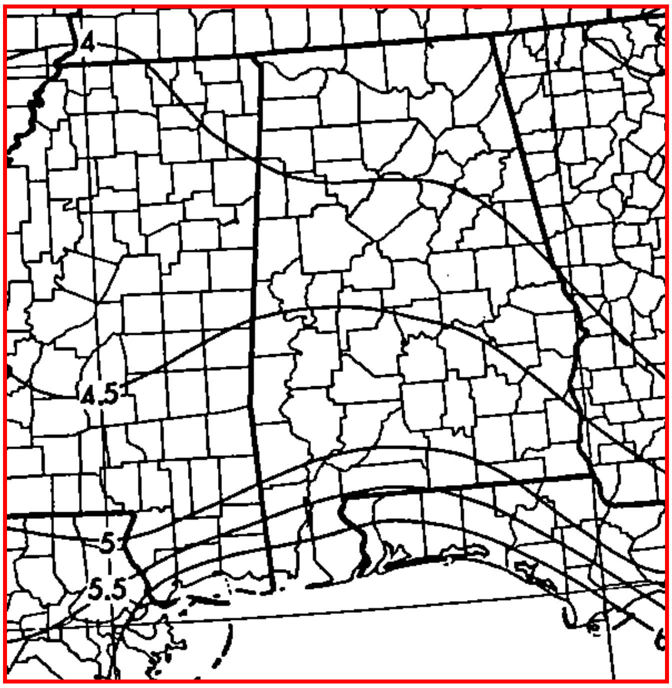
FOR ALABAMA.



IDF Curves for Alabama



(a) 2-yr, 24-hr Cumulative rainfall for the United States



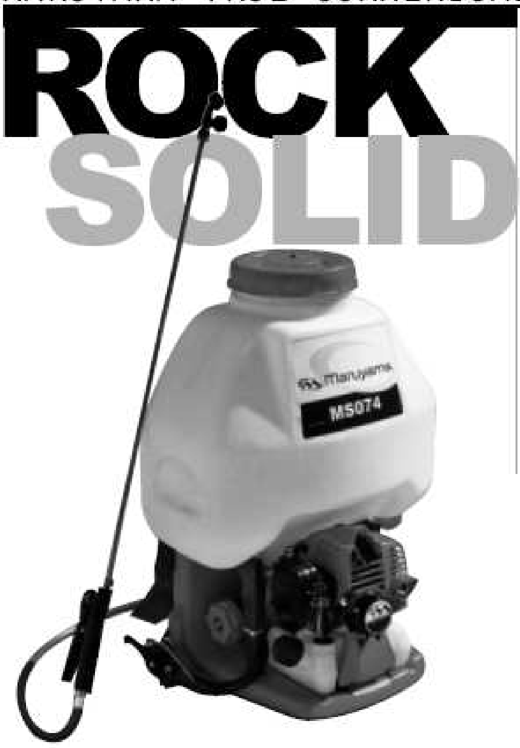
(b) 2-yr, 24-hr Cumulative rainfall for Alabama

APPENDIX C

MANUFACTURER'S SPECIFICATIONS FOR EQUIPMENT

USED DURING EXPERIMENTATION

MARUYAMA TRUE COMMERICAL OUTDOOR POWER EQUIPMENT



COMPACT POWER SPRAYERS
LOW PRESSURE EXTREME-DUTY

1. Driven by commercial-grade, high performance, low weight engines. 2. The superior quality, positive displacement duplex piston pump provides remarkable performance and extreme durability, up to 1.9 gallons per minute volume at 356 psi. 3. A wide variety of optional nozzles, wands, extensions, guns and booms offer extraordinary flexibility and productivity. 4. Compact, highly portable designs. 5. Five year commercial warranty.

MARUYAMA IRON 5 YEAR COMMERCIAL WARRANTY

SPECIFICATIONS

MODEL	MS074	MS072EH
ENGINE	Maruyama	Honda
DISPLACEMENT (cc)	22.5	25.0
APPROX. WEIGHT (lbs)	18.7	16.3
TANK CAPACITY (gal)	6.1	-
PUMP TYPE	duplex piston	duplex piston
MAXIMUM VOLUME (gpm)	1.9	1.9
PRESSURE (psi)	356	356
TRANSPORT	backpack	barrel-top
AGITATION	liquid bypass	liquid bypass
COMMERCIAL WARRANTY	5 year	5 year
STANDARD ACCESSORY	dual head nozzle	U2L gun

Maruyama. extraordinary.

MARUYAMA U.S., INC. | DENTON, TEXAS | PH 940.383.7400 | FX 940.383.7466
EMAIL MARUYAMA@MARUYAMA-US.COM | WWW.MARUYAMA-US.COM

Backpack Sprayer

ANALITE

ANALITE NEP160
TURBIDITY METER
for Field and Laboratory Applications

The ANALITE NEP160 is a truly portable turbidity meter. Readings are taken by simply inserting the probe into the steam or media to get an immediate result truly representative of the turbidity level at that point and time. It allows for easy and fast multiple readings at a site to ascertain the real turbidity profile of a stream or water body.

The ANALITE 160 turbidity meter allows the user to set up measurement parameters through a user-friendly menu system displayed on the in-built 2 line alphanumeric display.

Three probes are currently available to suit the ANALITE NEP160 display unit, the NEP260 (ISO7027 to 3,000NTU), NEP280 (retro-scatter to 30,000NTU) and the high temperature rated NEP285 (retro-scatter to 30,000NTU). Other probes may be added to the range from time to time. The probes have a depth rating of 100 meters and the display unit is IP65 rated.

All ANALITE NEP160 compliant probes are "hot swappable" and contain their calibration data in the probe proper thereby avaoiding the need to calibrate every time another probe is connected. The NEP160 (and its probes) comes supplied precalibrated however the user can calibrate a probe at any time using the simple menu driven interface. Both 2 and 3 point calibrations can be preformed.

Measurements can be read directly from the display at any time or downloaded to a computer/printer through the RS232 output at user selectable periodic intervals.

The ANALITE NEP160 will power up automatically to its last settings whenever external power is applied making it ideal for logging applications when using the analogue output or RS232 port.

The NEP160 comes complete in a convenient carry case. The carry case can accommodate a probe with a cable length of up to 10 meters, an ac adapter, the display unit, the RS232 cabling and the User Manual.

Turbidity Meter (a)

Specifications:	
Range:	0 to 30,000NTU (3,000NTU limit on NEP260, 90° probe) over four ranges automatically determined.
Display:	2 line, 16-character dot matrix alphanumeric liquid crystal display.
Displayed:	Turbidity (NTU) - default Relative Turbidity Reference (NTU) Relative Turbidity REL (Turbidity - Relative Turbidity Reference) Date/Time - default
Reading:	Updated approximately every 1 second.
Averaging period:	0.5 second or 8 seconds nominal – user selectable.
Range Steps:	1 <0.1 to 20NTU 2 <1 to 200NTU 3 <10 to 2,000NTU 4 <100 to 20,000NTU
Resolution	1 0.02NTU 2 0.1NTU 3 1NTU 4 10NTU
Repeatability:	2% ± 1 digit on all ranges.
Data Logging:	User set for one reading every 1 to 90 seconds or minutes. All readings stored in the Notepad.
Notepad:	100 readings each with time and date.
Setup :	Menu driven, including: – Calibration – Automatic Logging – Analogue Output range selection – Reference Turbidity value – Setting date and time.
Setup Memory:	Non volatile EEPROM.
Clock:	Calendar clock displays date and time.
GLP:	Good Laboratory Practice. All readings as well as calibration constants are stored together with the Time and Date and can be recalled at any time.
Analogue Output:	0 – 2 volts full scale corresponding to preset measurement range. Output impedance 600 ohms nominal.
Power:	***Internal:*** 6V NiMH rechargeable battery. ***External:*** 10 to 16V dc, 400mA max. incl. NiMH Charge current. External power connection is via jack plug male with 2.5mm pin. Centre pin is NEGATIVE polarity.
Power Manag't:	Automatic power down perating from batteries after approx. 5 minutes may be selected. Automatic power up when powered externally. Continuous operation of at least 5 hours on a fully charged battery. For normal intermittent operation a full charge may last several days. Low battery indication prior to shut down.

Outputs:	Inbuilt LCD, analogue output and RS232 port.
RS232 Port :	The RS232 port can output readings on request or at preset intervals of time from 1 to 99 seconds or minutes. The Notepad memory can also be downloaded on request. 4800 baud rate, 8 bits, no parity, 1 stop bit, Xon/Xoff protocol.
Dimensions:	187mm x 110mm x 51mm (display unit). 238mm x 32mm dia (probes incl gland).
Weight:	Display Unit 0.5kg. 180° Probe 0.4kg with 5m lead. 90° Probe 0.4kg with 5m lead.
Operating Temp':	0° to 50°C. Operating -10° to 60°C Storage
Humidity:	0 to 90% R.H. operating
Case Rating:	IP65 with all connectors sealed with dust caps (supplied) or probe properly connected and dust caps on remaining two connectors.
Probe Rating:	100 meters water column.
Ordering Info:	
NEP160-1-05R	NEP160 with **NEP280** - 180° general purpose probe.
NEP160-2-05R	NEP160 with **NEP285** - 180° hi-temp probe.
NEP160-3-05R	NEP160 with **NEP260** - ISO7027 90° probe.
NEP160R	Display unit only.

All probes are supplied with 5 meters of cable unless otherwise indicated at time of order.

Specifications subject to change without notice.
File: NEP160 Series Brochure Mar 2004.indd

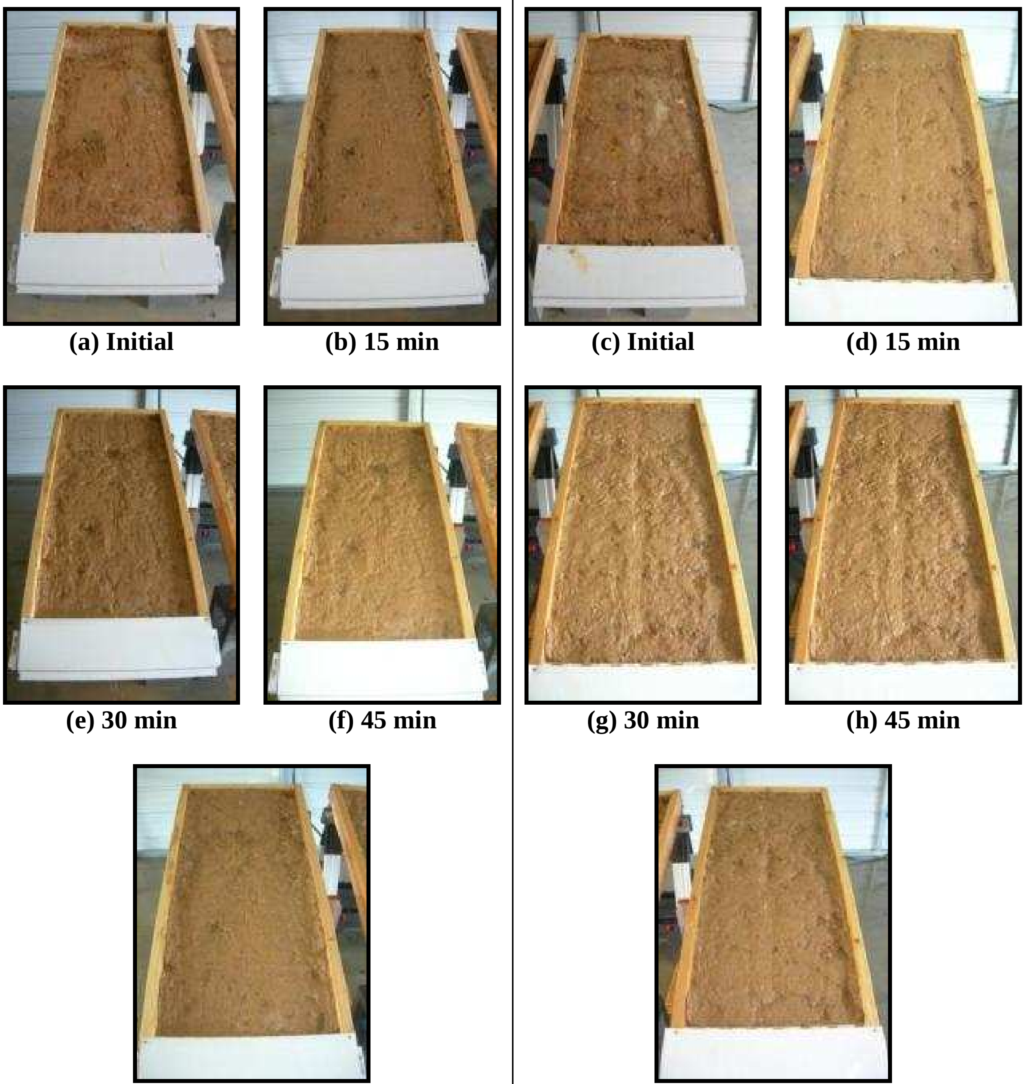
Turbidity Meter (b)

APPENDIX D

EXPERIMENTAL RESULTS

Experiment: Control (1)	**Date:** 9/28/08
Treatment: Bare Soil	**Exp #:** 1

Left Test Plots	**Right Test Plots**



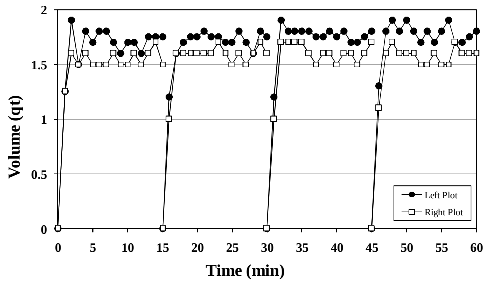
(a) Initial **(b) 15 min** **(c) Initial** **(d) 15 min**

(e) 30 min **(f) 45 min** **(g) 30 min** **(h) 45 min**

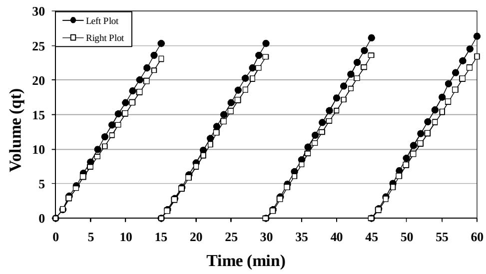
(i) 60 min **(j) 60 min**

Photographs Documenting Test Plot Conditions during Experimentation.

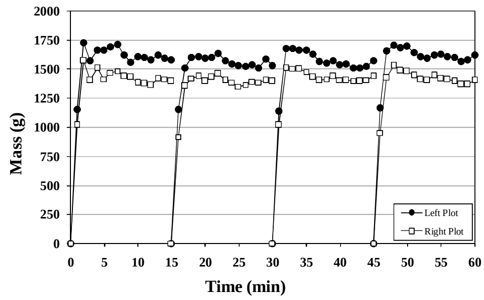
Experiment: Control (1) **Date:** 9/28/08
Treatment: Bare Soil **Exp #:** 1



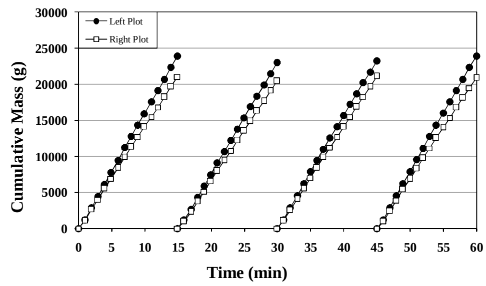
(a) Runoff Volume



(b) Cumulative Runoff Volume

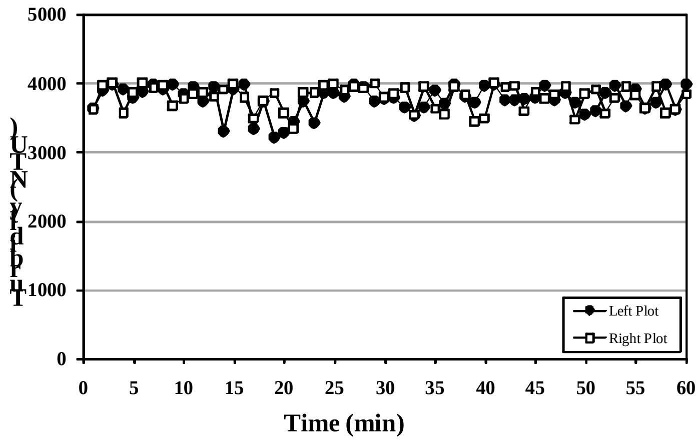


(c) Runoff Mass



(d) Cumulative Runoff Mass

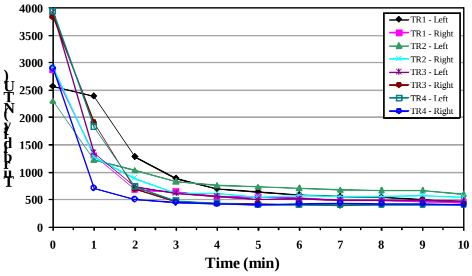
Surface Runoff Measurements vs. Time.



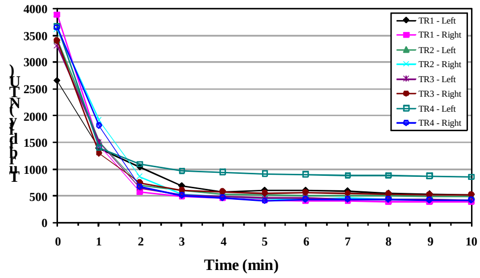
Surface Runoff Initial Turbidity vs. Time.

Experiment: Control (1) **Date:** 9/28/08

Treatment: Bare Soil **Exp #:** 1

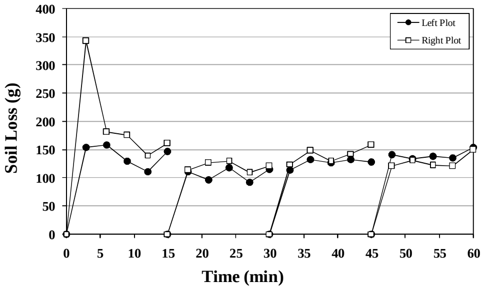


(a) Turbidity vs. Time at 5 Minutes

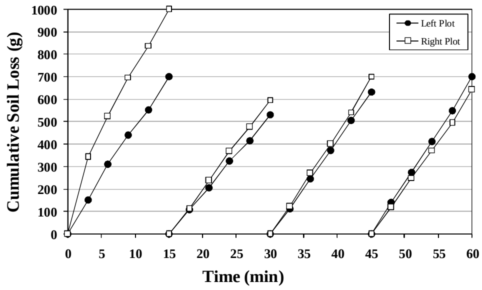


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

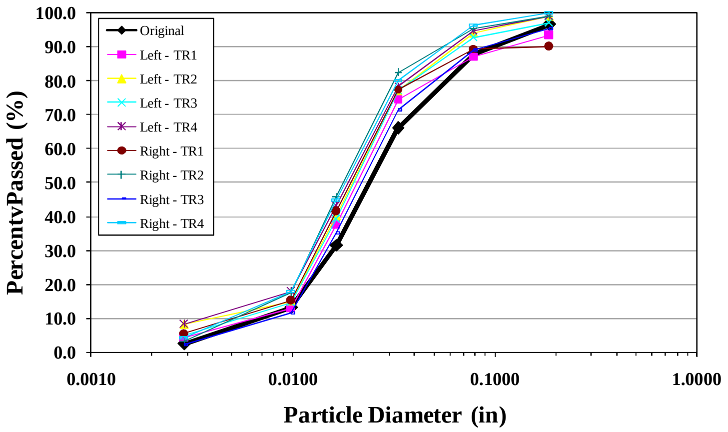


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Control (2) **Date:** 10/03/08
Treatment: Bare Soil **Exp #:** 2

Left Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min

Photograph Not Available

(i) 60 min

Right Test Plots


(c) Initial


(d) 15 min


(g) 30 min

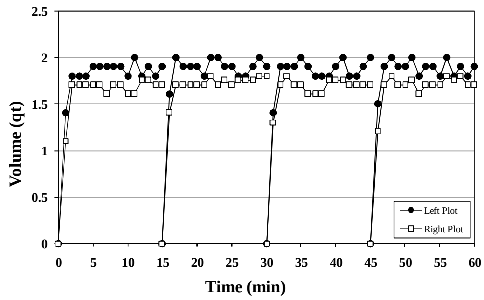

(h) 45 min

Photograph Not Available

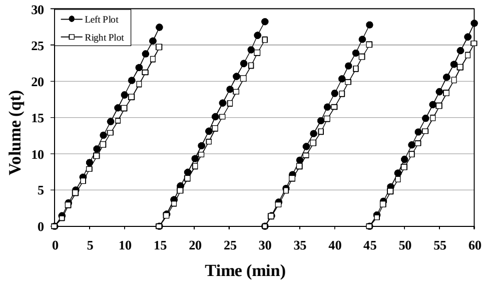
(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation

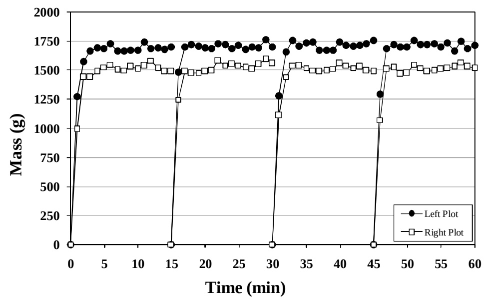
Experiment: Control (2) **Date:** 10/03/08
Treatment: Bare Soil **Exp #:** 2



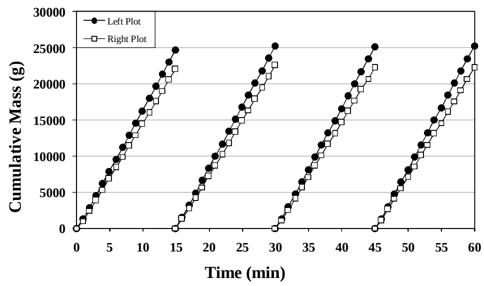
(a) Runoff Volume



(b) Cumulative Runoff Volume

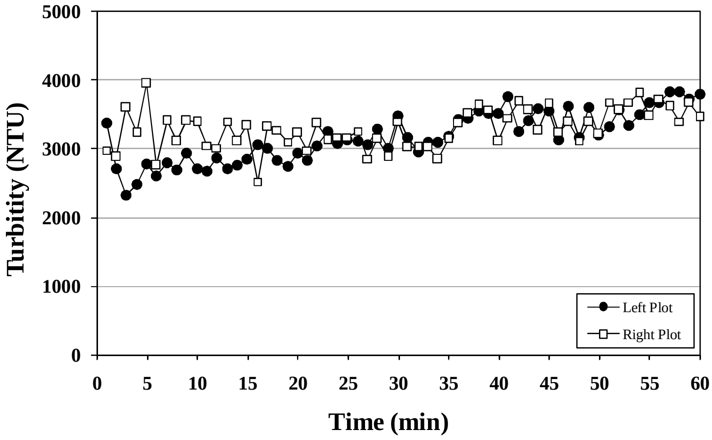


(c) Runoff Mass



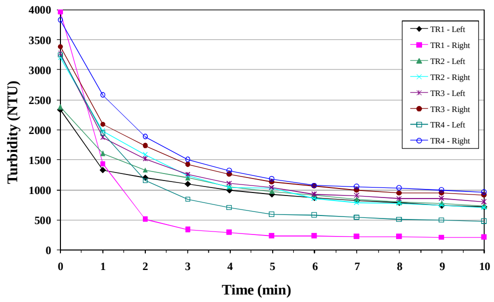
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

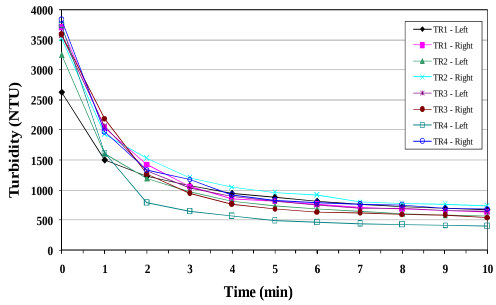


Surface Runoff Initial Turbidity vs. Time.

Experiment: Control (2) **Date:** 10/03/08
Treatment: Bare Soil **Exp #:** 2

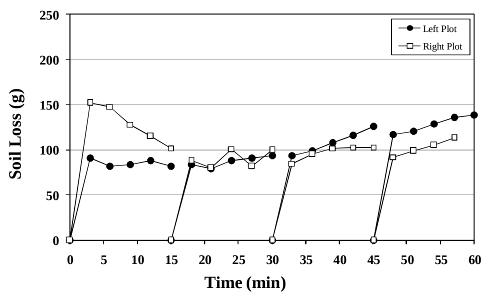


(a) Turbidity vs. Time at 5 Minutes

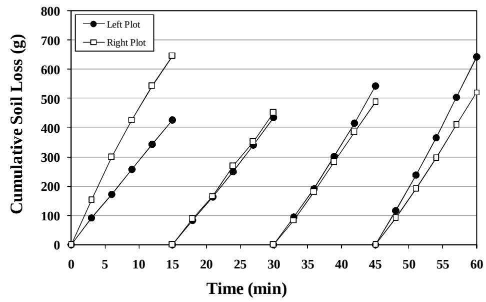


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

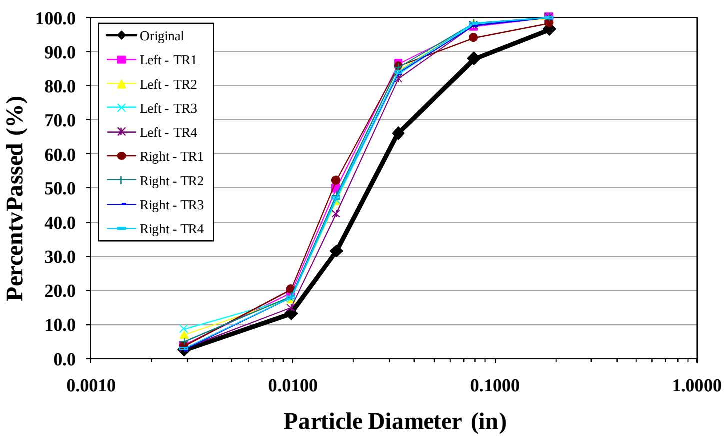


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 35 (1) **Date:** 10/13/08
Treatment: 35 lbs/acre **Exp #:** 3

Left Test Plots	**Right Test Plots**

Left Test Plots

(a) Initial

(b) 15 min

(e) 30 min

(f) 45 min

(i) 60 min

Right Test Plots

(c) Initial

(d) 15 min

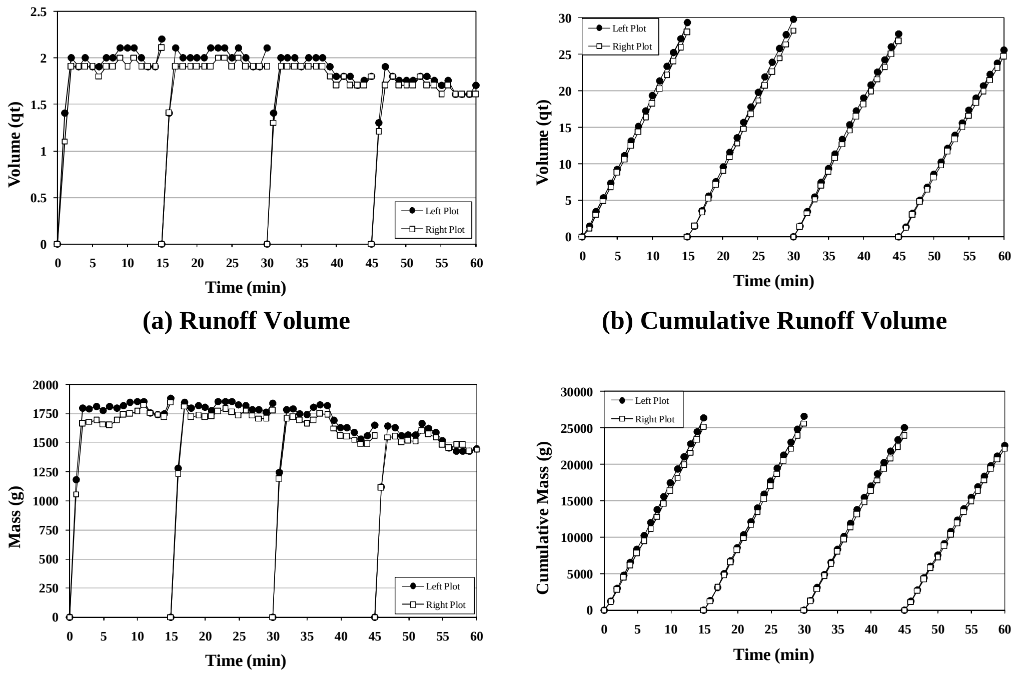
(g) 30 min

(h) 45 min

(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

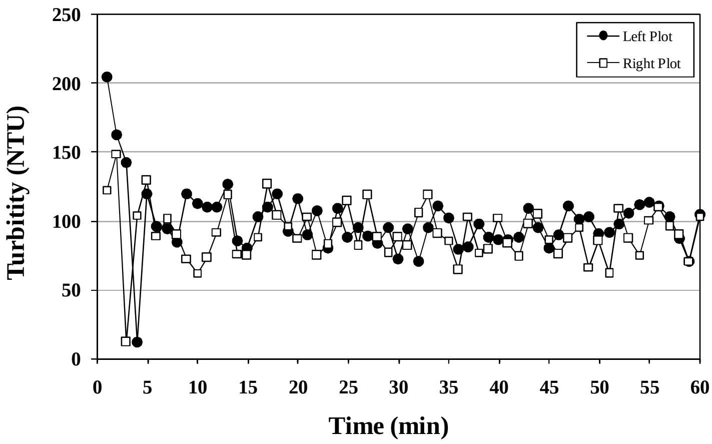
Experiment: Dry PAM 35 (1)	**Date:** 10/13/08
Treatment: 35 lbs/acre	**Exp #:** 3



(a) Runoff Volume **(b) Cumulative Runoff Volume**

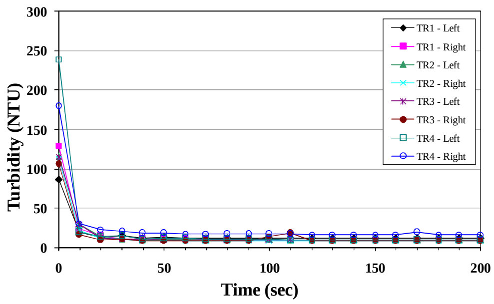
(c) Runoff Mass **(d) Cumulative Runoff Mass**

Surface Runoff Measurements vs. Time.

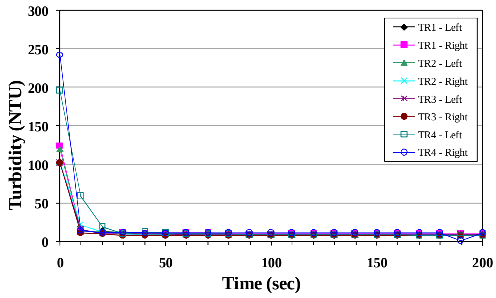


Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 35 (1) **Date:** 10/13/08
Treatment: 35 lbs/acre **Exp #:** 3

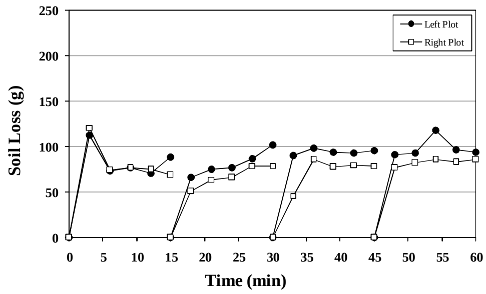


(a) Turbidity vs. Time at 5 Minutes

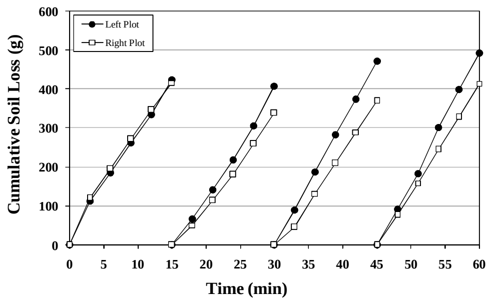


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

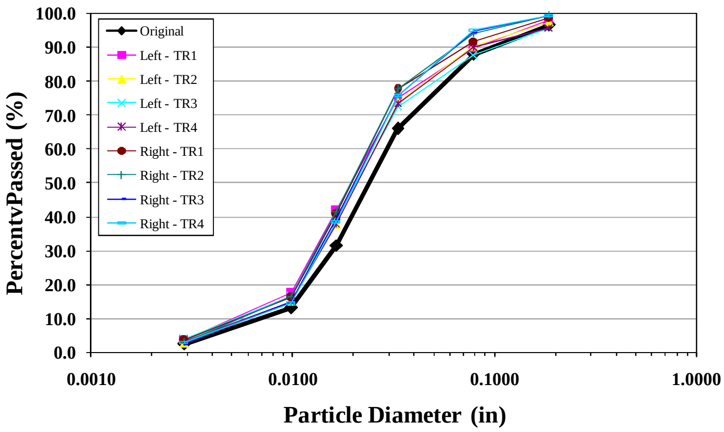


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 35 (2) **Date:** 10/17/08
Treatment: 35 lbs/acre **Exp #:** 4

Left Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min

Right Test Plots


(c) Initial

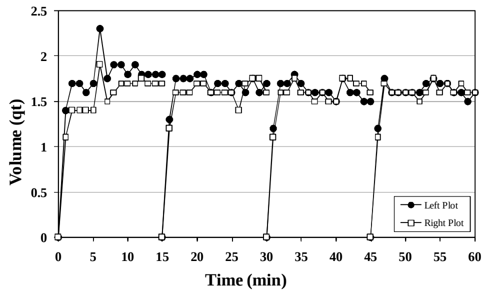

(d) 15 min


(g) 30 min

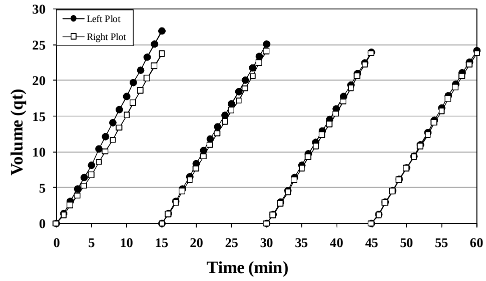

(h) 45 min


(j) 60 min

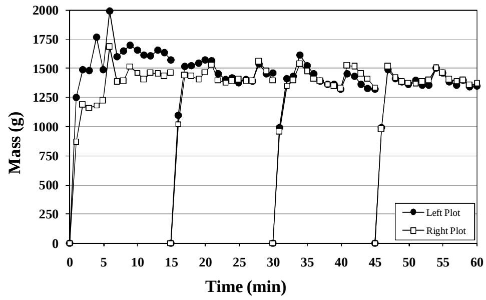
Photographs Documenting Test Plot Conditions during Experimentation.



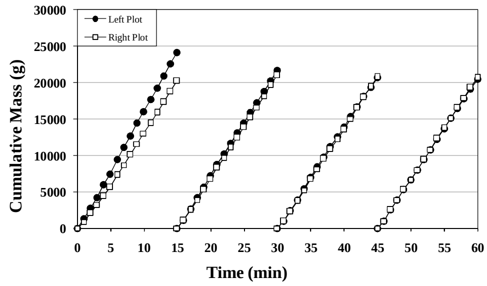
(a) Runoff Volume



(b) Cumulative Runoff Volume

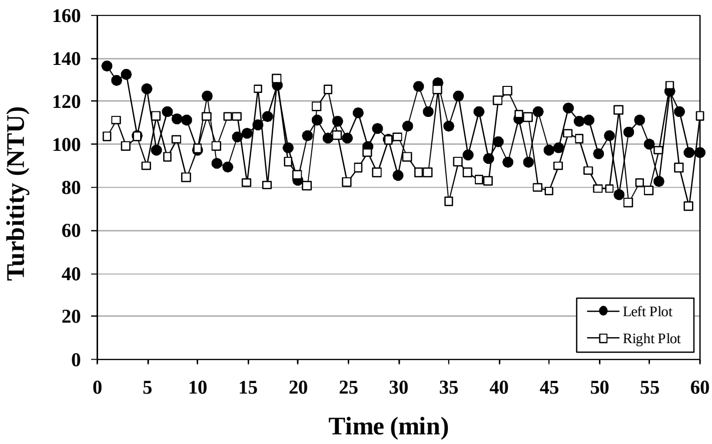


(c) Runoff Mass



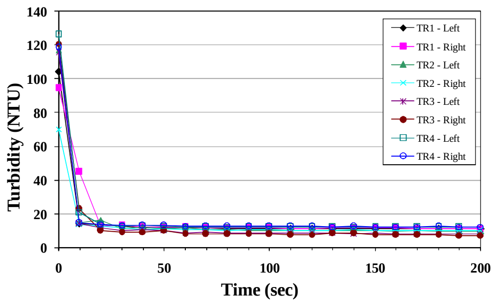
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

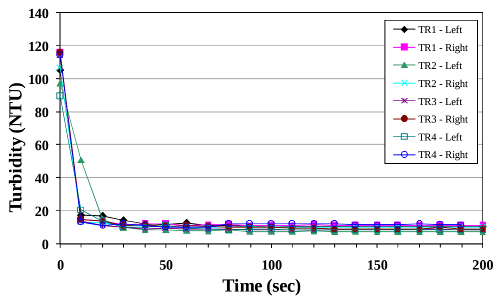


Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 35 (2) **Date:** 10/17/08
Treatment: 35 lbs/acre **Exp #:** 4

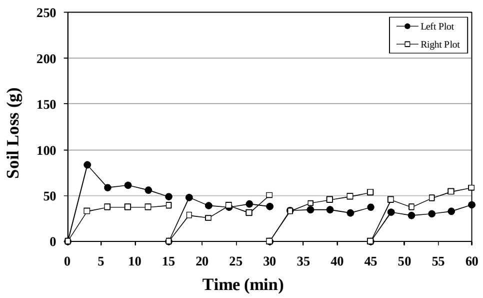


(a) Turbidity vs. Time at 5 Minutes

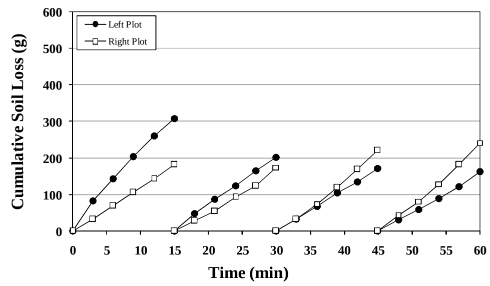


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

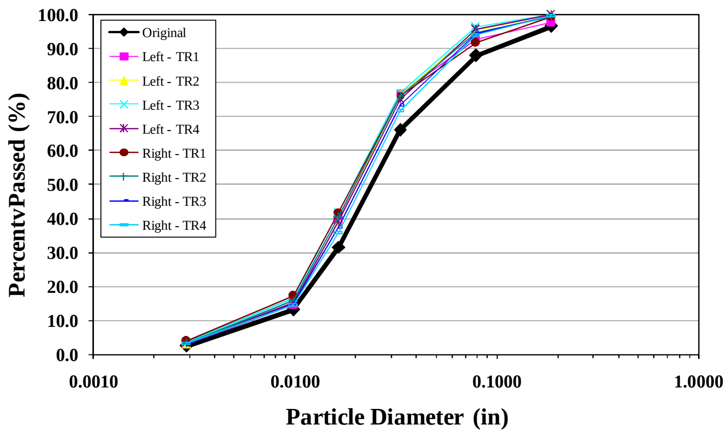


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 15 (1) **Date:** 10/20/08
Treatment: 15 lbs/acre **Exp #:** 5

Left Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min

Right Test Plots


(c) Initial


(d) 15 min

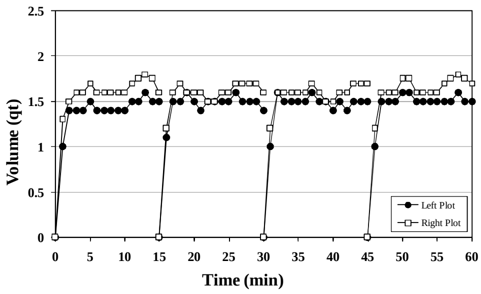

(g) 30 min


(h) 45 min

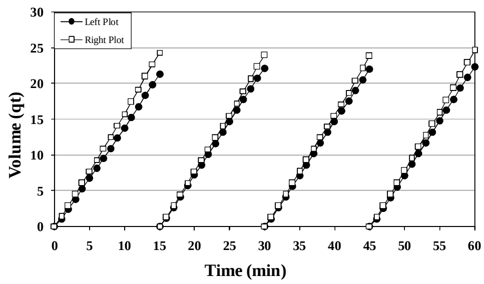

(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

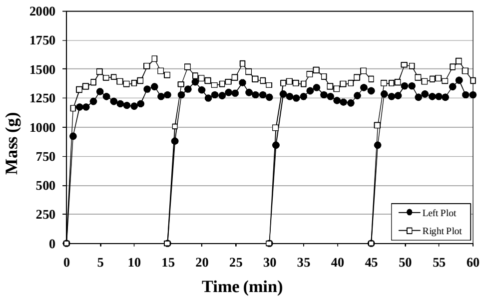
Experiment: Dry PAM 15 (1) **Date:** 10/20/08
Treatment: 15 lbs/acre **Exp #:** 5



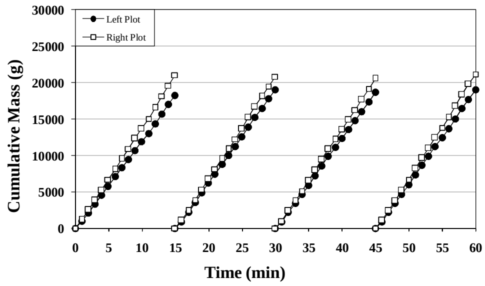
(a) Runoff Volume



(b) Cumulative Runoff Volume

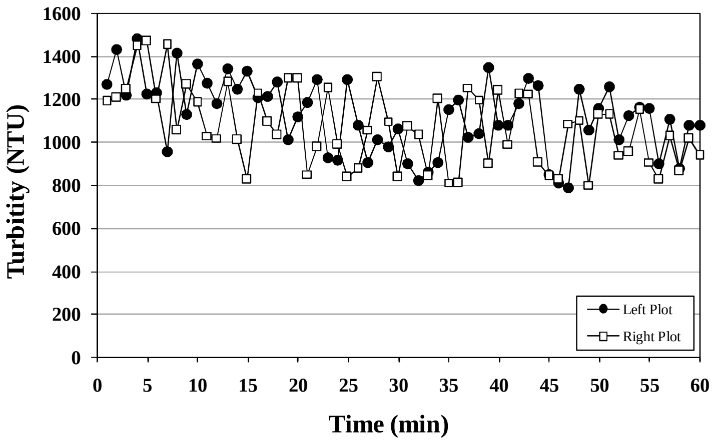


(c) Runoff Mass



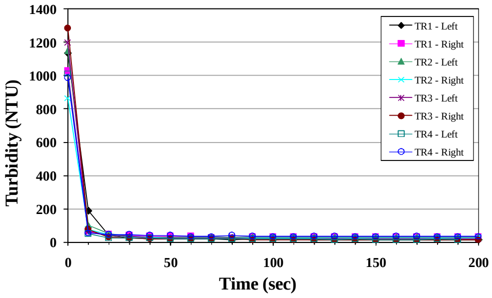
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time

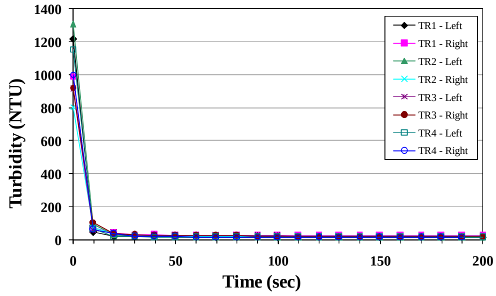


Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 15 (1) **Date:** 10/20/08
Treatment: 15 lbs/acre **Exp #:** 5

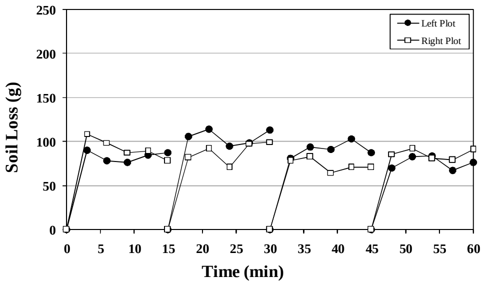


(a) Turbidity vs. Time at 5 Minutes

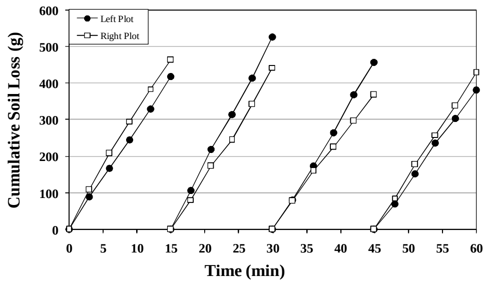


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

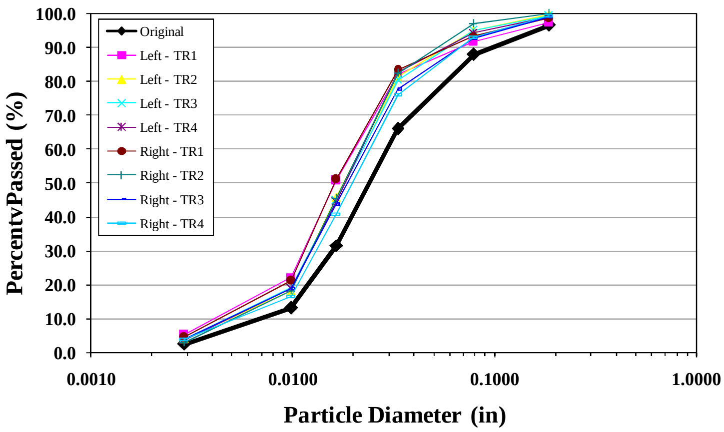


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 15 (2) **Date:** 10/22/08
Treatment: 15 lbs/acre **Exp #:** 6

Left Test Plots


(a) Initial

Photograph Not Available
(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min

Right Test Plots


(c) Initial

Photograph Not Available
(d) 15 min

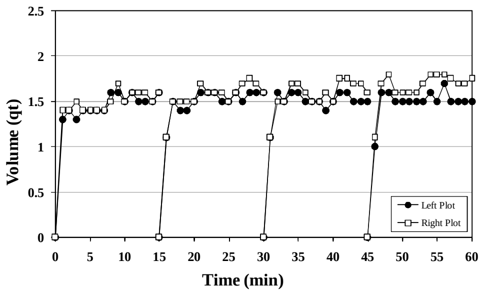

(g) 30 min


(h) 45 min

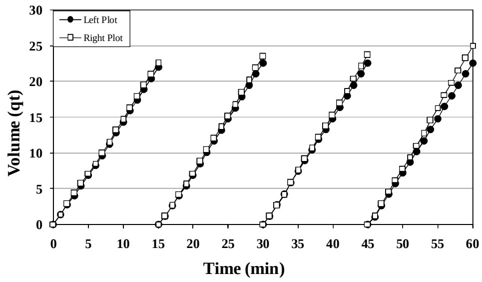

(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

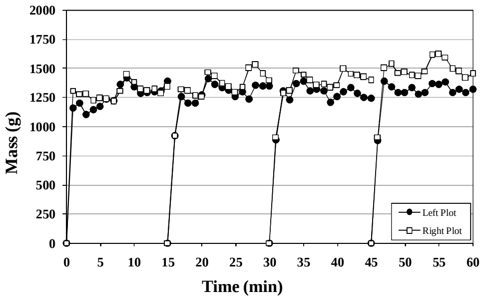
Experiment: Dry PAM 15 (2) **Date:** 10/22/08
Treatment: 15 lbs/acre **Exp #:** 6



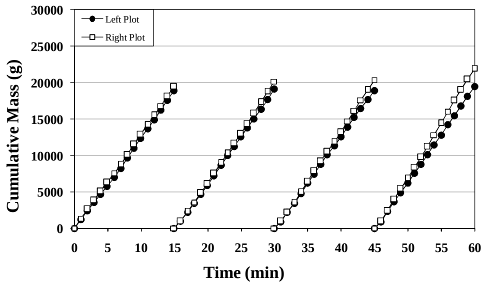
(a) Runoff Volume



(b) Cumulative Runoff Volume

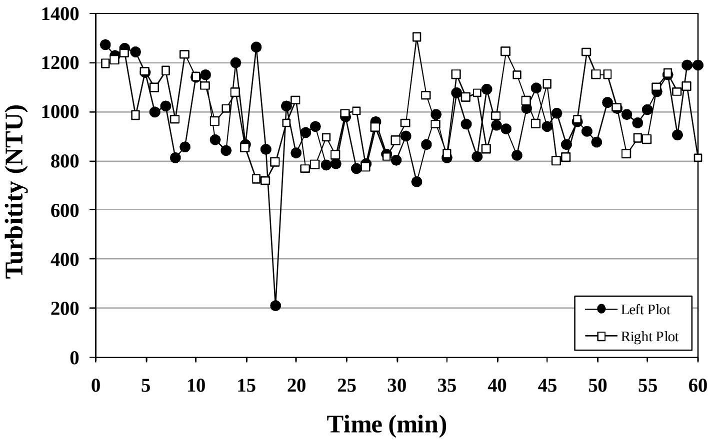


(c) Runoff Mass



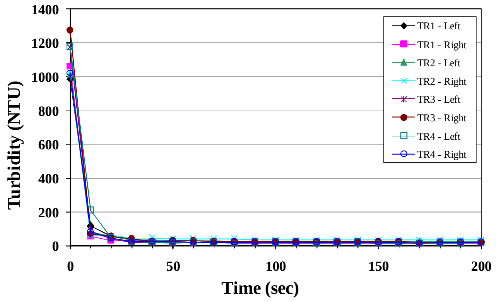
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

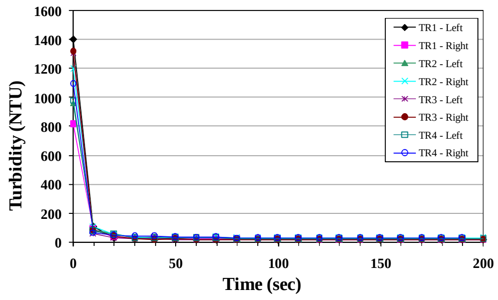


Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 15 (2) **Date:** 10/22/08
Treatment: 15 lbs/acre **Exp #:** 6

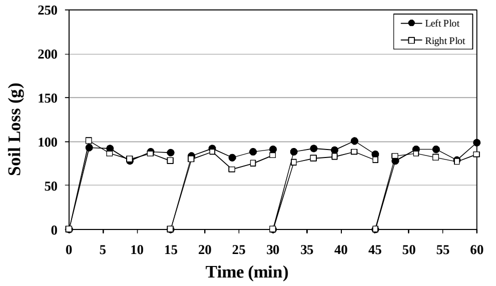


(a) Turbidity vs. Time at 5 Minutes

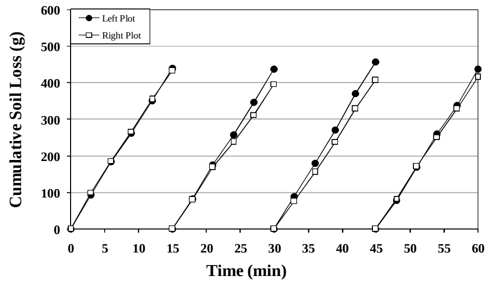


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

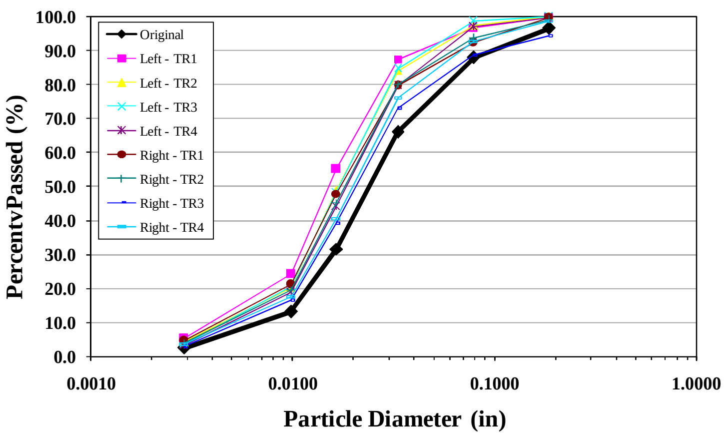


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 25 (1) **Date:** 10/27/08
Treatment: 25 lbs/acre **Exp #:** 7

Left Test Plots	Right Test Plots

Left Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min

Right Test Plots


(c) Initial


(d) 15 min

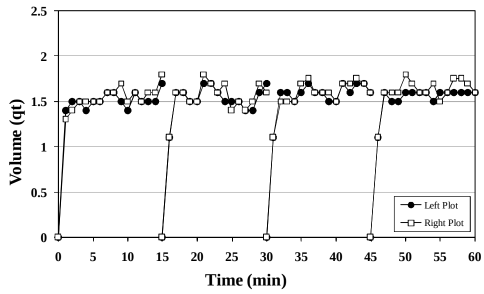

(g) 30 min


(h) 45 min

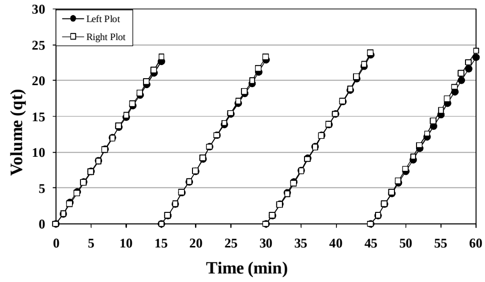

(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

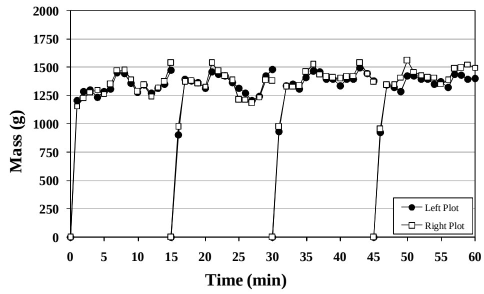
Experiment: Dry PAM 25 (1) **Date:** 10/27/08
Treatment: 25 lbs/acre **Exp #:** 7



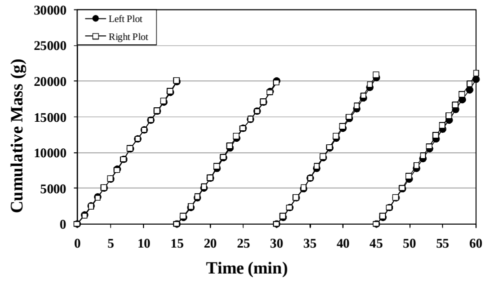
(a) Runoff Volume



(b) Cumulative Runoff Volume

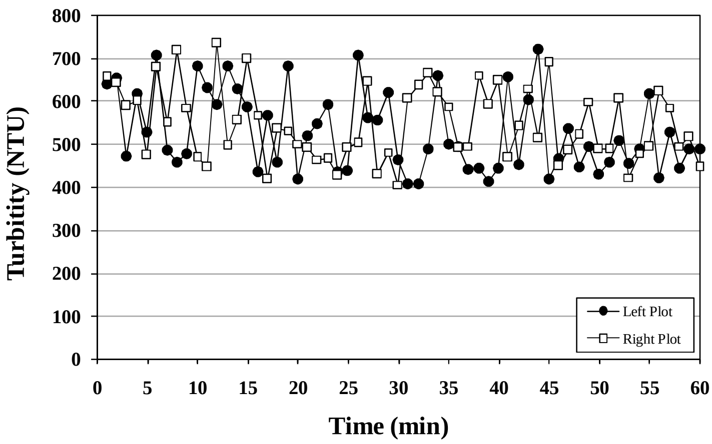


(c) Runoff Mass



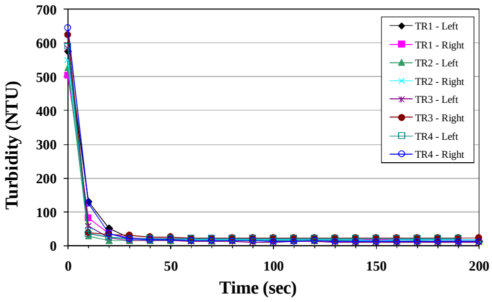
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

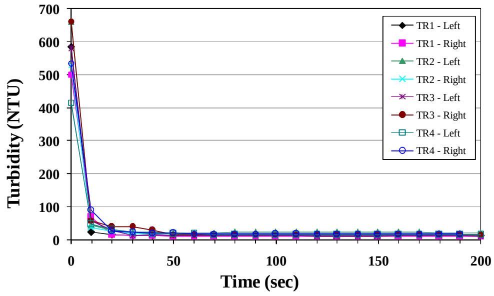


Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 25 (1) **Date:** 10/27/08
Treatment: 25 lbs/acre **Exp #:** 7

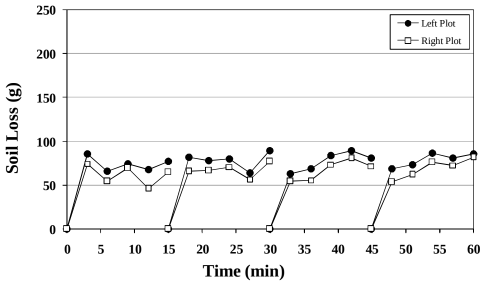


(a) Turbidity vs. Time at 5 Minutes

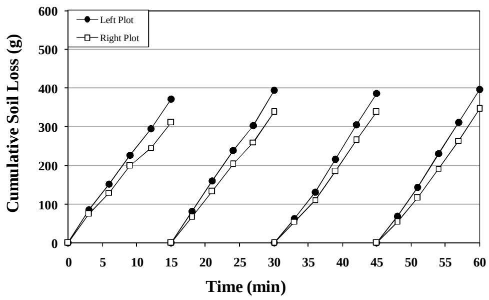


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

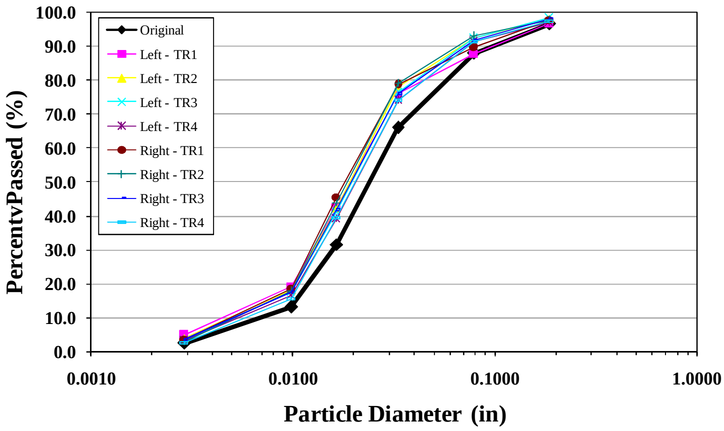


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Dry PAM 25 (2)	**Date:** 10/29/08
Treatment: 25 lbs/acre	**Exp #:** 8

Left Test Plots

(a) Initial

(b) 15 min

(e) 30 min

(f) 45 min

(i) 60 min

Right Test Plots

(c) Initial

(d) 15 min

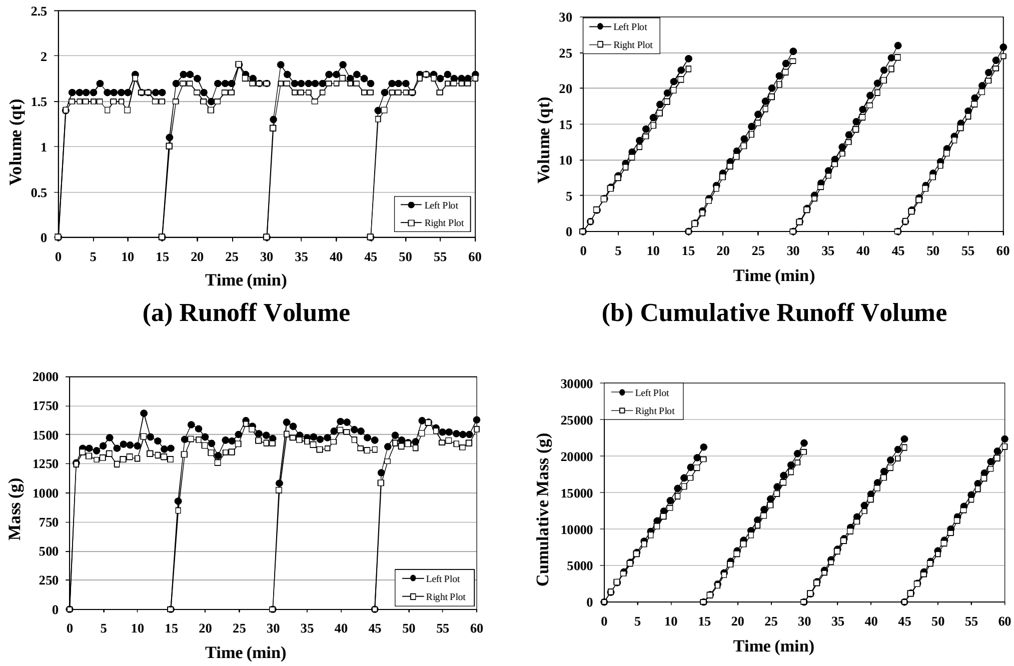
(g) 30 min

(h) 45 min

(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation

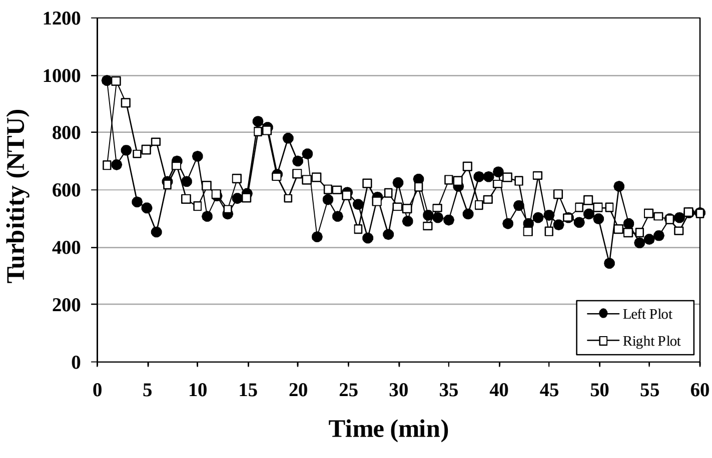
Experiment: Dry PAM 25 (2) **Date:** 10/29/08
Treatment: 25 lbs/acre **Exp #:** 8



(a) Runoff Volume (b) Cumulative Runoff Volume

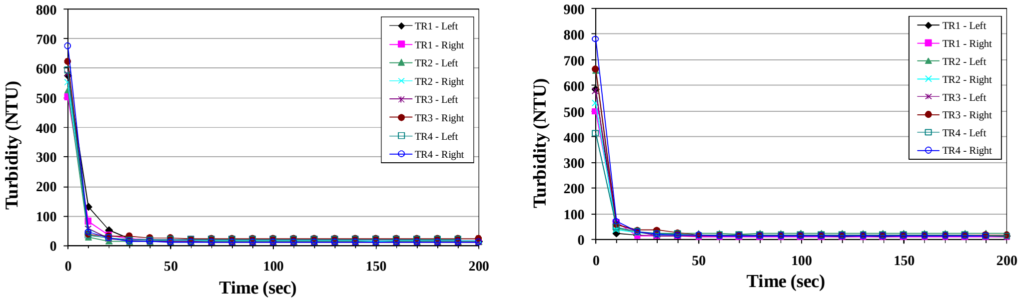
(c) Runoff Mass (d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.



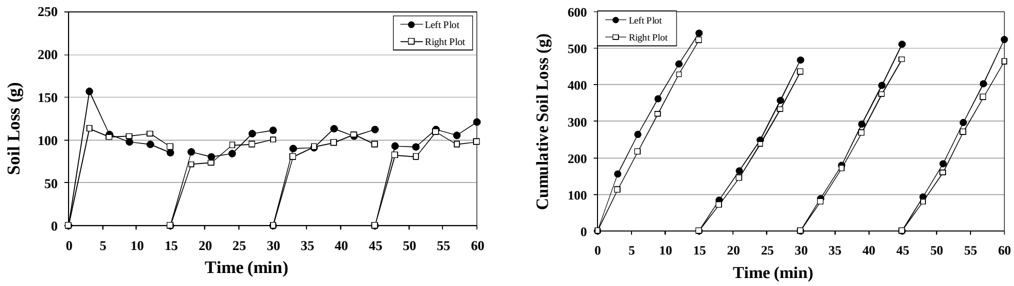
Surface Runoff Initial Turbidity vs. Time.

Experiment: Dry PAM 25 (2) **Date:** 10/29/08
Treatment: 25 lbs/acre **Exp #:** 8



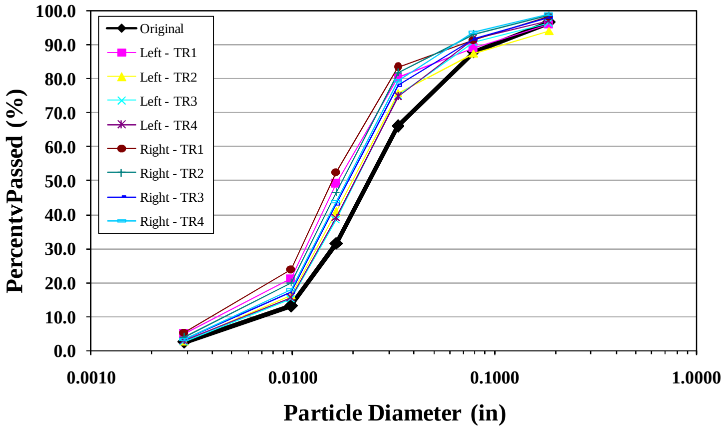
(a) Turbidity vs. Time at 5 Minutes **(b) Turbidity vs. Time at 10 Minutes**

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.



(a) Soil Loss vs. Time **(b) Cumulative Soil Loss vs. Time**

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 35 (1) **Date:** 11/7/08
Treatment: 35 lbs/acre **Exp #:** 9

Left Test Plots

(a) Initial

(b) 15 min

(e) 30 min

(f) 45 min

(i) 60 min

Right Test Plots

(c) Initial

(d) 15 min

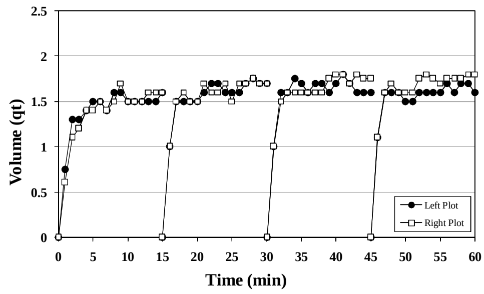
(g) 30 min

(h) 45 min

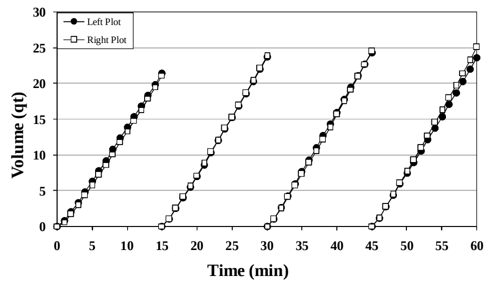
(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

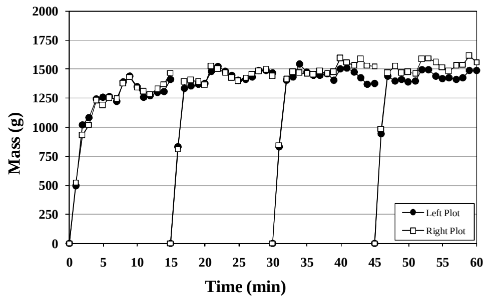
Experiment: Liquid PAM 35 (1) **Date:** 11/7/08
Treatment: 35 lbs/acre **Exp #:** 9



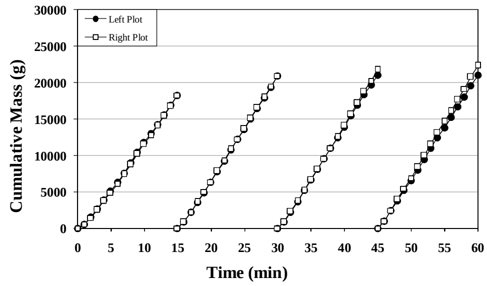
(a) Runoff Volume



(b) Cumulative Runoff Volume

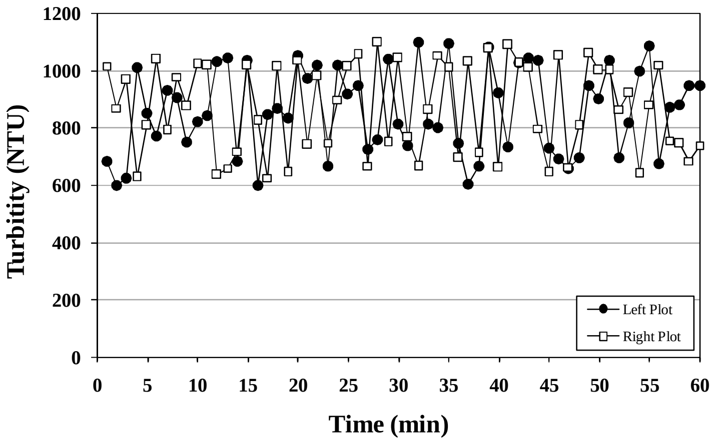


(c) Runoff Mass



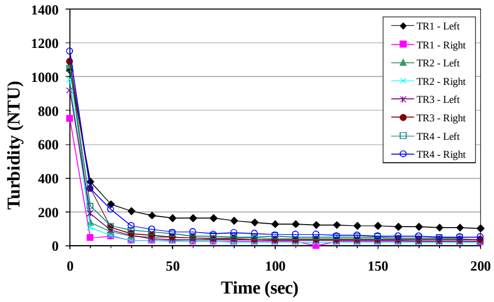
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

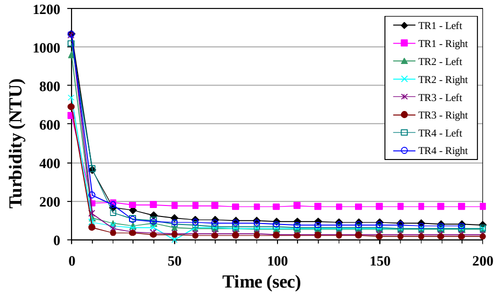


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 35 (1) **Date:** 11/7/08
Treatment: 35 lbs/acre **Exp #:** 9

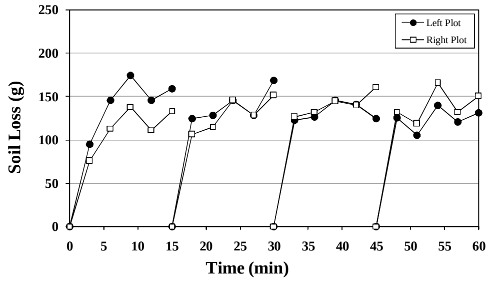


(a) Turbidity vs. Time at 5 Minutes

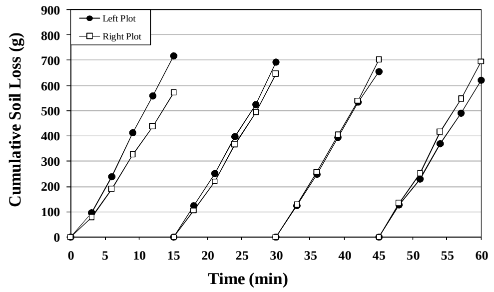


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

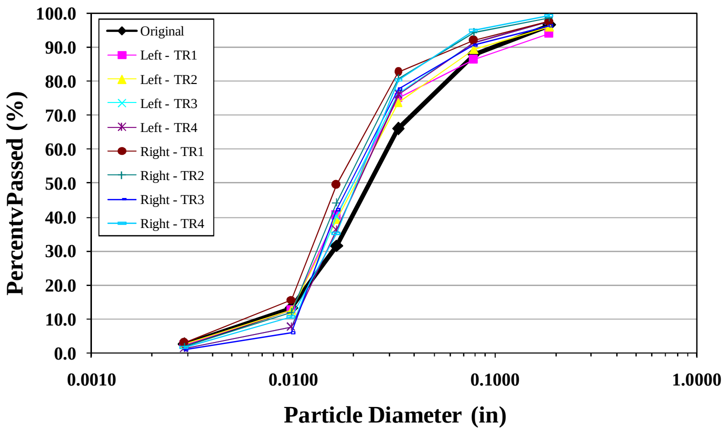


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 35 (2) **Date:** 11/10/08
Treatment: 35 lbs/acre **Exp #:** 10

Left Test Plots	Right Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min


(c) Initial

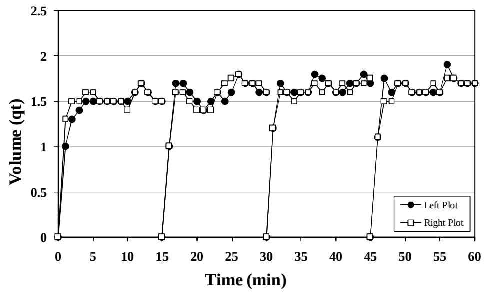

(d) 15 min


(g) 30 min

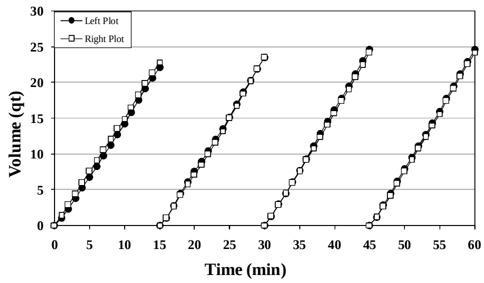

(h) 45 min


(j) 60 min

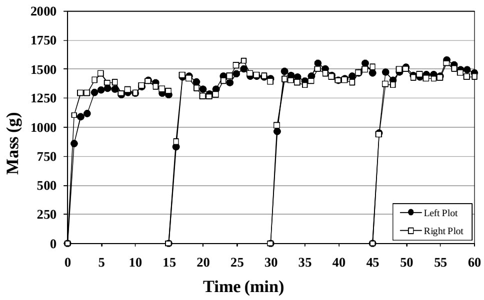
Photographs Documenting Test Plot Conditions during Experimentation.



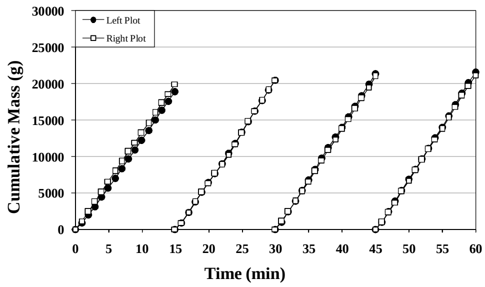
(a) Runoff Volume



(b) Cumulative Runoff Volume

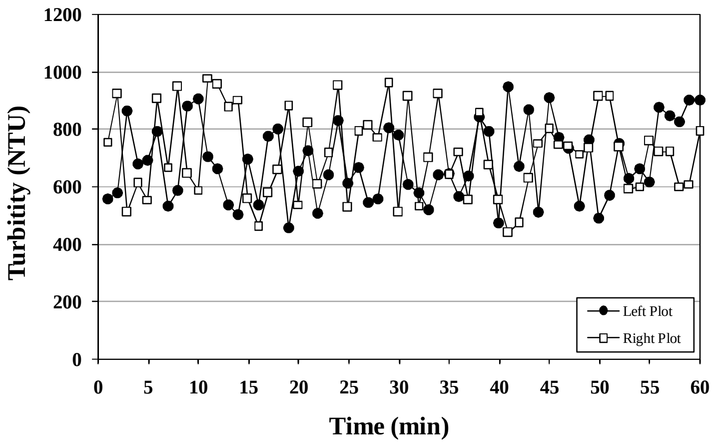


(c) Runoff Mass



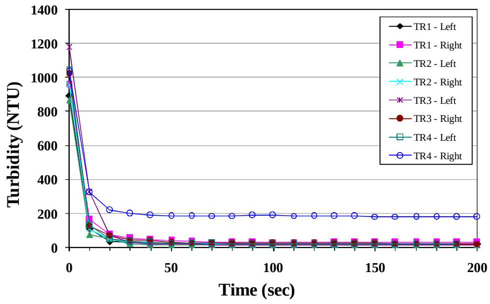
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

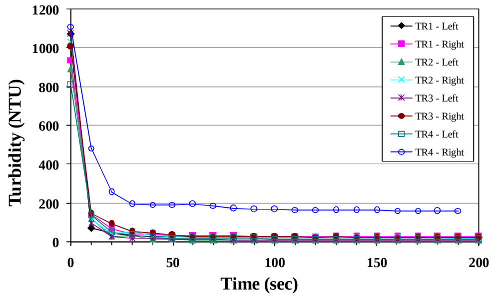


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 35 (2) **Date:** 11/10/08
Treatment: 35 lbs/acre **Exp #:** 10

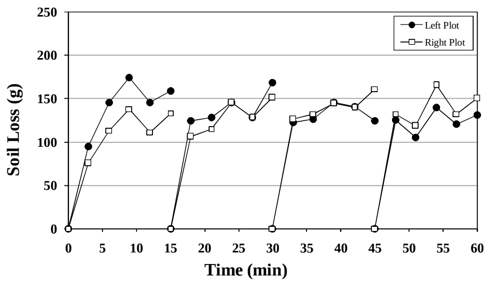


(a) Turbidity vs. Time at 5 Minutes

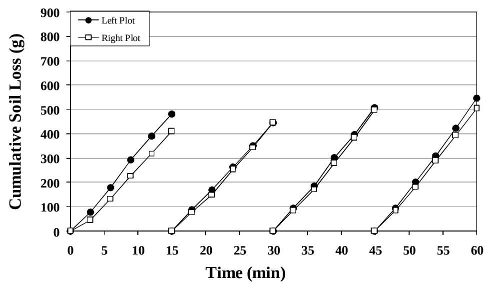


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

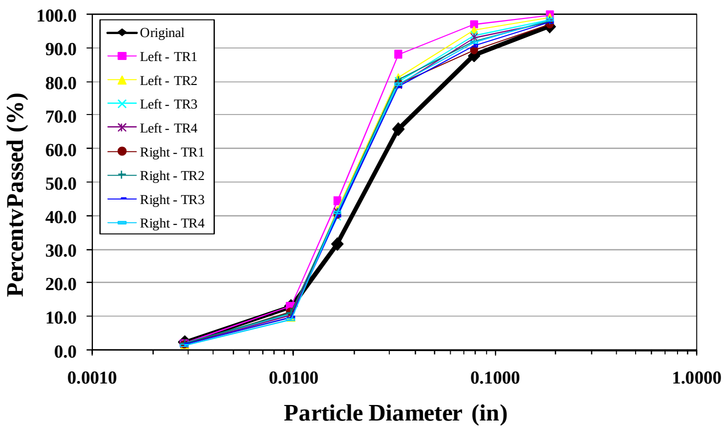


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 15 (1) **Date:** 11/17/08
Treatment: 15 lbs/acre **Exp #:** 11

Left Test Plots	Right Test Plots

Left Test Plots

(a) Initial

(b) 15 min

(e) 30 min

(f) 45 min

(i) 60 min

Right Test Plots

(c) Initial

(d) 15 min

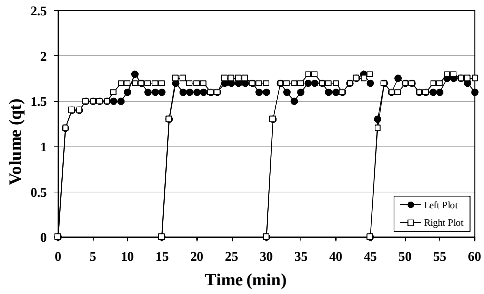
(g) 30 min

(h) 45 min

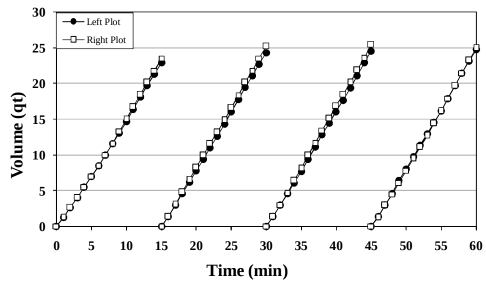
(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

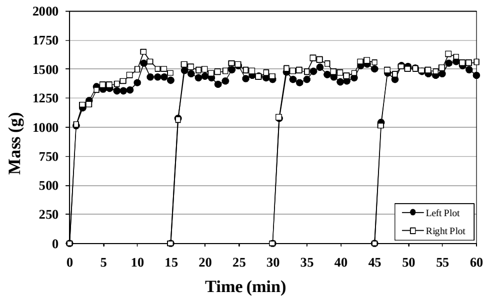
Experiment: Liquid PAM 15 (1) **Date:** 11/17/08
Treatment: 15 lbs/acre **Exp #:** 11



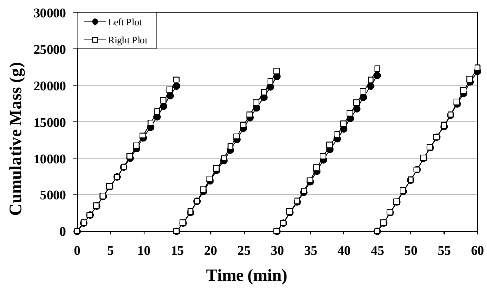
(a) Runoff Volume



(b) Cumulative Runoff Volume

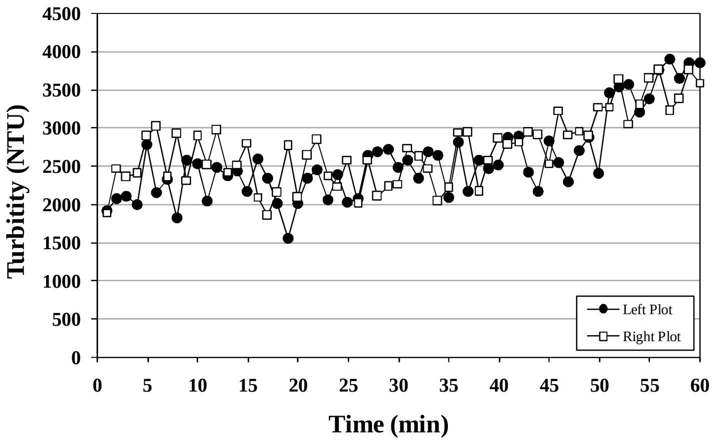


(c) Runoff Mass



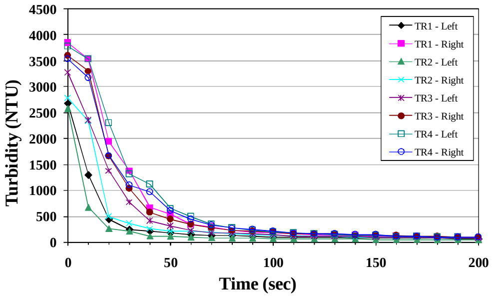
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

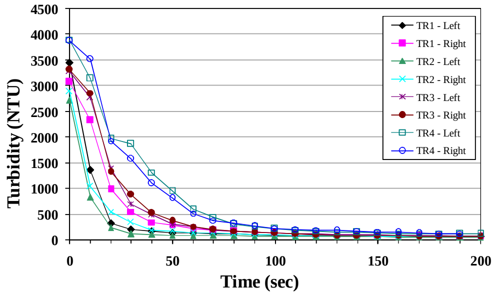


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 15 (1) **Date:** 11/17/08
Treatment: 15 lbs/acre **Exp #:** 11

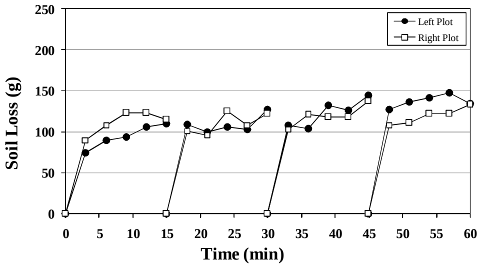


(a) Turbidity vs. Time at 5 Minutes

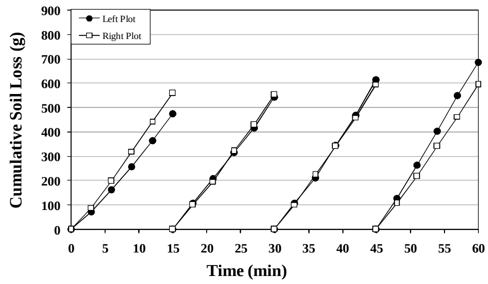


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

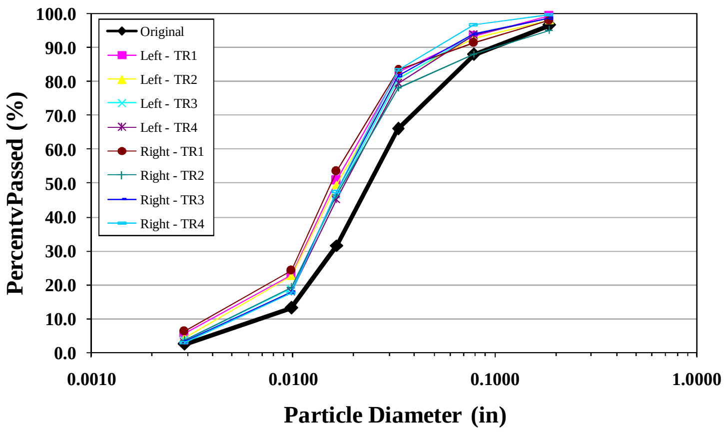


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 15 (2) **Date:** 11/19/08
Treatment: 15 lbs/acre **Exp #:** 12

Left Test Plots


(a) Initial


(b) 15 min


(e) 30 min


(f) 45 min


(i) 60 min

Right Test Plots


(c) Initial

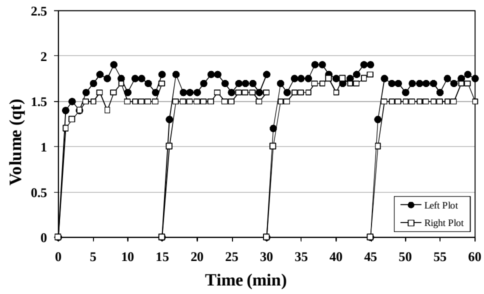

(d) 15 min


(g) 30 min

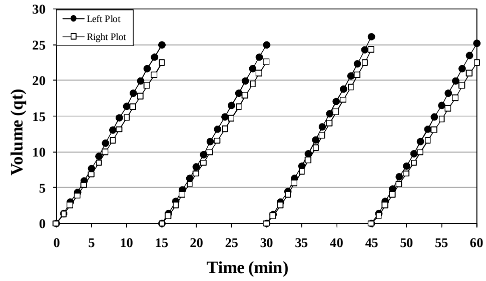

(h) 45 min


(j) 60 min

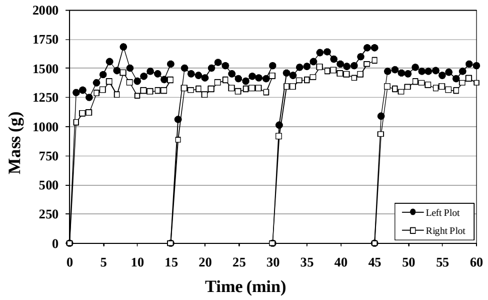
Photographs Documenting Test Plot Conditions during Experimentation.



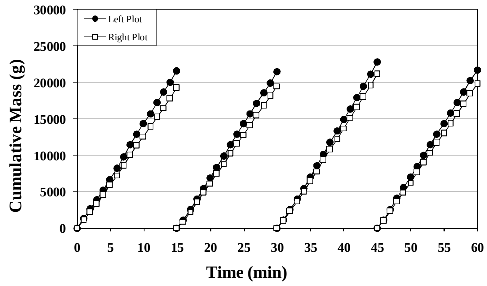
(a) Runoff Volume



(b) Cumulative Runoff Volume

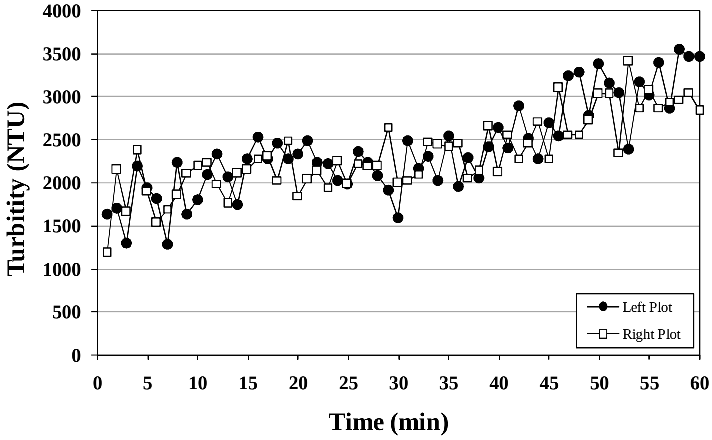


(c) Runoff Mass



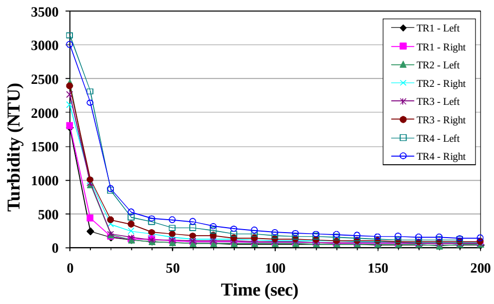
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

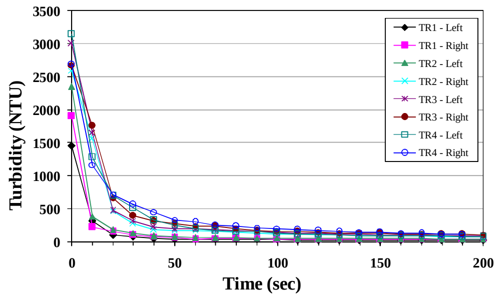


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 15 (2) **Date:** 11/19/08
Treatment: 15 lbs/acre **Exp #:** 12

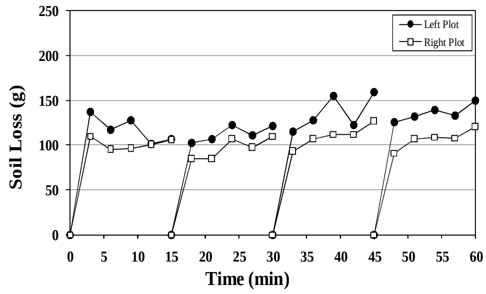


(a) Turbidity vs. Time at 5 Minutes

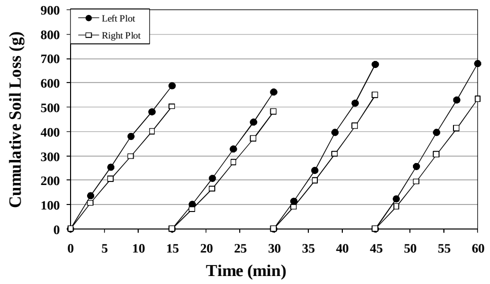


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

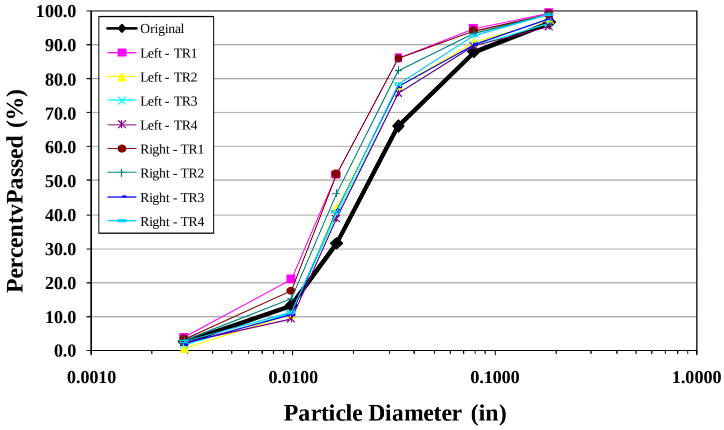


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 25 (1) **Date:** 12/1/08
Treatment: 25 lbs/acre **Exp #:** 13

Left Test Plots	Right Test Plots

(a) Initial

(b) 15 min

(c) Initial

(d) 15 min

(e) 30 min

(f) 45 min

(g) 30 min

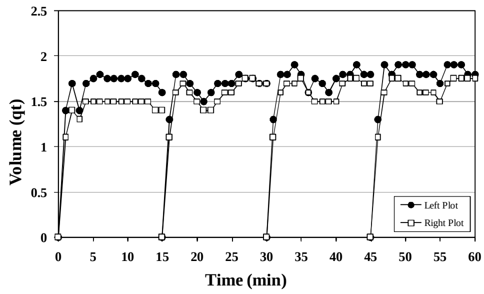
(h) 45 min

(i) 60 min

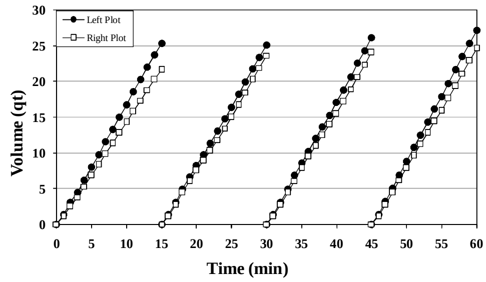
(j) 60 min

Photographs Documenting Test Plot Conditions during Experimentation.

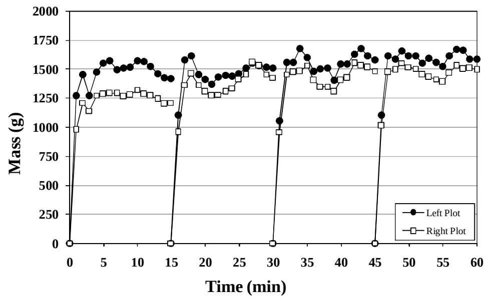
Experiment: Liquid PAM 25 (1) **Date:** 12/1/08
Treatment: 25 lbs/acre **Exp #:** 13



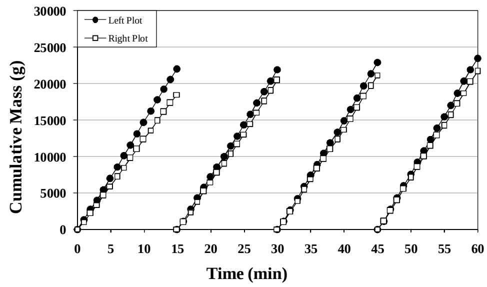
(a) Runoff Volume



(b) Cumulative Runoff Volume

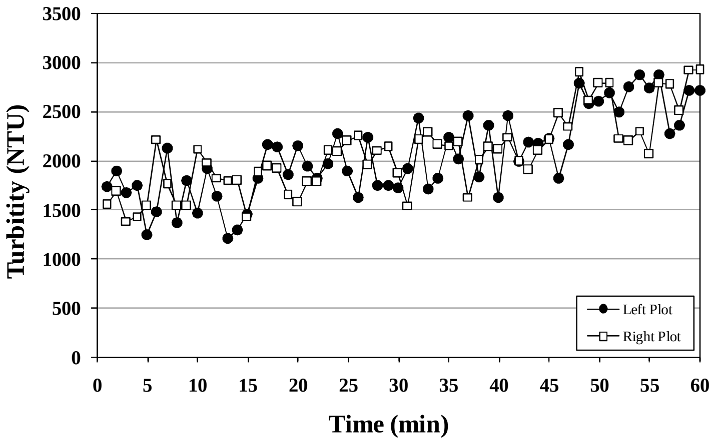


(c) Runoff Mass



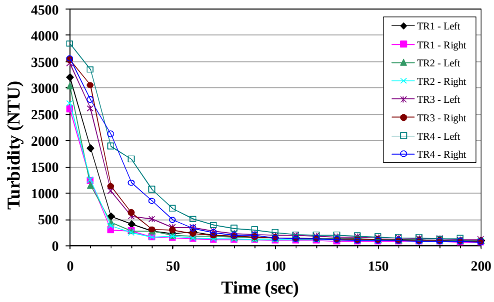
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

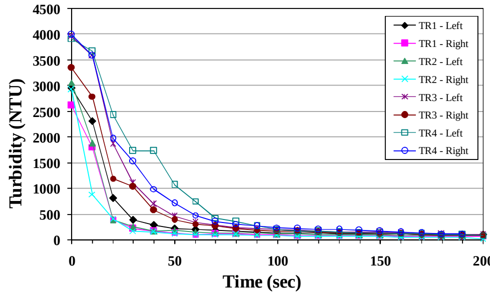


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 25 (1) **Date:** 12/1/08
Treatment: 25 lbs/acre **Exp #:** 13

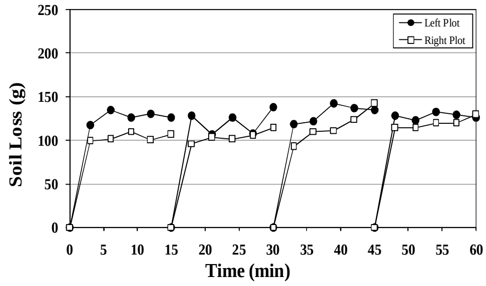


(a) Turbidity vs. Time at 5 Minutes

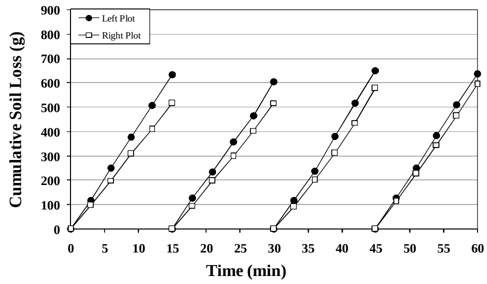


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

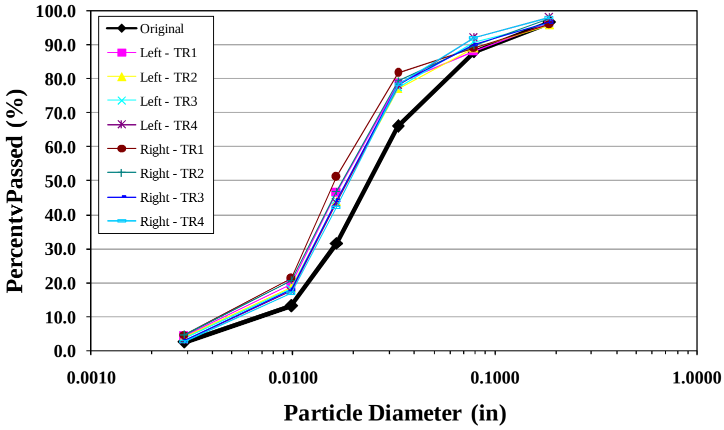


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

Experiment: Liquid PAM 25 (2) **Date:** 12/5/08
Treatment: 25 lbs/acre **Exp #:** 14

Left Test Plots		Right Test Plots	


(a) Initial


(b) 15 min


(c) Initial


(d) 15 min

Photograph Not Available
(e) 30 min


(f) 45 min

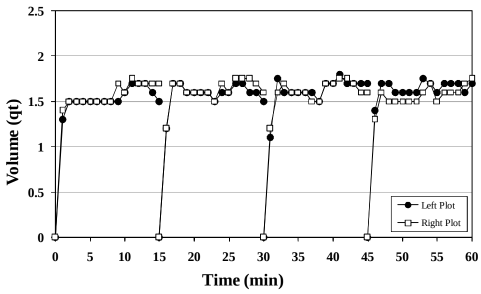
Photograph Not Available
(g) 30 min


(h) 45 min

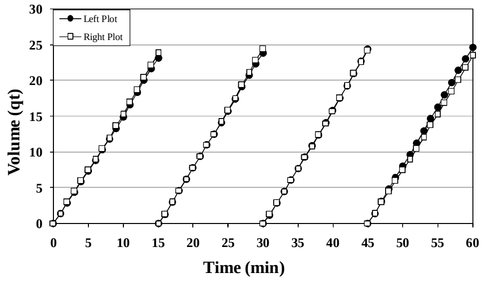

(i) 60 min


(j) 60 min

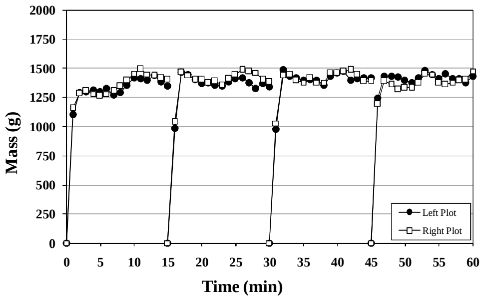
Photographs Documenting Test Plot Conditions during Experimentation.



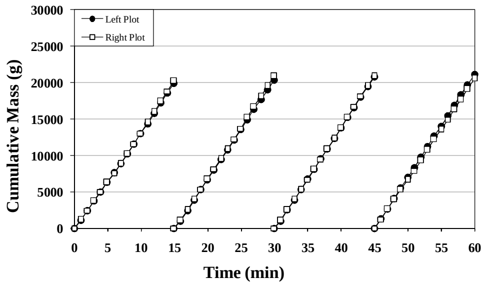
(a) Runoff Volume



(b) Cumulative Runoff Volume

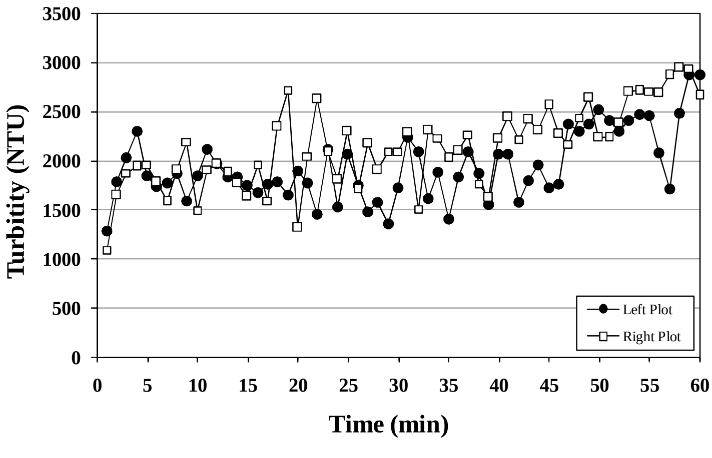


(c) Runoff Mass



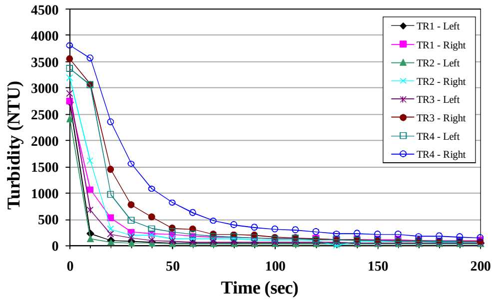
(d) Cumulative Runoff Mass

Surface Runoff Measurements vs. Time.

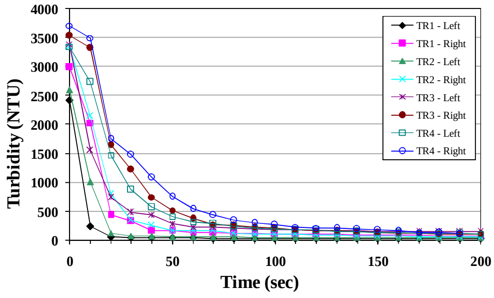


Surface Runoff Initial Turbidity vs. Time.

Experiment: Liquid PAM 25 (2) **Date:** 12/5/08
Treatment: 25 lbs/acre **Exp #:** 14

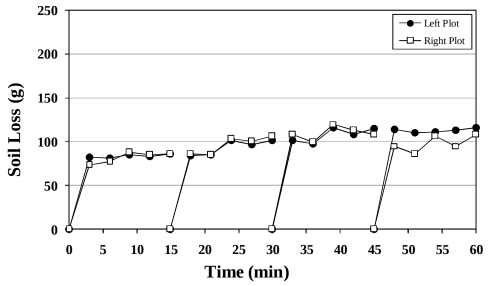


(a) Turbidity vs. Time at 5 Minutes

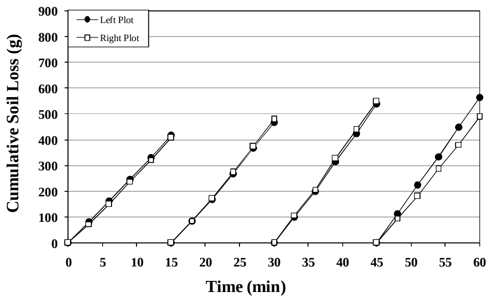


(b) Turbidity vs. Time at 10 Minutes

Turbidity vs. Time for Samples Collected at 5 and 10 Minutes.

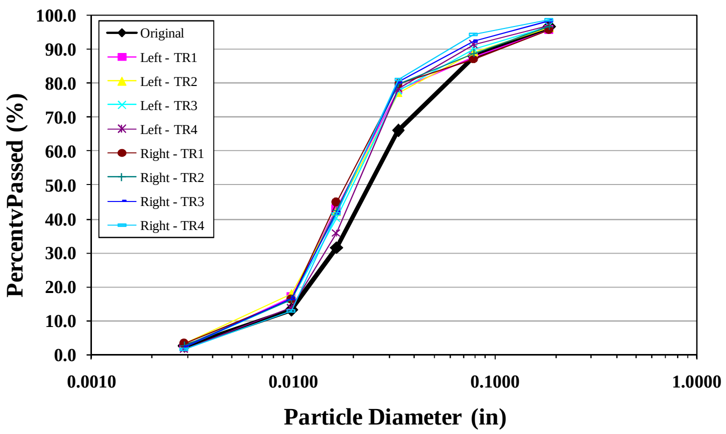


(a) Soil Loss vs. Time



(b) Cumulative Soil Loss vs. Time

Soil Loss and Cumulative Soil Loss vs. Time.



Surface Runoff Sediment Particle Distributions.

APPENDIX E

ANOVA TABLES

Analysis of Variance (ANOVA) Tables for Surface Runoff

Hypothesis:

H_o: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6 = \mu_7$

H_a: All μ_i are *not* equal

Source of Variation	SS	df	MS	F	P-value	F_{crit}	Hypothesis
			Test 1				
Between Groups	2204123	6	367353.9	**12.18**	3.43E-10	**2.19**	$\mathbf{H_a}$
Within Groups	2956310	98	30166.42				
Total	5160433	104					
			Test 2				
Between Groups	1284069	6	214011.6	**6.25**	1.37E-05	**2.19**	$\mathbf{H_a}$
Within Groups	3353084	98	34215.14				
Total	4637153	104					
			Test 3				
Between Groups	610288.3	6	101714.7	**2.76**	0.02	**2.19**	$\mathbf{H_a}$
Within Groups	3607099	98	36807.13				
Total	4217387	104					
			Test 4				
Between Groups	319003	6	53167.17	**1.65**	0.14	**2.19**	$\mathbf{H_o}$
Within Groups	3165506	98	32301.08				
Total	3484509	104					

Where,

μ_i = Mean for i^{th} group [e.i. (1) Control, (2) Dry 35, … ,(7) Liquid 15]
SS = Sum of Squares,
df = Degrees of Freedom,
MS = Mean Square, and
F = F-value
Accept Null Hypothesis: $F_{crit} > F$
Reject Null Hypothesis: $F_{crit} < F$

Analysis of Variance (ANOVA) Tables for Initial Turbidity

Hypothesis:

H_o: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6 = \mu_7$

H_a: All μ_i are *not* equal

Source of Variation	SS	df	MS	F	P-value	F_{crit}	Hypothesis
			Test 1				
Between Groups	111870479.2	6	18645079.87	**1486.55**	7.4E-94	**2.193**	H_a
Within Groups	1229167.264	98	12542.52311				
Total	113099646.5	104					
			Test 2				
Between Groups	119261622.2	6	19876937.03	**2271.97**	8.4E-103	**2.193**	H_a
Within Groups	857380.6778	98	8748.782426				
Total	120119002.8	104					
			Test 3				
Between Groups	136062642.2	6	22677107.03	**2405.26**	5.2E-104	**2.193**	H_a
Within Groups	923956.6102	98	9428.128675				
Total	136986598.8	104					
			Test 4				
Between Groups	177342235.6	6	29557039.27	**1755.24**	2.3E-97	**2.193**	H_a
Within Groups	1650254.49	98	16839.33153				
Total	178992490.1	104					

Where,

μ_i = Mean for i^{th} group [e.i. (1) Control, (2) Dry 35, … ,(7) Liquid 15]

SS = Sum of Squares,

df = Degrees of Freedom,

MS = Mean Square, and

F = F-value

Accept Null Hypothesis: $F_{crit} > F$

Reject Null Hypothesis: $F_{crit} < F$

Analysis of Variance (ANOVA) Tables for Soil Loss

Hypothesis:

H_o: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6 = \mu_7$

H_a: All μ_i are *not* equal

Source of Variation	SS	df	MS	F	P-value	F_{crit}	Hypothesis
				Test 1			
Between Groups	904331.5	6	150721.9	**9.028**	1.59E-05	**2.445**	$\mathbf{H_a}$
Within Groups	467480	28	16695.7				
Total	1371812	34					
				Test 2			
Between Groups	1617987	6	269664.5	**23.23**	1.15E-09	**2.445**	$\mathbf{H_a}$
Within Groups	325011.1	28	11607.5				
Total	1942998	34					
				Test 3			
Between Groups	2329786	6	388297.6	**30**	5.89E-11	**2.445**	$\mathbf{H_a}$
Within Groups	362425.9	28	12943.8				
Total	2692212	34					
				Test 4			
Between Groups	2161449	6	360241.5	**45.65**	3.49E-13	**2.445**	$\mathbf{H_a}$
Within Groups	220947.8	28	7891.0				
Total	2382397	34					

Where,

μ_i = Mean for i^{th} group [e.i. (1) Control, (2) Dry 35, … ,(7) Liquid 15]
SS = Sum of Squares,
df = Degrees of Freedom,
MS = Mean Square, and
F = F-value
Accept Null Hypothesis: $F_{crit} > F$
Reject Null Hypothesis: $F_{crit} < F$

APPENDIX F

FURTHER RESEARCH ON LIQUID PAM

F.1 INTRODUCTION

Experiments previously conducted (i.e. dry vs. liquid PAM applications) by researchers focused on a worst case scenario for testing PAM treatments. This was identified by performing experiments and exposing test plots to rainfall soon after the initial application of both dry and liquid PAM. However, as seen in the literature reviewed in this report, many researchers provided time for liquid PAM treatments to dry prior to performing any testing. The drying times allowed varied and ranged in duration between 1 to 10 days. In the research that had allow treatments to dry prior to testing and had also examined the differences in performance between both dry and liquid PAM treatments, reported that liquid PAM was more effective (Roa-Espinosa et al., 1999 and Peterson et al., 2002). While allowing liquid PAM applications to dry may provide better protection by allowing PAM molecules to bond with the soil surface, the time to permit PAM to dry and provide this quality of protection may be unfeasible due to weather constraints.

As presented in this report, the effectiveness of both dry and liquid PAM applications were examined and compared to determine which treatments were more effective as an erosion and sediment control measure. It was concluded that in these experiments, dry PAM performed significantly better than liquid PAM applications by improving water quality and providing some measure of erosion control. To further examine these results, researchers conducted ancillary experiments with the goal to determining if by allowing liquid PAM treatments time to dry prior to exposure to a storm event, that a better protection against erosion and sedimentation could be provided.

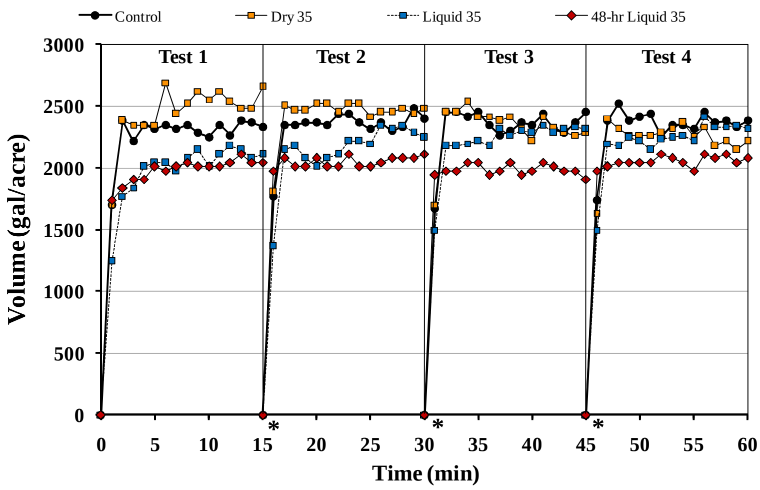
Test plots were set-up using the exact same procedures as outlined in Chapter 3 except that liquid PAM treatments were given 48-hours to dry prior to conducting an experiment (herein referred to as the condition of 48-hr liquid PAM). Two experiments were conducted to provide researchers the same amount of data that were generated in previous conditions examined. The following sections cover the results generated from these additional experiments.

F.2 EXPERIMENTAL RESULTS

Data collection for these additional experiments followed the same procedures as outlined earlier. This included measuring and recording: (1) surface runoff volume, (2) surface runoff mass, (3) initial turbidity, (4) runoff samples (turbidity versus time) and, (5) amount of soil eroded from test plots. Particle size information was not collected since no observable differences occurred between treatments in past experiments. The following sections focus solely on results generated by the recommended application rate of 35 lbs/acre for the three various application methods (i.e. dry granular PAM, liquid PAM, and 48-hr liquid PAM).

F.2.1 Surface Runoff

Surface runoff volumes recorded for each replication are illustrated in Figure F1. Test plots treated with '48-hr liquid PAM were observed to have slightly lower amounts of surface runoff. As stated from the previous experimental results, any difference in runoff amounts was attributed to fluctuations in the operation of the rainfall simulator (i.e. slight pressure increases or decreases). This was confirmed through the fact that runoff amounts did not vary during individual experiments. Specifically, no observable increase or decrease in surface runoff occurred during an experiment duration and the runoff rates remained constant. Therefore, since the runoff rate remained steady throughout an experiment, it was concluded that PAM treatments had no effect on the amount of runoff exiting a test plot.



Note: '*' denotes 15 minute break in between tests

Figure F1 Average Surface Runoff vs. Time.

Table F1 shows the specific values for the average runoff values generated from the additional tests. These values confirm what was illustrated with the runoff volumes shown in Figure F1. The percent reductions in runoff showed that 48-hr liquid PAM experienced an average difference of approximately 11.6% when compared to the control condition. As observed in the previous experiments, this difference in runoff volume was not considered indicative of PAM treatments' performance qualities, but rather the fluctuating conditions of the rainfall simulator, as further confirmed using statistical analyses.

Table F1 Average Surface and Cumulative Runoff for Each Test

Condition	Runoff [a] (gal/acre)	Standard Deviation [b] (gal/acre)	Percent Reduction [c]	Cumulative Runoff [d] (gal/acre)
		Test 1		
Control	2279.0	236.9	-	34184.4
Dry 35	2448.0	328.9	-7.4%	36719.7
Liquid 35	1984.0	264.9	12.9%	29760.3
48-hr Liquid 35	1978.4	107.7	13.2%	32636.0
		Test 2		
Control	2331.1	236.6	-	34967.1
Dry 35	2432.1	289.8	-4.3%	36481.5
Liquid 35	2140.6	251.4	8.2%	32108.5
48-hr Liquid 35	2044.1	81.2	10.3%	32227.6
		Test 3		
Control	2326.6	243.8	-	34899.0
Dry 35	2324.3	263.4	0.1%	34865.0
Liquid 35	2212.0	221.2	4.9%	33180.5
48-hr Liquid 35	1982.9	113.1	13.0%	31802.2
		Test 4		
Control	2335.7	241.2	-	35035.2
Dry 35	2227.9	195.7	4.6%	33418.7
Liquid 35	2210.9	222.6	5.3%	33163.5
48-hr Liquid 35	2051.0	65.7	10.0%	36481.5

Notes: ‘a’ Average surface runoff vs. time for each test
‘b’ Standard deviation of surface average runoff vs. time
‘c’ Denotes values normalized by control condition
‘d’ Average cumulative surface runoff for each 15 min. test

F.2.1.1 Statistical Analysis: Surface Runoff

Following similar procedures to analyze the collected data, an ANOVA analysis with Tukey-Kramer multiple comparisons was used to determine if there was a statistically significant differences observed between treatment pairs. Tables F2 through F5 illustrate the results generated from the Tukey-Kramer analyses and whether or not a specific condition was statistically significant. During the course of the 4 tests, different treatments conditions were observed to have statistically significant differences.

However, these differences varied between tests with little consistency. Therefore, since the different treatment pairs that were statistically significant appear to have no appreciable consistency, it was concluded that the previous assumption that PAM treatments had no affect on surface runoff amounts was validated.

Table F2 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 1*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	169.0	-16.7	169.0	No
Control vs. Liquid 35	**294.9**	**109.2**	**294.9**	**Yes**
Control vs. 48-hr Liquid 35	**300.6**	**114.9**	**300.6**	**Yes**
Dry 35 vs. Liquid 35	**464.0**	**278.3**	**464.0**	**Yes**
Dry 35 vs. 48-hr Liquid 35	**469.6**	**283.9**	**469.6**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	5.7	-180.0	5.7	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

Table F3 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 2*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	101.0	-64.3	101.0	No
Control vs. Liquid 35	**190.6**	**25.3**	**190.6**	**Yes**
Control vs. 48-hr Liquid 35	**287.0**	**121.7**	**287.0**	**Yes**
Dry vs. Liquid 35	**291.5**	**126.2**	**291.5**	**Yes**
Dry vs. 48-hr Liquid 35	**388.0**	**222.7**	**388.0**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	96.4	-68.9	96.4	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

Table F4 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	2.3	-165.0	2.3	No
Control vs. Liquid 35	114.6	-52.7	114.6	No
Control vs. 48-hr Liquid 35	**343.7**	**176.4**	**343.7**	**Yes**
Dry 35 vs. Liquid 35	112.3	-55.0	112.3	No
Dry 35 vs. 48-hr Liquid 35	**341.4**	**174.1**	**341.4**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	**229.1**	**61.8**	**229.1**	**Yes**

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

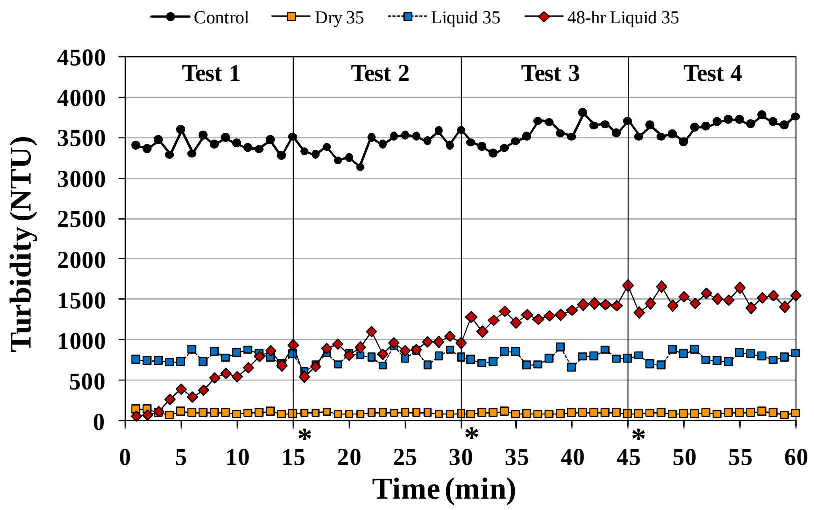
Table F5 Tukey-Kramer Multiple Comparisons on Average Surface Runoff [*Test 4*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	107.8	-52.4	107.8	No
Control vs. Liquid 35	124.8	-35.4	124.8	No
Control vs. 48-hr Liquid 35	**284.7**	**124.6**	**284.7**	**Yes**
Dry 35 vs. Liquid 35	17.0	-143.2	17.0	No
Dry 35 vs. 48-hr Liquid 35	**177.0**	**16.8**	**177.0**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	159.9	-0.2	159.9	No

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

F.2.2 Initial Turbidity

Turbidity levels were recorded from surface runoff that was collected every minute. These recorded levels were referred to as an initial turbidity as surface runoff exited each test plot. The averaged values from experimental replications are illustrated below in Figure F2. It was observed that the 48-hr liquid PAM initial performed similarly to dry PAM, but quickly began to reach turbidity levels that were recorded from liquid PAM treatments without a drying period. This trend continued during the first two tests, but subsequent tests (i.e. test 3 and test 4) showed that turbidity was higher than recorded in the liquid PAM that had no drying period. This difference was observed to be approximately 500 NTU or higher.



Note: '*' denotes 15 minute break in between tests

Figure F2 Average Initial Turbidity of Surface Runoff vs. Time.

Table F6 shows the specific average values from these experiments. On average, 48-hr liquid PAM reduced turbidity levels over time by approximately 69%. Following test 2, these turbidity levels began to increase, as indicated by the decrease in percent reduction to the control condition over time. This increase in turbidity observed in the 48-hr liquid PAM was attributed to how PAM molecules interact with the soil surface when applied. When dry PAM granules are added to water, they become 'activated'. The application is sprayed on to a test plot, and the drying period permits the PAM to bond with surface soil particles and creates an extremely thin layer of protection. This molecular bonding occurred once the PAM was activated by the initial mixture with water, and as rainfall was initiated, the 48-hr liquid PAM remained active in keeping soil attached on the surface. However, once PAM activates, it cannot 'reactivate' and as the PAM was washed away by the runoff, it was incapable of acting as an effective sedimentation control measure by bonding with the suspended soil particles, as witness with dry PAM applications. Once the protective layer of PAM was washed away, the test plots are effectively 'untreated' and result in higher turbidity levels, as observed.

Table F6 Average Initial Turbidity Results for Surface Runoff

Condition	Average Turbidity [a] (NTU)	Standard Deviation [b] (NTU)	Percent Reduction [c]
	Test 1		
Control	3414.7	513.6	-
Dry 35	103.4	28.9	97.0%
Liquid 35	784.8	167.3	77.0%
48-hr Liquid 35	481.3	545.6	85.9%
	Test 2		
Control	3405.4	395.6	-
Dry 35	99.0	14.7	97.1%
Liquid 35	776.7	176.0	77.2%
48-hr Liquid 35	892.3	613.0	73.9%
	Test 3		
Control	3553.6	304.3	-
Dry 35	96.1	15.7	97.3%
Liquid 35	775.5	187.4	78.2%
48-hr Liquid 35	1343.5	453.8	60.7%
	Test 4		
Control	3636.6	233.5	-
Dry 35	95.5	15.2	97.4%
Liquid 35	789.6	145.1	78.3%
48-hr Liquid 35	1498.3	365.5	56.1%

Notes: 'a' Average of initial turbidity vs. time for each test
'b' Standard deviation for average initial turbidity vs. time
'c' Denotes values normalized by control condition

Conversely, liquid PAM treatments that were not given time to dried had recorded turbidity levels that were lower than 48-hr liquid PAM. Since these treatments were not given the time to dry, the molecular bonding with the soil surface did not adequately form. Therefore, liquid PAM treatments were washed off without the means to provide protection on the soil surface. However, the PAM molecules were still active and were able to bond with suspended soil particles in the surface runoff and act as a more effective sedimentation control measure than liquid PAM applications that had dried for 48 hours.

F.2.2.1 Statistical Analysis: Initial Turbidity

Tables F7 through F10 illustrate the results from the Tukey-Kramer multiple comparison. As observed in previous experiments, differences between all possible pairs of condition options were statistically significant. This shows that the all possible combinations of PAM treatments had a significant effect on initial turbidity levels. Combinations with higher values between the mean differences indicate which treatments had a greater effect at reducing turbidity. As observed, dry PAM applied 35 lbs/acre performed the best as a sediment control measure over both different liquid PAM application methods.

Table F7 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 1*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3311.3	3165.1	3311.3	Yes
Control vs. Liquid 35	2629.9	2483.7	2629.9	Yes
Control vs. 48-hr Liquid 35	2933.4	2787.2	2933.4	Yes
Dry 35 vs. Liquid 35	681.4	535.2	681.4	Yes
Dry 35 vs. 48-hr Liquid 35	377.9	231.7	377.9	Yes
Liquid 35 vs. 48-hr Liquid 35	303.5	157.3	303.5	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 3.75

Table F8 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 2*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3306.4	3202.3	3306.4	Yes
Control vs. Liquid 35	2628.7	2524.5	2628.7	Yes
Control vs. 48-hr Liquid 35	2513.1	2409.0	2513.1	Yes
Dry 35 vs. Liquid 35	677.8	573.6	677.8	Yes
Dry 35 vs. 48-hr Liquid 35	793.3	689.2	793.3	Yes
Liquid 35 vs. 48-hr Liquid 35	115.6	11.5	115.6	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

Table F9 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3457.5	3355.4	3457.5	Yes
Control vs. Liquid 35	2778.2	2676.1	2778.2	Yes
Control vs. 48-hr Liquid 35	2210.2	2108.1	2210.2	Yes
Dry 35 vs. Liquid 35	679.3	577.2	679.3	Yes
Dry 35 vs. 48-hr Liquid 35	1247.3	1145.2	1247.3	Yes
Liquid 35 vs. 48-hr Liquid 35	568.0	465.9	568.0	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

Table F10 Tukey-Kramer Multiple Comparisons on Average Initial Turbidity [*Test 4*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	3541.1	3470.2	3541.1	Yes
Control vs. Liquid 35	2847.0	2776.1	2847.0	Yes
Control vs. 48-hr Liquid 35	2138.3	2067.4	2138.3	Yes
Dry 35 vs. Liquid 35	694.1	623.1	694.1	Yes
Dry 35vs. 48-hr Liquid 35	1402.8	1331.8	1402.8	Yes
Liquid 35 vs. 48-hr Liquid 35	708.7	637.7	708.7	Yes

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 3.75$

F.2.3 Turbidity vs. Time

Additional surface runoff samples were collected at every 5 and 10 minutes periods during each test. These samples were used to determine turbidity over time. The three PAM treatments discussed in this section and the control are illustrated together in Figure F3. As observed with previous experiments, the average turbidity levels over time for all of the PAM treatments performed much better than the control condition, by reducing turbidity much quicker. However, when the different PAM treatments were compared together, as seen in Figure F4(a) through F4(f), dry PAM at 35 lbs/acre was able to reduce turbidity levels over time better than both liquid PAM applications throughout all four tests.

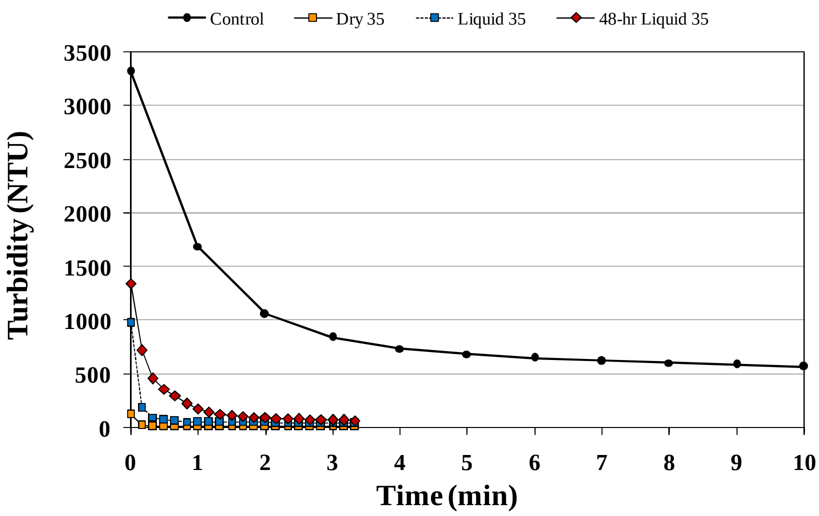
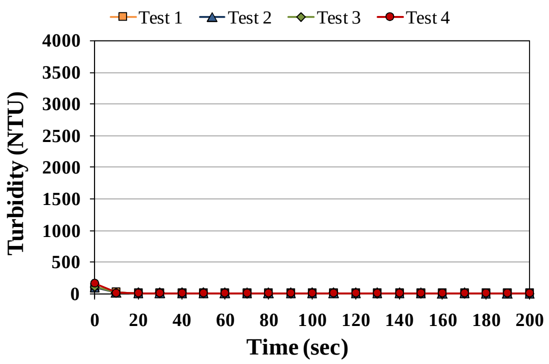
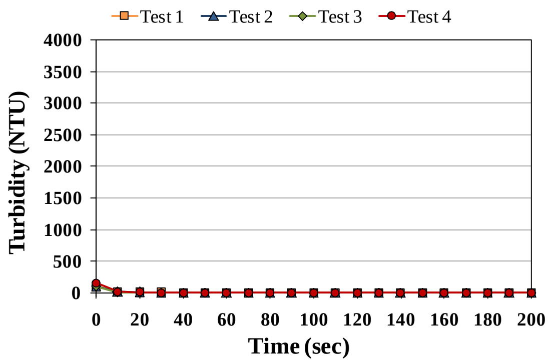


Figure F3 Average Recorded Turbidity for All Samples vs. Time.

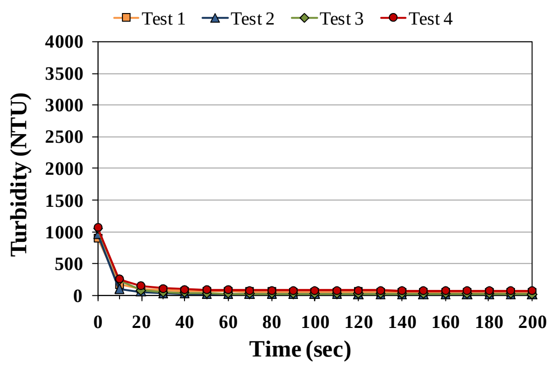
As observed with the recorded initial turbidity levels, 48-hr liquid PAM was able to reduce turbidity during the initial tests, but subsequent tests show that turbidity over time increased, as the PAM treatment were being washed away. Liquid PAM with no drying period was able to provide better sedimentation protection, since the PAM molecules were still relatively active as they were washed away. These figures confirm that dry PAM performs better as a sedimentation control measure than liquid PAM applications.



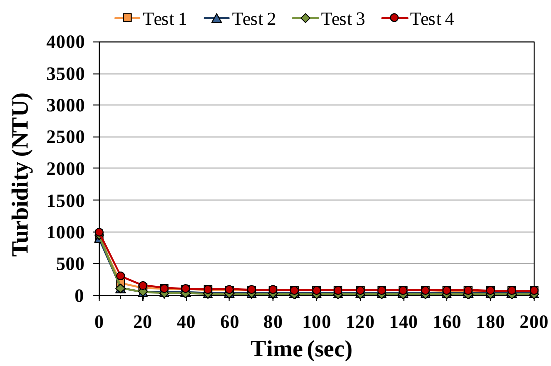
(a) 35 lbs/acre at 5 Minutes [*Dry PAM*]



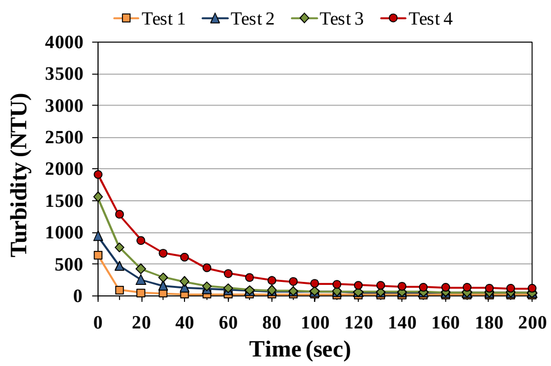
(b) 35 lbs/acre at 10 Minutes [*Dry PAM*]



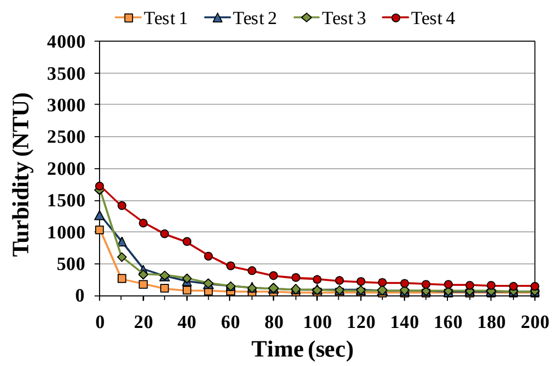
(c) 35 lbs/acre at 5 Minutes [*Liquid PAM*]



(d) 35 lbs/acre at 10 Minutes [*Liquid PAM*]



(e) 48-hr 35 lbs/acre at 5 Minutes [*Liquid PAM*]



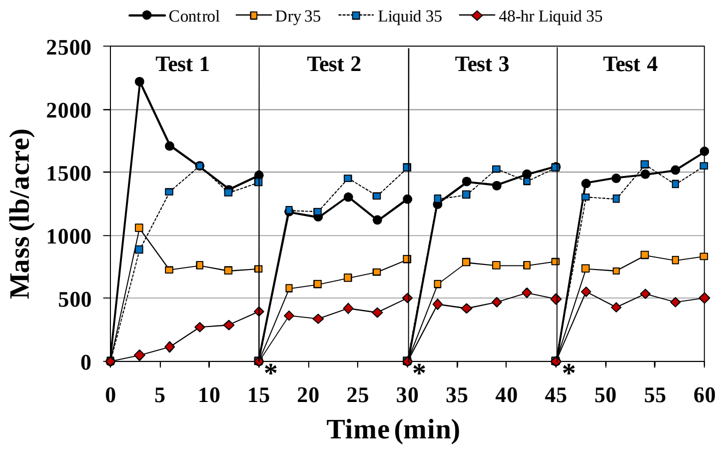
(f) 48-hr 35 lbs/acre at 10 Minutes [*Liquid PAM*]

Figure F4 Treatment's Average Recorded Turbidity from 5 and 10 Minute Samples.

F.2.4 Soil Loss

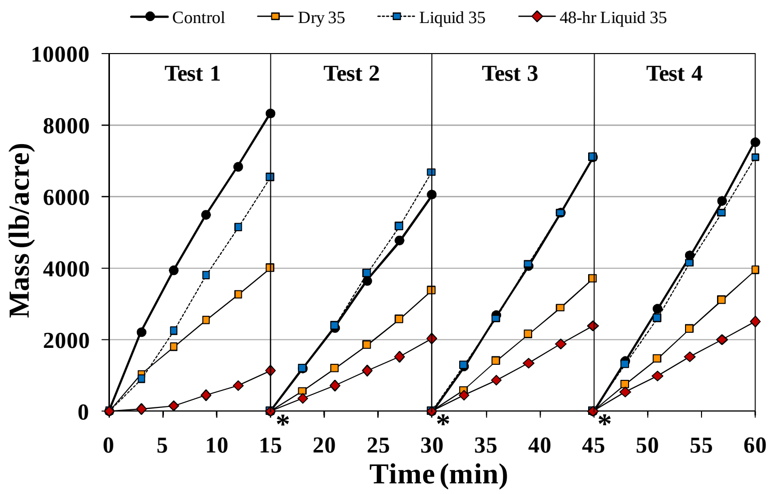
The soil transported from each test plot was collected and filtered at three minute intervals. These soil samples were oven dried and a weight was measured to determine the amount of soil that was eroded from test plots during experimentation. Figure F5 illustrates average soil loss from the test plots versus time and Figure F6 shows cumulative soil loss during an experiment's duration. The additional experiments with 48-hr liquid PAM indicated that the amount of eroded soil from a test plot was much lower than previous experiments of dry PAM and liquid PAM with no drying period.

During test 1, 48-hr liquid PAM experienced very little soil loss, but as the duration of an experiment increased, so did the amount of eroded soil. These increased levels of eroded soil were still observed to be less than previous experiments as shown in Figure F5. Figure F6 illustrates that the total accumulated soil from 48-hr liquid PAM was approximately 2,300 lbs/acre per 15 minute test interval, compared to dry PAM at 35 lbs/acre eroded soil of approximately 4,000 lbs/acre.



Note: '*' denotes 15 minute break in between tests

Figure F5 Average Soil Loss versus Time.



Note: '*' denotes 15 minute break in between tests

Figure F6 Average Cumulative Soil Loss versus Time.

Table F11 shows the specific values of the average soil loss from the experiments. It was observed that 48-hr liquid PAM reduced soil loss when compared to the control by an average of approximately 76%. This is much higher than the dry PAM at 35 lbs/acre by approximately 28%. This indicates that when liquid PAM was allotted a period to dry, it was capable of performing better than dry PAM as an erosion control measure. This is attributed to how liquid PAM bonds with the soil surface as previously stated. Since the liquid PAM was activated when the dry granules were mixed with water, it was able to bond with the soil surface when it was applied. By providing a period of 48 hours for the application to dry, the liquid PAM treatments in this case had ample time to bond with the soil surface and provide a layer of protection against erosion. This layer of protection kept soil particles from being detached from the soil surface and transported in the stormwater. The slight increase observed in soil loss as an experiment's duration increased indicated how this protective layer was slowing being washed away by surface runoff. Therefore, liquid PAM (when allowed to dry) performed better as an erosion control measure, when compared to dry PAM treatments, which performed better as a sediment control measure by improving water quality and reducing turbidity levels.

Table F11 Average Soil Loss due to Surface Runoff

Condition	Soil Loss [a] (lbs/acre)	Standard Deviation [b] (lbs/acre)	Percent Reduction [c]
	Test 1		
Control	1663.8	693.8	-
Dry 35	798.9	293.5	52.0%
Liquid 35	1307.2	377.5	21.4%
48-hr Liquid 35	225.1	157.0	86.5%
	Test 2		
Control	1210.6	189.7	-
Dry 35	674.6	262.9	44.3%
Liquid 35	1337.9	322.9	-10.5%
48-hr Liquid 35	403.9	105.5	75.7%
	Test 3		
Control	1420.7	236.3	-
Dry 35	740.6	308.2	47.9%
Liquid 35	1419.5	256.0	0.1%
48-hr Liquid 35	476.6	120.8	71.4%
	Test 4		
Control	1506.5	194.0	-
Dry 35	787.5	334.6	47.7%
Liquid 35	1421.9	233.5	5.6%
48-hr Liquid 35	499.4	160.7	70.0%

Notes: ‘a’ Average of eroded soil vs. time for each test
‘b’ Standard deviation for average soil loss vs. time
‘c’ Denotes values normalized by control condition

F.2.4.1 Statistical Analysis Soil Loss

Tables F12 through F15 illustrate the Tukey-Kramer analyses on the soil loss for the multiple test plots. For all four tests, dry PAM at 35 lbs/acre and 48-hr liquid PAM at 35 lbs/acre were observed to be statistically significant when compared to the control and other treatments. Liquid PAM 35 did not provide any significant results when compared to the control, indicating that it had no effect in reducing soil loss. The differences in means for 48-hr liquid PAM indicate that this treatment option performed the best out the different combinations.

Table F12 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 1*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**386.5**	**216.0**	**386.5**	**Yes**
Control vs. Liquid 35	121.8	-48.7	121.8	No
Control vs. 48-hr Liquid 35	**960.3**	**789.8**	**960.3**	**Yes**
Dry 35 vs. Liquid 35	**508.4**	**337.8**	**508.4**	**Yes**
Dry 35 vs. 48-hr Liquid 35	**573.8**	**403.3**	**573.8**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	**1082.2**	**911.6**	**1082.2**	**Yes**

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 4.05$

Table F13 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 2*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**569.0**	**458.0**	**569.0**	**Yes**
Control vs. Liquid 35	94.2	-16.7	94.2	No
Control vs. 48-hr Liquid 35	**839.7**	**728.7**	**839.7**	**Yes**
Dry 35 vs Liquid 35	**663.2**	**552.3**	**663.2**	**Yes**
Dry 35 vs. 48-hr Liquid 35	**270.7**	**159.7**	**270.7**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	**933.9**	**822.9**	**933.9**	**Yes**

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 4.05$

Table F14 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 3*]

Comparison	$\mu_i - \mu_j$	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**650.0**	**553.9**	**650.0**	**Yes**
Control vs. Liquid 35	28.8	-67.3	28.8	No
Control vs. 48-hr Liquid 35	**914.1**	**818.0**	**914.1**	**Yes**
Dry 35 vs. Liquid 35	**678.8**	**582.7**	**678.8**	**Yes**
Dry 35 vs. 48-hr Liquid 35	**264.1**	**167.9**	**264.1**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	**942.9**	**846.8**	**942.9**	**Yes**

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
$q_{crit} = 4.05$

Table F15 Tukey-Kramer Multiple Comparisons on Average Soil Loss [*Test 4*]

Comparison	μ_i - μ_j	CI [LB]	CI [UB]	Significantly Different
Control vs. Dry 35	**585.2**	**502.0**	**585.2**	**Yes**
Control vs. Liquid 35	49.2	-34.0	49.2	No
Control vs. 48-hr Liquid 35	**873.3**	**790.1**	**873.3**	**Yes**
Dry 35 vs. Liquid 35	**634.4**	**551.2**	**634.4**	**Yes**
Dry 35 vs. 48-hr Liquid 35	**288.1**	**204.9**	**288.1**	**Yes**
Liquid 35 vs. 48-hr Liquid 35	**922.5**	**839.3**	**922.5**	**Yes**

Notes: [LB] signifies lower bound of confidence interval
[UB] signifies upper bound of confidence interval
q_{crit} = 4.05

F.2.5 Initial Turbidity vs. Soil Loss

The amount of eroded soil was plotted together with its respective turbidity level and this relationship is illustrated in Figure F7. The control condition with all the tested PAM treatments is displayed below and shows the overall performance. As stated, it was observed that dry PAM applications were more effective as a sediment control measure by examining turbidity versus time measurements, and this is also observed in Figure F7. Dry PAM treatments are grouped together towards lower turbidity levels (200 NTU to 1400 NTU). The groupings of data are also more aligned vertically, rather than horizontally, indicating that a relatively more consistent range of turbidity was achieved, while variations occurred in the amount of eroded soil.

Conversely, liquid PAM treatments were more distributed over turbidity measurements, while more consistent levels of soil loss were achieved, especially as observed with 48-hr liquid PAM. This relationship between turbidity and soil loss, as shown, indicates which treatments perform better as either an erosion or sediment control measure. The liquid PAM applications, specifically the 48-hr liquid PAM, were much more efficient at reducing soil loss during the storm duration. Dry PAM, specifically applied at 35 lbs/acre, and was tightly grouped around lower turbidity levels, indicating that this treatment measure was more effective at reducing sedimentation.

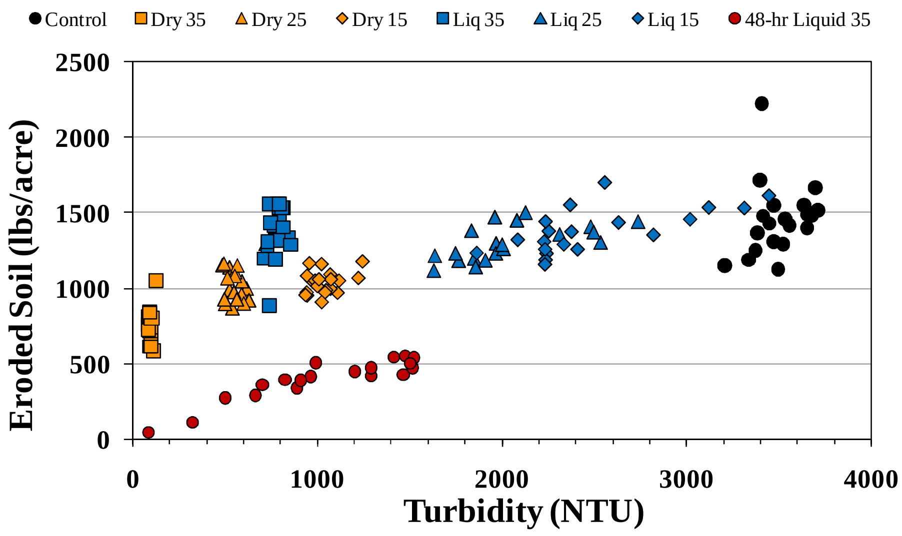


Figure F7 Average Initial Turbidity vs. Average Eroded Soil.

F.3 SUMMARY

These results validate the researcher's claim on how PAM treatments performance was dependent on the method of application. Dry granular PAM performed better as a sediment control measure, due to the fact that as rainfall and surface runoff activated the PAM molecules, they were introduced into the stormwater and bonded with suspended soil particles, promoting flocculation and settling. Liquid PAM that was allowed to dry for 48 hours on the soil surface had time to adequately bond with soil particles and seal the surface, providing a thin layer of protection against erosion. This layer was effective at keeping soil particles from being detached and becoming transported in the stormwater. However, since the PAM was already activated during the application process and bonded with the surface soil particles, any PAM that was washed away in the surface runoff would not bond with the suspended particles, resulting in the higher observed turbidity levels.

The liquid PAM applications that were not given time to dry, were initially activated when applied, but did not have the time to bond to the surface. This resulted in a higher amount of eroded soil from test plots. Since the PAM was still active as it was being washed away by the surface runoff, it was still capable of bonding with some of the suspended soil particles present in the runoff. This resulted in low turbidity levels but were not as effective as dry PAM treatments. This was also the reason why liquid PAM treatments with no drying period performed poorly when it came to erosion control.

F.4 CONCLUSIONS

Two additional experiments conducted by researchers examined the effectiveness of liquid PAM spray applications with a 48 hour dry period prior to exposing test plots to rainfall. Experiments were set-up using the procedures and methods created to simulate the effectiveness of different erosion and sediment control technologies on compacted, 3:1 slopes, representative of typical highway embankments.

Liquid PAM applications were allowed to dry for 48-hours prior to the initiation of rainfall. The period of drying time permitted the PAM molecules to adequately bond with soil particles on the soil surface. This bonding occurred once the PAM was activated by water during its initial mixing. Once the PAM had been activated and bonded with the soil surface, an extremely thin layer protected the surface of the soil and assisted in preventing erosion. This effect was confirmed during experimentation, with the observed values of soil loss being the lowest recorded amount, with an average reduction of 76% when compared to the control condition. This was approximately a 28% increase in difference between dry PAM at 35 lbs/acre, which was reported as the most effective treatments from previous experiments.

However, when looking at the quality of the water in surface runoff, the 48-hr liquid PAM did not perform as well as the dry and liquid PAM treatments (with no drying time). As stated, PAM treatments become active once water is introduced to the PAM molecules. When the liquid PAM treatments were permitted to dry, this activation of molecules had already occurred, and would not occur again. Therefore, there was little bonding occurring with the suspended soil particles in surface runoff, resulting in the higher turbidity levels as observed in the 48-hr liquid PAM treatments. The other liquid PAM treatments were also activated during application, but since the PAM molecules were not given time to bond with the soil surface, they remained active during an experiment's duration. As treatments were washed off the test plots, PAM molecules were still active and could bond with the suspended soil particles and promote flocculation, resulting in better turbidity levels than the PAM treatments that had been given time to dry.

Since this activation of PAM molecules occurs once water is introduced, the dry PAM treatments could not bond with the soil surface during initial application. During the initiation of rainfall the PAM molecules were slowly and consistently introduce into the surface runoff. These newly activated PAM molecules in the runoff could then bond with suspended soil particles, increasing the particle size, and promoting flocculation. This resulted in the very low observed turbidity levels in the surface runoff.

These results indicate that liquid PAM applications (that were given 48-hours to dry) were more effective at reducing the amount of soil loss from test plots. Conversely, dry PAM applications were more effective in reducing turbidity, resulting in improved water quality. These differences in results illustrated that liquid PAM performs better as an erosion control measure, while dry PAM application perform better as an sediment control measure.

F.4.1 Recommendations for Practice

The following recommendations, as outlined below, represent the researcher's opinions on the proper methods for using PAM as an erosion and sediment control measure based on the research presented in this report. Additional recommendations can be found in Applied Polymer's, *"Polymer Enhanced Best Management Practice (PEBMP) Application Guide"* for various products with and without PAM.

RECOMMENDATIONS FOR USING LIQUID PAM (EROSION CONTROL):

1. Obtain soil sample(s) to determine which PAM formulation to use for a specific site location
2. To apply PAM, a type of hydro-seeder with a method of agitation is required.
3. Ensure that PAM application will have time allotted for drying after application.
4. When preparing treatment, ensure that the recommended rate of dry PAM granules are *slowly* added to the water and remain agitated to prevent clogging.
5. Ensure that PAM has been fully mixed in water prior to application

6. Spray application **must** be *uniformly* sprayed with *100% coverage* of the soil surface; else treatment will not be effective.
7. Additional sediment control technologies must be used in conjunction with liquid PAM treatment to ensure maximum protection.

RECOMMENDATIONS FOR USING DRY PAM (SEDIMENT CONTROL):

1. Obtain soil sample(s) to determine which PAM formulation to use for a specific site location.
2. The recommended dry PAM granules must be spread (by hand or mechanically) uniformly on the soil surface.
3. Additional erosion control technologies must be used in conjunction with dry PAM to ensure maximum protection is provided.

F.4.2 Recommendations for Future Research

As stated in the recommendations for practice, PAM should never be used by itself as an erosion and sediment control measure. This was confirmed through the research presented, by demonstrating that neither application method was fully capable of providing both erosion and sediment control effectively. Therefore, additional research should be conducted to investigate which combination of PAM and additional erosion and sediment control technologies will provide the best solution from preventing excess NPS pollution, through cost-effective measures. Examples of these erosion and sediment control technologies to test with and without PAM in regards to slope stabilization include: (1) Organic Erosion Control Blankets (ECBs), (2) Inorganic ECBs, (3) Soft-Armoring, (4) Mulching, (5) Jute matting, and (6) Geo-synthetic materials.

By examining these products, with and without the addition of PAM, best management practices (BMPs) could be recommended and selected for practical use based on the cost and quality of performance. Analyses could focus the long-term effectiveness for each product and how this would relate to maintenance costs and the necessary time for more permanent products to be implemented (i.e. vegetative cover). This research would provide an invaluable tool for contractors, with the potentially stricter EPA effluent guidelines currently under review, which would require more proactive responses to erosion and sedimentation issues, rather than many reactive responses current in use today. Therefore, these erosion and sediment control technologies would be examine, analyzed, and evaluated using stringent scientific and engineering methods to ensure the best solution, for all interested parties, were selected.