Novel Biopolymer Treatment for Wind Induced Soil Erosion

by

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ABSTRACT

It is estimated that wind induced soil transports more than 500 x 10^6 metric tons of fugitive dust annually. Soil erosion has negative effects on human health, the productivity of farms, and the quality of surface waters. A variety of different polymer stabilizers are available on the market for fugitive dust control. Most of these polymer stabilizers are expensive synthetic polymer products. Their adverse effects and expense usually limits their use. Biopolymers provide a potential alternative to synthetic polymers. They can provide dust abatement by encapsulating soil particles and creating a binding network throughout the treated area. This research into the effectiveness of biopolymers for fugitive dust control involved three phases. Phase I included proof of concept tests. Phase II included carrying out the tests in a wind tunnel. Phase III consisted of conducting the experiments in the field. Proof of concept tests showed that biopolymers have the potential to reduce soil erosion and fugitive dust transport. Wind tunnel tests on two candidate biopolymers, xanthan and chitosan, showed that there is a proportional relationship between biopolymer application rates and threshold wind velocities. The wind tunnel tests also showed that xanthan gum is more successful in the field than chitosan. The field tests showed that xanthan gum was effective at controlling soil erosion. However, the

chitosan field data was inconsistent with the xanthan data and field data on bare soil.

DEDICATION

To Aziz and Hana.

ACKNOWLEDGEMENTS

I am heartily thankful to my advisor, Dr. Edward Kavazanjian, whose guidance and support throughout the course of this research enabled me to reach the point I am at now. I would like also to thank my parents and my wife who gave me the moral support I required.

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Chapter 1

INTRODUCTION

Windblown soil is a source of both air pollution and water pollution. Windblown soil can have significant adverse impacts on human health and the environment. Adverse impacts of blown soil, or fugitive dust, include increased respiratory symptoms, soil loss, sediment fouling of streams, visibility reduction, changed nutrient balance of lakes and rivers, and aesthetic damage. Extensive fugitive dust can cause some urban areas to be classified as non-attainment zones by the U.S. Environmental Protection Agency. Phoenix is an example of an air quality non-attainment zone due to fugitive dust. Other parts of the world, including large areas of the Middle East, also are susceptible to large amount of wind erosion. In the extreme, lack of vegetative cover combined with uncontrolled wind erosion may lead to what it is called dust bowls. Among regions described as dust bowls is the United States Great Plains in 1930s. The Great Plains dust bowl forced hundreds of thousands of farm families to leave their states.

Until recently, finer grained particles present the greatest potential threat with respect to health effects. Air quality standards have been based upon the concentration of suspended particles greater than 10 microns (0.01 mm) in dimension (PM_{10}). Recent research has suggested an even smaller threshold particle size, on the order of 2.5 microns ($PM_{2.5}$) should be employed in air quality standards.

Several mitigation measures can be used to reduce wind erosion and fugitive dust generation. In general, these goals can be achieved by either protecting the soil surface or reducing the surface wind velocity. Some of the better soil erosion control measures are establishment of vegetative cover, application of mulch, soil stabilizers, or water, surface roughening procedures, and physical wind construction of barriers (Idaho Department of Environmental Quality, 2005). Construction sites are a significant source of fugitive dust, as they disturb natural stabilizing agents such as vegetation and biological soil crusts, leaving the ground very susceptible to wind erosion.

This dissertation focuses on evaluating unique stabilizing agents for short-term dust control at construction sites and other areas where temporary protection is needed. The unique stabilizing agents evaluated in this dissertation are biopolymers; biopolymers are environmentally friendly products that bind soil particles together upon application, making them harder to erode. Some biopolymers are water soluble whereas others are not water soluble. Logically, non water soluble biopolymers may provide enhanced effectiveness against water erosion. Therefore, the effectiveness of one water soluble biopolymer and one non water soluble biopolymer in controlling wind erosion of soil was evaluated in this research.

Wind Erosion

Erosion is defined as the result of processes that involve wearing or grinding the earth’s surface. Soil and rock debris can be eroded and carried away from their original locations by streams, ocean currents, waves, wind, groundwater, glaciers, and gravity. Each of these erosional agents may cause physical changes; and these changes depend on the magnitude of the agents and the nature of the soil and rock (Mitchell & Soga, 2005). When the transporting agent is wind, the erosion is called wind erosion. In a different usage, when the land surface affected by eroding agents is rock or soil, the process is referred to as rock or soil erosion, regardless of the nature of the erosion agent.

Erosion occurs when the drag and lift of the eroding substance surpasses the gravitational, cohesive, and frictional forces that hold the particles together (Mitchell & Soga, 2005). As shown in figure 1, air is slightly more effective than running water as an erosion agent for fine grained particles (i.e., particle size < 0.2 mm or fine sand). On the other hand, water is more effective than air as an erosional agent for particles larger than sand. Figure 1 shows the general relationship among velocity, particle size, erosion, transport, and deposition for wind water erosion.

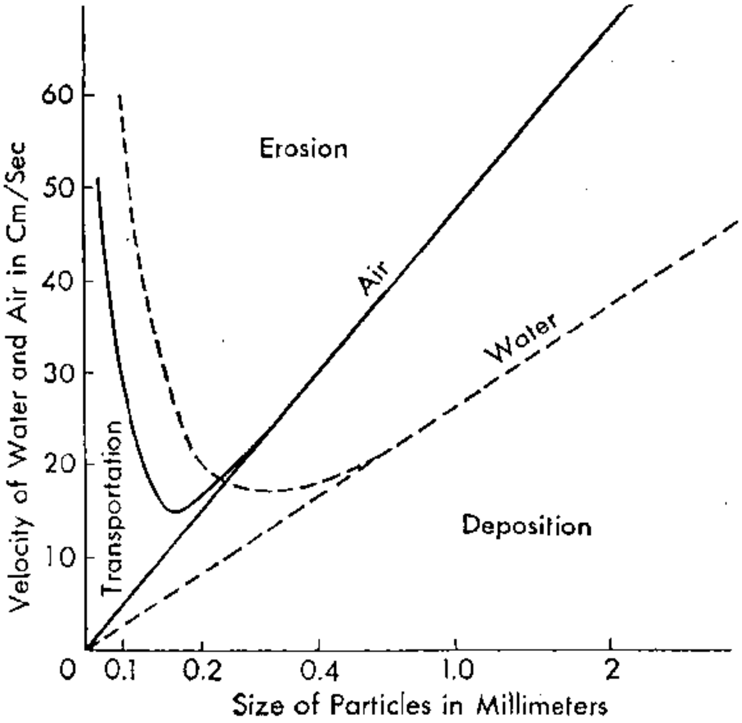


Figure 1: Comparison of Erosion and Transport Curves for Air and Running Water. Source: (Garrels, 1951)

Particle size plays a significant role in wind erosion. Wind usually detaches and moves smaller soil particle at lower velocities than larger particles for cohesionless sand and silt sized particles. However, very fine grained particles will be resistant to detachment due to inter particle attraction (cohesion). Once particles are detached, the moving particles abrade the soil surface and dislodge other particles, intensifying erosion. Therefore, a soil with high clay content has less wind erosion potential than a soil with low clay content. This is due to the stability of soil aggregates created by inter-particle cohesion (Wilson, Smith, Miller, & Fornstorm, 2001).

Table 1 compares sediment transport agents in terms of the type of flow (turbulent or laminar), typical velocities, maximum eroded particle size, area affected, and relative effect on a geological scale. Streams and rivers are the most important agents on a geological scale with respect to the overall amount of sediment moved. Wind may be a significant source of erosion, particularly in arid climates. Settling velocities of particles as well as the laws of fluid motion control the movement of sediment in suspension by wind or water (Mitchell & Soga, 2005). Particle movement can be described as occurring in three stages: erosion (or detachment), transport, and deposition.

Table 1

Comparison of Sediment Transport Agents

Agent	Type of Flow	Approximate Average Velocity	Maximum Size Eroded by Average Velocity	Areas Affected	Relative Effect
Streams	Turbulent	A few km/h	Sand	All land	1
Waves	Turbulent	A few km/h	Sand	Coastlines	2
Wind	Turbulent	15 km/h	Sand	Arid, semiarid, beaches, plowed fields	3
Groundwater	Laminar	A few m/yr	Colloids	Subsurface	3
Gravity		cm/yr to a few m/s	Boulders	Steep slopes, sensitive clays, saturated cohesionless soils, unconsolidated rock	3

Source: excerpted from (Mitchell & Soga, 2005)

Soil Loss Problems

One of the most significant effects of wind erosion is soil loss. Soil loss may interfere with human needs and cause crises. The world food programme (WFP) describes the situation in Lesotho, a small country in South Africa, by saying: “Agriculture in Lesotho faces a catastrophic future, crop production is declining and could cease altogether over large tracts of the country if steps are not taken to reverse soil erosion, degradation and the decline in soil fertility" (World Food Programme, 2002). Lack of vegetative cover as well as uncontrolled wind erosion may lead to what are called dust bowls. Among well-known dust bowls are the United Stated Great Plains in 1930s, Soviet Virgin Lands in 1960s, and Northwest China and the Sahelian region of Africa in 2006. The Great Plains incident forced hundreds of thousands of farm families to leave their states.

It is estimated that two to three billion tons of fine soil particles leave Africa annually in the form of dust storms. As a result, the land's fertility is highly diminished. These dust storms can transport sediment or dust to the West where it can settle in the Caribbean, affecting its coral reefs (Brown, 2003). The U.S. EPA classifies soil loss impacts as on-farm impacts and off-farm impacts. Among on-farm impacts are lower fertility levels, development of rills and gullies in the field, poorer crop yields, less water infiltration into the soil, more soil crusting, and more runoff in the spring and after storms. Off-farm impacts include eroded soil deposited in depressions and adjacent fields, decreased water quality downstream, declining downstream aquatic ecosystems due to sedimentation and addition of nutrients, pesticides, and bacteria associated with the soil, and clogged drainage ditches (U. S. Environmental Protection Agency, 2009).

Wind Erosion Globally

Natural and disturbed soil surfaces susceptible to wind erosion are not region specific. Such surfaces are stretched over five continents (Shao, 2000). Below are major wind erosion regions around the world.

The Sahara. The Sahara is both the largest desert on earth and the largest source of dust. It covers almost all of North Africa. The exact locations of the dust sources within the Saharan desert are controversial due to the geomorphology of the region which consists of rock deserts, gravelly soils, loamy silts, salt deserts, sand deserts, and a mixture of these types. Wind erosion peaks between March and June and is somewhat weak between September and January.

The Middle East. The highest rate of dust storms in the Middle East occur in the alluvial plains of Iraq and Kuwait, as well as the city of Abadan in Iran. The maximum dust activity is observed in summer (Kutiel & Furman, 2003). The shamal winds (northwest winds) play a major role in these dust storms (Shao, 2000). These storms have negative effects on the region. For example, in June 2008, oil exports from Iraq and Kuwait were halted for several days due to dust storms from the northern gulf (Nouiehed, Benham, Rasheed, & Hammond, 2008). On March 10th 2009, dense dust storms enveloped the capital of Saudi Arabia (Riyadh), which led to the closure of King Khalid International Airport for several hours (AFP, 2009). A picture of a 2009 dust storm in Saudi Arabia is shown in figure 2.

Figure 2: March 10th, 2009 Dust Storm in Riyadh (Saudi Arabia). Image Courtesy of Maurizio Pani. Used with Permission

China. Desert areas such as the Sandy lands in western and northwestern China as well as in the Gobi desert in the northern and northeastern regions of China are major sources of Asian dust. These areas occupy about 13 percent of China's total surface area. Dust storms are common in spring and winter season, peaking in the month of April. Soil previously frozen in winter season becomes loose upon thawing and hence susceptible to wind erosion (Shao, 2000).

North America. Figure 3 shows areas in the United States susceptible to large amounts of wind erosion. Wind erosion events in Northern America are widespread in the Great Plain (U. S. Environmental Protection Agency, 2009). These areas include Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas and Wyoming in the United States, and Alberta, Manitoba and Saskatchewan in Canada. Wind erosion is attributed to high wind speed and lack of vegetative cover (Shao, 2000).

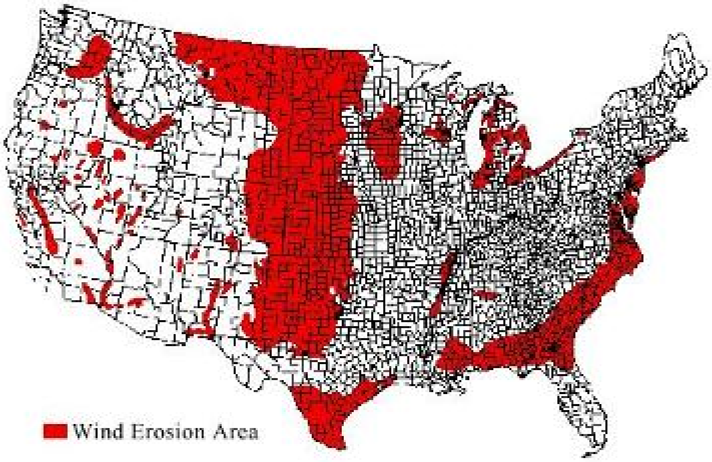


Figure 3: Map of Wind Erosion Areas in the United States. Source: (U. S. Environmental Protection Agency, 2009)

Australia. Most wind erosion events in Australia are seen in agricultural areas. The clearance of vegetation, intensive farming, and grazing in past two centuries has increased the extent of wind erosion in Australia. Dust storms frequencies are the highest in these six regions: Central Australia, Central Queensland, the Mallee region, the eastern and western Nullarbor region, and coastal Western Australia. Drought years influenced by El Nino phenomena have induced more wind erosion events (Shao, 2000).

Economic Damage from Soil Erosion

Peterson and Junge, 1971, estimated that wind transports more that 500 x 10^6 metric tons of dust annually, as cited in (Greeley & Iversen, 1985). Soil erosion has negative effects on the productivity of farms and the quality of surface waters. Since the 1930s, the Federal government in the U.S. spent \$15 billion on soil conservation practices. This is in addition to the many billions farmers have spent themselves on their farms. Others have estimated the national losses to farmers to range from \$500 million to \$1 billion a year.

The productivity of farms is affected in terms of reduced yields and increased costs of inputs (i.e., fertilizers). The yields are reduced due to the reduction of water holding capacity, infiltration rates, nutrient availability, organic matter, and other topsoil characteristics. The loss of rooting depth and water holding capacity can even cause permanent loss to yields. A breakdown of the costs associated with soil erosion is estimated to be, \$420 million for crop production losses, \$105 million to $168 million for fertilizer losses, and $1.2 billion for erosion control (Colacicco, Osborn, & Alt, 1989).

Health Effects

Airborne (suspended) particulate matter is one of the products of eroded soil. Inhaled particulate matter can cause exacerbation of airways disease, diminished lung function, and increased cardiovascular mortality (Gilmour, Brown, Lindsay, Beswick, MacNee, & Donaldson, 1996). Furthermore, particulate matter reduces visibility (especially $PM_{2.5}$), changes the nutrient balance of lakes and rivers due to the particles that settle in them, and causes aesthetic damage (U.S. Environmental Protection Agency, 2008).

Air Quality Regulations

The U.S. Environmental Protection Agency derives its responsibility toward the nation's air quality through the Clean Air Act. The Clean Act was last amended in 1990. Its goal is to provide adequate health and environmental protection by enforcing clean air standards such as NAAQS or the National Ambient Air Quality Standards (40 CFR part 50). NAAQS defines six principal pollutants which are as follows: carbon monoxide (CO), lead (Pb), nitrogen dioxide

(NO_2), particulate matter (PM_{10}, $PM_{2.5}$), ozone (O_3), and sulfur dioxide (SO_2) (U.S. Environemental Protection Agency, 2010).

An area is designated as an air quality non-attainment area when air pollution levels exceed the national ambient air quality standards for several consecutive years. Non-attainment areas are subject to further actions by EPA to improve the area's air quality based on the State Implementation Plans (SIPs). As of March 3rd 2010, Phoenix, Arizona is one of eight cities in the United States listed as being "serious" non-attainment zones for PM_{10}. A serious non-attainment classification refers to a severe violation of the standard PM_{10} (U.S. Environemental Protection Agency, 2010).

EPA first designated the Phoenix area as a serious non-attainment area in 1996. Since the "non-attainment area" in the Phoenix area failed to attain the NAAQS by the December, 31, 2006 deadline set by EPA in its notification, a special requirement under Section 189(d) of the Clean Air Act was triggered. Under the special requirement, the Phoenix area (Maricopa County) was to have not less than 5 percent annual reductions of PM_{10} or PM_{10} precursors until the NAAQS are attained. According to Maricopa County, the primary sources of particulate matter (PM) pollution in the county are construction activities, paved road dust, unpaved roads and parking lots, agricultural activities, windblown dust from disturbed vacant lots, construction sites and agricultural fields, fires and open burning, dust from off-road recreational vehicles, leaf blowers, and exhaust from cars.

Project Statement

A variety of different polymer stabilizers are available on the market for fugitive dust control. Most of these polymer stabilizers are expensive synthetic polymer products. Their expense usually limits the use of the polymers to either long-term stabilization or temporary stabilization of small areas. Being synthetic often means that there are one or more constituents that might have adverse effects on the environment. Biopolymers on the other hand are considered environmentally friendly and could be cost effective when the source is carefully selected (e.g., food industry byproducts that are usually considered wastes). This research is attempting to evaluate the feasibility of biopolymer alternatives to synthetic polymers for short-term stabilization against wind erosion that are both effective and economical.

As the next section will demonstrate, biopolymers play a role in the formation of biological soil crusts that are known to provide effective resistance against wind erosion. Cyanobacteria and microfungi, which are components of biological soil crust, have biopolymer filaments that glue loose particles together by weaving through the top few millimeters of soil. Some of the biopolymers tested in this research have filaments like those in biological soil crust. Part of the guiding philosophy of this research is to use biopolymers in a manner that simulates some of the characteristics that allow biological soil crusts to create a surface able to resist wind erosion.

The primary objective of this research is to experimentally evaluate selected biopolymers as stabilizing agents against wind erosion. Three phases of experimentation will be incorporated in this proposed research. Beside soil sampling and biopolymer preparations, the phases of research include the following: Phase I consisted of proof of concept tests; Phase II consisted of wind erosion tests conducted in a more scientific manner, with more sophisticated equipment and controlled parameters. Phase III consisted of biopolymer stabilization experiments in the field. Table 2 briefly summarizes each Phase of the research program.

Table 2

Phases of Research

Phase	Surrounding Surface	Wind source	Purpose
I	Aluminum Duct Work	Industrial Fan Leaf blower	Proof of Concept
II	Full Scale Wind Tunnel (Planetary Geology Wind Tunnel)	Wind Turbine	Quantitative Evaluation of Erosion Resistance
III	Open Field (Butterfield Station Landfill)	Daily Climate	Field Evaluation of Erosion Resistance

Specific tasks undertaken to achieve the research objectives include:

- Conduct a literature review to determine possible biopolymers that could be used as soil stabilizers.
- Develop a method for determining soil loss caused by wind erosion and a method for quantifying biopolymer effects.

- Carry out experiments to determine the effectiveness of certain biopolymers in meeting soil stabilizing objectives.

Organization

This dissertation is organized as follows. Chapter 2 presents a literature review. Chapter 3 states the research plan. Chapter 4 describes the initial proof of concept experiments. Chapter 5 presents the results of wind tunnel experiments. Chapter 6 describes the field experiments. Chapter 7 presents conclusions and discusses potential future research opportunities.

Chapter 2

LITERATURE REVIEW

Wind

Wind is generated from the unequal solar heating. The flow of wind is similar to that of streams; laminar when slow and turbulent when fast. Furthermore, wind flow can be slowed down by the same frictional forces as that of running water (Garrels, 1951).

Wind velocity can be described qualitatively using the Beaufort scare. The Beaufort scale was invented by Admiral Sir Francis Beaufort of the British Navy in 1805 based on observed sea conditions (i.e., wave heights and foams). It simplifies wind speeds to the public (Coasts, 1993).

Table 3

Beaufort Wind Scale

Beaufort Number	Description	m/s
1	Light air	0.3 – 1.5
2	Light breeze	1.6 – 3.3
3	Gentle breeze	3.4 – 5.4
4	Moderate breeze	5.5 – 7.9
5	Fresh breeze	8.0 – 10.7
6	Strong breeze	10.8 – 13.8
7	High wind, Moderate gale, Near gale	13.9 – 17.1
8	Gale, Fresh gale	17.2 – 20.7
9	Strong gale	20.8 – 24.4
10	Storm, Whole gale	24.5 – 28.4
11	Violent storm	28.5 – 32.6
12	Hurricane-force	> 32.7

Source: (Coasts, 1993)

Particle Dynamics

There is extensive literature on the three principal types of particle movement: suspension, saltation, and surface creep. Figure 4 illustrates these three windblown (aeolian) transport of soil particles. Each type of particle movement is described briefly below.

Suspension particulates are those who range in size from about 2 to 100 µm. The particles can stay suspended in air as long as there is an upward air force strong enough to carry their weight. Suspension of particles causes loss of agricultural productivity in open fields. Saltation is when wind dislodges individual particles (100 to 500 µm) from the ground and then the particles follow a trajectory movement. Saltation occurs prior to, and at lower velocity than, suspension. Particles that are too large to leave the surface (500 to 1000 µm) creep along the surface. Surface creep depends on wind speed, particle size distribution, and roughness (Lyles, Hagen, & Skidmore, 1983).

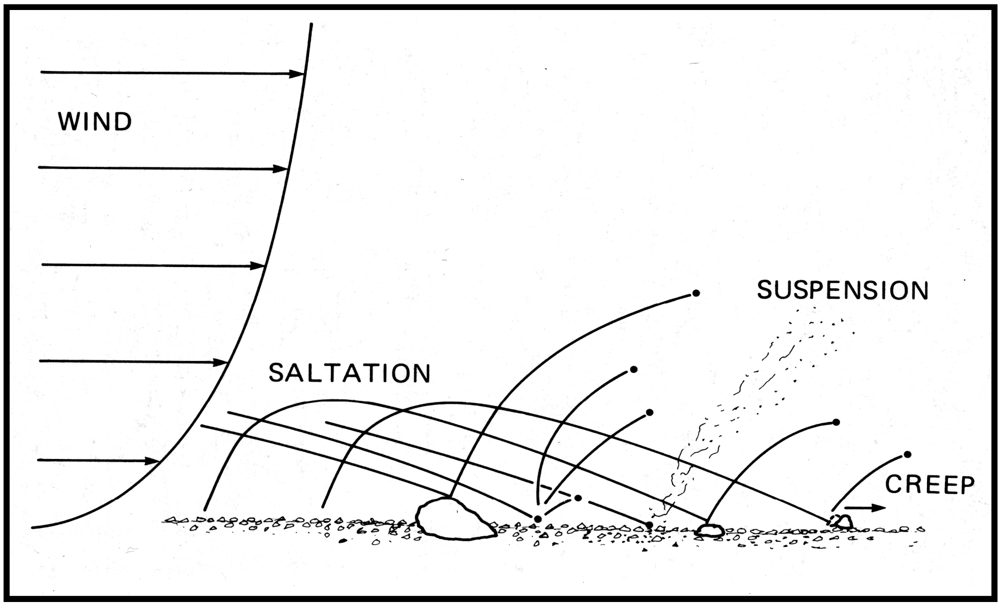


Figure 4: Diagram Showing the Principal Modes of Aeolian Transport of Grains. Source: (Greeley & Iversen, 1985)

The threshold friction velocity (TFV) is an important parameter in wind erosion studies. It is important because it controls the frequency and the intensity of wind erosion events (Gillette & Belnap, 1997). Threshold friction velocity is defined as the minimum velocity required to detach soil particles from the surface (Belnap & Gillette, 1998). Factors that influence the TFV include roughness of the surface, size of erodible units, and the presence of cyanobacterial-lichen soil crusts (Gillette & Belnap, 1997).

Particulate Matter

Air pollution has a significant health impact on humans. These impacts can range from premature deaths and respiratory symptoms to simply discomfort. Air pollution is a mixture of various pollutants; particulate matter is one of them. Particulate matter refers to both solid and liquid particles suspended in air. Some particulate matter may be hazardous. The solid particles in suspension in the air are the ones of concern in the research. Geographic area, season, source, and climate are all factors that determine the composition of solid particulate matter.

Particles in the suspension in the air are classified by their aerodynamic diameter, which is "the diameter of a uniform sphere of unit density that would attain the same terminal settling velocity as the particle of interest" (Frumkin, 2005, p. 341). PM_{10} are those particles with an aerodynamic diameter of 10 microns or less, while $PM_{2.5}$ (or fine PM) are those with an aerodynamic diameter up to 2.5 microns. Ultrafine particles refer to particles with an aerodynamic diameter up to 0.1 microns. Total suspended particles, or TSP, are all particles suspended in the air up to 45 microns in diameter (Frumkin, 2005). Figure 5 shows a typical size distribution for particles suspended in the air. Note the bi-model nature of this distribution. In practice, the mass of particles less than 2.5 microns ($PM_{2.5}$) and the mass of particles less than 10 microns (PM_{10}) are used to quantify potential health impacts of suspended particles.

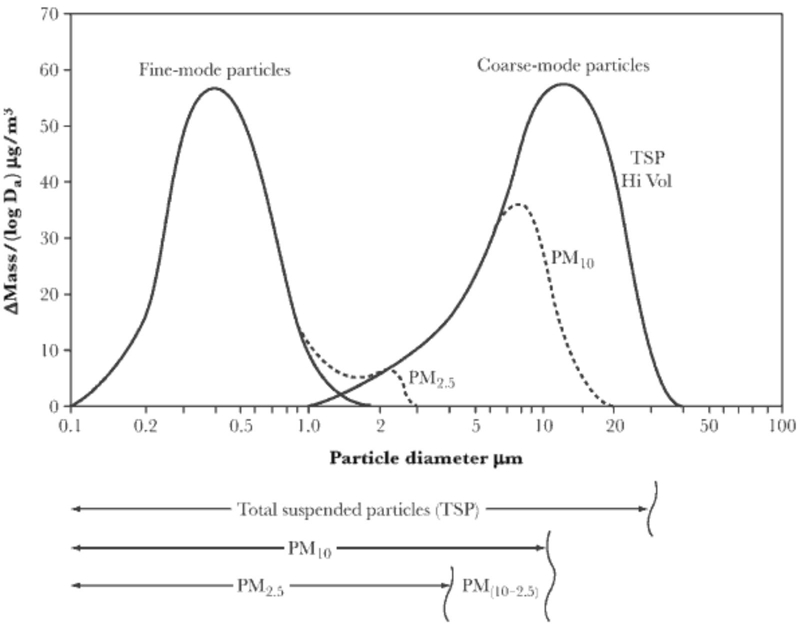


Figure 5: Particulate Matter Mass Distribution. Source: (Frumkin, 2005)

Knowing the size of a particle is essential in knowing its source, the way it is transported, and the way it is deposited in the environment as well as in a human respiratory system. The smaller the particle size, it can remain in suspension and be transported and the easier it can penetrate deeply into the lungs.

According to the Environmental Protection Agency, particulate matter has adverse effects on both human health and the environment. Some of the health effects of suspended particulate matter are increased respiratory symptoms. For example, irritation of the airways, coughing or difficulty breathing, decreased lung function, aggravated asthma, development of chronic bronchitis, irregular heartbeat, nonfatal heart attacks, and premature death in people with heart or lung disease are all health effects associated with suspended particles. Environmental effects of suspended particles include visibility reduction (especially $PM_{2.5}$), changing the nutrient balance of lakes and rivers by the traveled particles that settle over them, and aesthetic damage (U.S. Environmental Protection Agency, 2008). In 1971, the National Ambient Air Quality Standards under the Clean Air Act (40 CFR part 50) only included total suspended particles (TSP). Then, due to the increased knowledge of the effects of smaller particles (i.e., PM_{10} health effects), a PM_{10} standard replaced TSP's standard in 1987. The same occurred with $PM_{2.5}$ standard which replaced PM_{10} in 1997 (Frumkin, 2005).

Dust

There are several definitions for dust. One of them is a cloud of fine dry particles that are formed by disintegration processes like grinding, crushing, or impact. In this dissertation, dust refers to any fine soil particle suspended in the air. Dust is composed of different particle sizes. The particle size determines the transport and placement of the particles (i.e., particles that are too large to remain in the air settle on the ground while the others stay airborne) (Mody & Jakhete, 1988).

Even though dust formation is inevitable in many cases, it is important to control it to minimize its undesirable impacts. Among the undesirable impacts of dust are: 1) health hazards such as occupational respiratory diseases, irritation to eyes, ears, nose, throat, and skin. 2) Risk of dust explosions and fire. 3) Damage to equipment. 4) Impaired visibility. 5) Unpleasant odors. 6) Problems in community relations. Workers that are directly exposed to excessive amounts of dust are subject to significant risks. The American Conference of Governmental Industrial Hygienists (ACGIH) has adopted threshold limit values (or TLVs) as standards to regulate health hazards in the work place (Mody & Jakhete, 2008).

Types of Dust

Types of dust include biologically toxic dust, nuisance dust, respirable dust, inhalable dust, and total dust. Biologically toxic dust such fibrogenic dust (i.e., free crystalline silica (FCS) or asbestos) can form scar tissue and impair the lungs ability to function properly if retained in the lungs. Dust that contains less than one percent quartz is called nuisance dust. Due to its low quartz content, it will not cause serious health problems. However, higher concentrations of nuisance dust may reduce visibility, cause unpleasant deposits in eyes, ears, and nasal passages, and may cause injury to the skin or mucous membranes by chemical or mechanical action.

From an occupational health perspective, dust is divided into three classes based on the particle size. These classes are:

Respirable dust. Dust particles that are small enough to penetrate the nose and upper respiratory system. Due to their deep penetration, those particles are most likely to be retained in the lungs.

Inhalable dust. According to EPA, inhalable dust particles are those particles which, when entering the human body, get trapped in the nose, throat, and upper respiratory tract. The median aerodynamic diameter of inhalable dust is about 10 microns.

Total Dust. Total dust includes all dust particles (Mody & Jakhete, 2008).

Methods for Short-term Erosion Control at Construction Sites

1. In the Phoenix state implementation plan (SIP), construction sites have been identified as a significant source of fugitive dust.
2. Construction activities strip vegetation, break-up biological crusts, making these disturbed areas very susceptible to wind erosion.
3. The most common dust suppression measure is the application of water. Other methods of dust suppression, like mulch, synthetic polymers, ecosynthetic covers are too expensive. However, particularly in hot and arid climates, water application may also be of limited effectiveness. In the summer in Phoenix, when it is over 40° C, water cannot be applied fast enough.
4. The objective of this research was to evaluate the potential of biopolymers as a cost-effective in hot and arid areas where application of water is not effective as a dust control measure at construction sites and other sites requiring short-term dust suppression (i.e., landfills).

Soil Stabilization Techniques

It would be great if people can always choose the site of their projects. However, in real life the site is usually pre-determined and people have to accommodate the site conditions. An essential part of the characteristics of a site is the soil type available on it, which may not be suitable for the requirements of construction engineer. Soil is a complex and variable material by its nature; hence, a great amount of understanding is required to properly deal with soil issues. In general, the site engineer should decide whether to:

1. Accept the site material and its existing quality as they are, then design to standards accordingly.
2. Remove the site material and replace it with a better material.
3. Adjust the properties of the existing soil in order to create a material that can sustain the site conditions and capable of meeting the requirements of the task. (Ingles & Metcalf, 1973)

Adjusting the properties of soil is known as soil stabilization, which is the topic of this research. There are several general methods available for soil stabilization control, though each method may be successful, only on a limited class of problems or on a limited number of soils. The limited effectiveness of any one stabilization method is because of the complexity of soil as mentioned above. Soil stabilization techniques may include, but are not limited to, chemical, thermal, and mechanical techniques. In non-cohesive materials, stabilization often involves changing the volume of the soil voids, replacing the void material, or both. In cohesive materials, stabilization often involves mixing the soil with stabilizers and preloading the soil to reduce future settlements (Karol, 2003).

Compaction

Compaction is the most common form of mechanical stabilization. It is the oldest and the mostly used method for modifying soil properties (Karol, 2003). Soil is composed of solid, air and water. Compaction may be defined as "the expulsion of the air from the system" (Ingles & Metcalf, 1973, p. 56). Compaction can be expressed in terms of dry density (weight of solids/total volume) and moisture content (weight of water/weight of solids). The response of a soil to compactive efforts depends upon the amount of liquid present.

There are two types of compaction: shallow and deep. Shallow compaction takes place in the field, at and near the soil surface. Shallow compaction can be used to control fugitive dust; observations show a well compacted soil generally is less susceptible to erosion than poorly compacted soil. It is influenced mostly by pressure applied to the soil surface (Daum, 1996). This can be achieved by rolling or vibrating. Rolling is done with sheepsfoot drums, round drums, and rubber tired vehicles. Vibrating machines can be hand propelled units or motor driven machines. Each successive pass of these compaction equipments produces less compaction (Karol, 2003).

Mixing

Mixing stabilization is generally accomplished by blending foreign materials together with soil particles ex-situ or at shallow depths. Surface soils can be treated up to about 0.5 meter deep economically. Portland cement is the most common additive (foreign material) used to stabilize soil. Cement hydration is very important in cement stabilization. In unsaturated soils, it is important to add water to make sure that cement is fully hydrated and the soil-cement material is strong. Granular materials maybe also added to increase the strength of the soil-cement mixture. Even though, the soil-cement material is not as strong as concrete, cement stabilization is effective for erosion control and for light traffic loads such as warehouse floors and bike paths.

The amount of cement to be used for stabilization can be determined by the freeze-thaw, wet-dry, and moisture-density tests. Usually 3 percent cement is used to stabilize coarse granular material. Cement content can go up to 15 percent for soils containing organic materials. Hydrated lime is more effective than cement in stabilizing clays (Karol, 2003).

Grouts

Cement grouts. Grouts are materials that fill the fissures, pores, voids and cracks in natural or synthetic materials for stabilization purposes. Nowadays, the most common grout for soil is Portland cement and its variations. Portland cement is composed of limestone, quartz sand, clay, and iron ore. The ratio of soil void opening size to grout particle size as well as the grout viscosity controls the penetration of grout in the soil. “It is usually considered that opening size must be at least three times the particle size in order to permit grouting” (Karol, 2003, p. 115).

Chemical grouts. Chemical grouts are colloidal materials that can penetrate more easily but cost more than cement grout. Sodium silicate and silicate chloride are the most common chemical grouts. They can be used to stabilize surface soil or prevent groundwater problems. The four major factors for selecting a chemical grout are permanence, penetrability, strength, and toxicity.

- Permanence: A grout’s permanence is generally correlated to the structural life (mostly 50 years).

- Penetrability: Viscosity governs the ability of a grout to penetrate a porous formation. Typically, grouts with viscosities less than 2 cP can be pumped into a soil with a permeability of 10^{-4} cm/s without any problem. At 5 cP, a grout can be pumped into the soil as long as the soil permeability is higher than 10^{-3} cm/s. At 10 cP, grouts cannot penetrate soils with permeabilities below 10^{-2} cm/s. When the silt fraction of a soil exceeds 20%, all grouts may have trouble penetrating.
- Strength: The desiccation of water in the grout shrinks the grout matrix.
- Toxicity: Some chemical grout components are known to be carcinogens, corrosive, and or toxic. Therefore, extra care should be taken for persons handling the grouts (Karol, 2003).

Bituminous stabilization

Bituminous stabilization is the process of mixing bitumen thoroughly with soil to form a wearing surface (Bituminous Stabalization, 2009). Bitumen stabilization is suitable for non-cohesive granular materials. Bitumen acts as waterproofing for soil. Therefore reducing any loss of strength associated with increasing the moisture content (Ingles & Metcalf, 1973). There are two major types of bituminous stabilization: emulsion stabilization and expanded asphalt stabilization.

Emulsion Stabilization. In emulsion stabilization, the materials extracted from the site are tested in the laboratory to determine the optimum fluid content as well as the optimum amount of emulsion to be added. The percentage of emulsion is typically between four and five percent, depending on the quality of extracted materials. The final emulsion is then injected though a spray bar to a specified depth (typically 100-200mm). The emulsion requires a certain curing time before the soil is stabilized.

Expanded Asphalt Stabilization. The expanded asphalt stabilization procedure is similar to emulsion stabilization. The foaming characteristics of the asphalt cement are determined in the laboratory to find the percentage of asphalt cement required for the stabilizing mixture. The percentage of asphalt in the final mixture to be injected into the soil can be between 2 to 2.5 percent, depending on the quality of extracted materials. Expanded asphalt stabilization is recommended over emulsion stabilization due to its low life cycle cost, low environmental impact, and ease of construction (Bituminous Stabalization, 2009).

Biological Soil Crusts

Biological soil crusts are stiff layers that form on the surface of a soil under the action of a community of highly specialized organisms. These organisms include cyanobacteria, green algae, lichens, mosses, microfungi, and other bacteria. Soil characteristics and disturbance regimes determine the components of these crusts (Belnap & Gillette, 1998). In a biological soil crust, cyanobacterial and microfungal filaments glue loose particles together by weaving through the top few millimeters of soil. The binding process forms a matrix that stabilizes and protects soil surface against wind and water erosion. Biological crusts can be found to some extent in desert and semi-desert plant communities, from shrubs to open woodlands, and in almost all hot, cool, cool-arid and semi arid environments throughout the world (USDI, BLM, & USGS, 2001). However, biological soil crusts can dominate the soil surface in hot and cold regions where the plant cover is absent (Belnap & Gillette, 1998).

Ecological roles of biological soil crusts include, protecting the soil from erosive forces (i.e., wind and water), carbon fixation, nitrogen fixation, rainfall absorption, and proving a nutrient-rich soils (healthier soils) (Harper & Belnap, 2001) (USDI, BLM, & USGS, 2001).

Structure and Composition of Biological Soil Crusts

As mentioned above, biological soil crusts are composed of multiple organisms. The density of the organisms in the crust controls its color; darker crusts refer to organism-rich soils. These organisms are "capable of drying out and temporarily suspending respiration without negative effects, unlike vascular plants that either die or must re-grow new tissue" (USDI, BLM, & USGS, 2001, p. 3). They do that by equilibrating their water content with the atmospheric humidity or soil surface moisture content. The crust thickness can reach up to 10 cm. Figure 6 illustrates the components of a biological soil crust. These components are listed below, along with a brief description of each component (USDI, BLM, & USGS, 2001):

- Bacteria: Bacteria are single-celled organisms. They can be either autotrophic or heterotrophic. Some bacteria contribute to soil fertility by fixing nitrogen.
- Microfungi: Microfungi function as decomposers. Microfungi bind soil particles together by increasing soil water-holding capacity.
- Cyanobacteria: Cyanobacteria are single-celled bacteria that can photosynthesize and, under anaerobic conditions, fix atmospheric nitrogen.

- Lichens: Lichens are fungi that capture and cultivate algae or cyanobacteria, resulting in a new morphological entity.
- Algae: Algae are nonvascular photosynthetic plant-like organisms
- Fungi: Fungi are non-photosynthetic multicellular organisms (USGS, 2006).

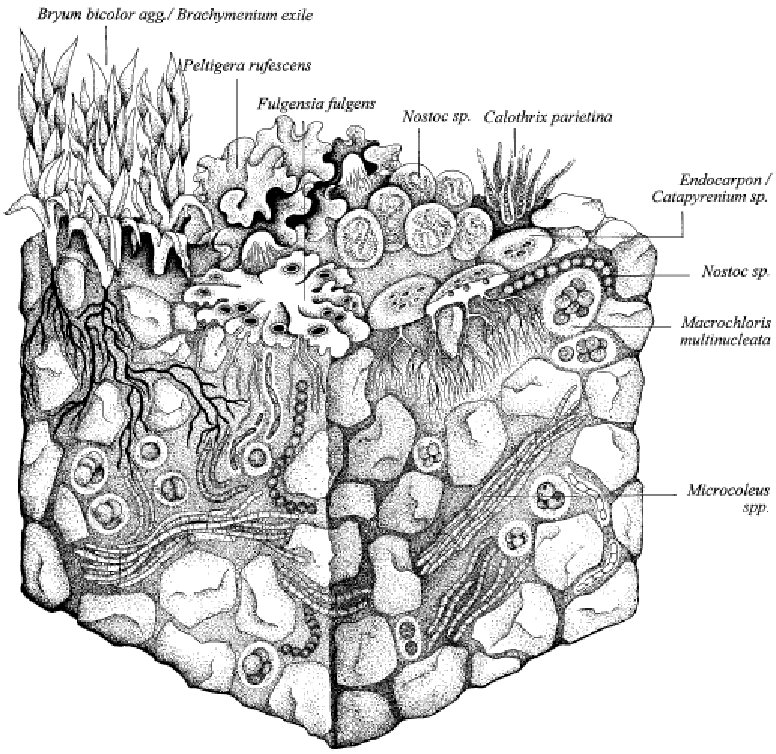


Figure 6: Schematic Block Diagram of a Biological Soil Crust with Typical Colonizers, Thickness of the Layer is about 3mm. Source: (Belnap & Lange, 2003).

Ecological Roles of Soil Crusts

The roles of biological soil crusts include: soil stabilization, carbon fixation, nitrogen fixation, and water infiltration (Belnap & Gillette, 1998). Depending on the composition of a biological soil crust as well as the characteristics of the specific ecosystem being studied, the ecological role of a soil crust can vary. For example, more mosses and lichens in the crust indicate higher carbon fixation inputs, whereas, a crust dominated by cyanobacteria indicate higher nitrogen fixation inputs (USDI, BLM, & USGS, 2001).

Carbon Fixation. Usually organic matter is contributed to soils through vascular plants. However, there are large spaces between these plants that might not receive any input. Biological soil crusts come into play by fixing carbon in these areas to keep them fertile. Fertilization serves as an energy source for soil microbial populations. As mentioned above, a crust dominated by mosses and lichen is most likely to have more carbon inputs than a crust dominated by cyanobacteria. Two factors can influence carbon inputs, timing and duration of precipitation. Metabolic functions of the crust begin immediately after wetting (USDI, BLM, & USGS, 2001).

Nitrogen Fixation. A soil crust rich with cyanobacteria is an important source of fixed nitrogen for soils and vascular plants tissues since it increases the macronutrient concentrations. These organisms will increase the site productivity and protect the soil surface against erosive forces (Belnap & Gillette, 1998). Since, there are only a few nitrogen fixing plants in cool deserts and nitrogen concentrations in general are low in desert soils (USDI, BLM, & USGS, 2001), the role of biological soil crusts is unique. It is estimated that biological soil crust are able to fix nitrogen at a rate of 2 to 365 kg/ha annually depending on crust composition (USDI, BLM, & USGS, 2001).

Effects of Crust on Vascular Plants. The potential effects of biological soil crusts on vascular plants include seed germination, plant establishment, and nutrient levels.

- *Seeds germination.* Unlike small-seeded plants which utilize the small cracks on the soil surface to germinate, large-seeded plants need soil or plant litter to germinate. Since biological soil crusts form in the interspaces of vascular plants, plant litter is often present in these areas. Figure 7 illustrates plant litter associated with a biological soil crust.
- *Plant Establishment and Cover.* Biological soil crusts differ from physical crusts in that they do not inhibit root penetration. It has been reported that these crusts are either not competing

with vascular plants or enhancing the vascular plant cover (USDI, BLM, & USGS, 2001).

Figure 7: Biological Soil Crusts in the Northern Great Basin. Source: (USDI, BLM, & USGS, 2001).

- *Nutrient Levels in Vascular Plants.* There are higher concentrations of nutrients in plants growing in biologically crusted soil than those growing in regular soils. This might be due to the trapping of blowing materials by biological soil crusts (USDI, BLM, & USGS, 2001).

Water Absorption. Water absorption at any given site is dependent upon biological crust composition, climatic regime, surface roughness, time of disturbance, soil texture, and soil structure. Biological soil crusts alter the soil surface in a manner that aids in water adsorption. In cool deserts, heaving associated with the formation of a biological crust increases the roughness of the surface. Roughness acts as a detention structures for water.

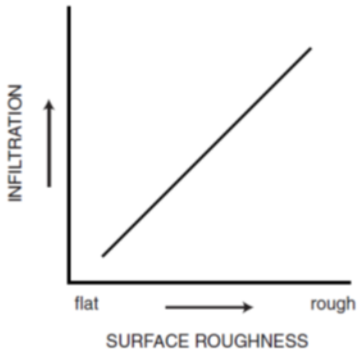


Figure 8: Biological Soil Crust and Soil Characteristics That Influence Infiltration. Source: (USDI, BLM, & USGS, 2001).

Soil Stabilization. Biological soil crusts are known to protect the soil against wind and water erosion. The protection mechanism is as follows: cyanobacteria and green algae secrete sticky sheaths that stick to soil particles, increasing the size and weight of the soil aggregates and making them harder to move by wind or water. Also, the roughness of the biological soil crust creates a still air boundary layer that protects the soil surface from wind erosion (USDI, BLM, & USGS, 2001).

Belnap and Gillette conducted a wind erosion study on a biological soil crust. These investigators disturbed the cursts with a cow hoof (applied by hand), and a four-wheel drive vehicle (Belnap &

Gillette, 1998). Figure 9 shows the threshold friction velocities (TFV) required to detach soil particles from the surface. The reduction percentages are shown on each column. Reductions ranged from 33% to 83%. Lower TFVs indicate soil surfaces more susceptible to erosion.

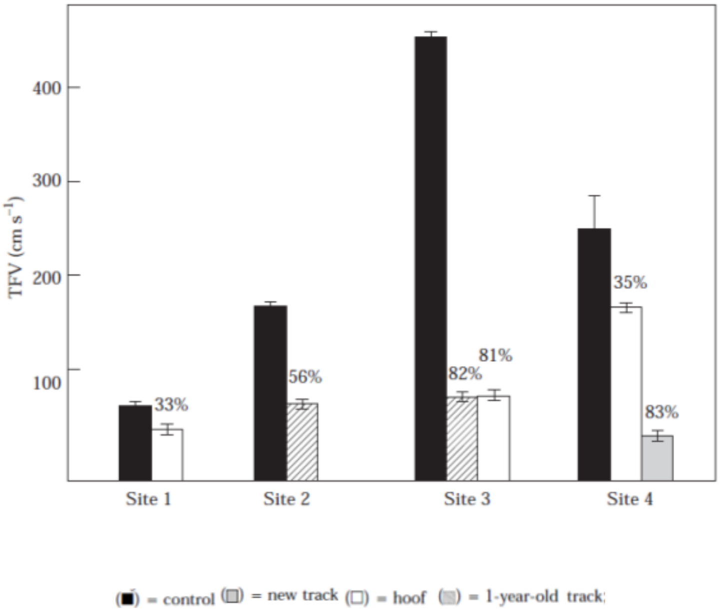


Figure 9: Decline in TFV Resulting from Applied Disturbances at Four sites. Source: (Belnap & Gillette, 1998).

The lower threshold friction velocities for the disturbed areas are expected. As well-developed crusts have higher wind resistance than less-developed crusts. This is due to the sticky sheaths that cyanobacteria and green algae secrete that binds soil particles together causing an increase in size and weight (USDI, BLM, & USGS, 2001). The results of the field experiments was consistent with the fact that disturbance will reduce the effectiveness of the biological soil crusts, regardless of the type or duration of disturbance. As the duration and magnitude of the disturbance increases, the less effective the crust is (as shown in site 4 with 83%).

Biopolymers

Biopolymers are environmentally friendly polymers that are produced by living organisms. There are many useful applications for biopolymers, i.e., they can glue soil particles together upon application, hence, making them harder to move. Common biopolymers include xanthan gum, guar gum, chitosan, polyglutamic acid, and polyhydroxy butyrate.

Xanthan gum. Xanthan gum is a naturally occurring complex polysaccharide (or sugar) polymer produced by the plant-pathogenic bacterium Xanthomonas campestris (Becker, Katzen, Pühler, & Ielpi, 1998). Xanthan gum is available in a white to cream colored free flowing powder that is derived from corn sugar by a fermentation process. Xanthan is one of the most researched polysaccharides. It is soluble in hot and cold water and the resulting solution is high viscosity solution, even at very low concentrations, in comparison with other polysaccharide solutions. Xanthan gum mixtures have excellent thermal stability with a uniform viscosity from freezing to near boiling temperatures. The mixtures are also soluble and stable in acidic, alkaline, and alcoholic systems (Sharma, Naresh, Dhuldhoya, Merchant, & Merchant, 2006). The figure below shows a structural unit of xanthan gum, which consists of repeating pentasaccharide subunits.

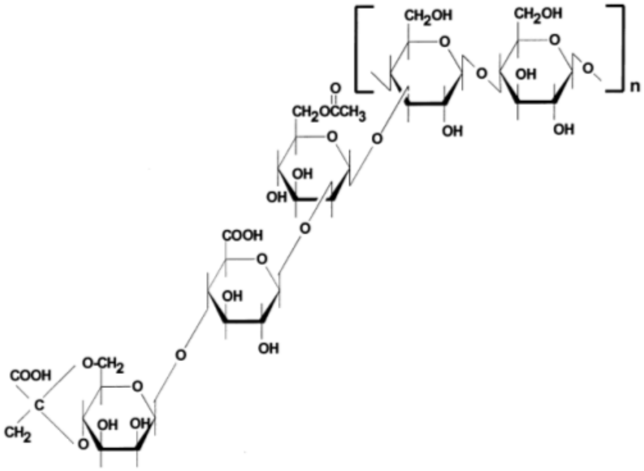


Figure 10: Structure of Xanthan Gum. Source: (Becker, Katzen, Pühler, & Ielpi, 1998)

Dry and wetting tests on xanthan gum solution indicated that no hysteresis is evident and that the solutions are highly pseudoplastic. This guarantees a high degree stability during mixing and pumping because the initial viscosity is recovered immediately even after high shear rates (Sharma, Naresh, Dhuldhoya, Merchant, & Merchant, 2006). Due to the already mentioned properties, xanthan gum is widely used in food and non-food industries as a thickener, viscosifier, and stabilizer for multiple suspensions, emulsions, and foams. The U.S. Food and Drug Administration (FDA) cleared xanthan gum for human consumption in 1969 and the European Union (EU) approved it for this purpose in 1980 (Becker, Katzen, Pühler, & Ielpi, 1998). Table 4 summarizes applications of xanthan gum.

Table 4

Xanthan Gum Applications

Industrial applications	Food and pharmaceutical applications
Abrasives (viscosity control)	Beer (foam stabilizer)
Ceramic glazes, polishes, thixotrophic paints (stabilization, pseudoplasticity)	Cheese (syneresis inhibitor) Juice drinks (suspension)
Explosives (gelling agent)	Confectionery (coating)
Firefighting fluids (foam stabilizer) Water clarification flocculant	Ice cream (stabilizer, crystallisation control)
Hydraulic fracturing (cross-linking)	Jams, sauces (thickening agent)
Oil-drilling muds (shear thinning)	Pharmaceuticals (retarded drug release)

Source: (Becker, Katzen, Pühler, & Ielpi, 1998) and (Sandvik & Maerker, 1977)

Guar gum. Guar gum is a polysaccharide extracted from the seeds of the cluster bean or Cyamopsis tetragonolobus (Jenkins, Leeds, Newton, & Cummings, 1975). Grinding the seeds results a white to yellowish powder. The major advantage of guar gum is that it thickens without applying heat. Other properties include:

- The powder is soluble in hot and cold water but insoluble in most organic solvents.
- It has strong hydrogen bonding properties.
- It has excellent thickening, emulsion, stabilizing and film forming properties.
- It has excellent ability to control rheology by water Phase management.
- The viscosity of guar gum is influenced by temperature, pH, presence of salts and other solids (Sharma, Chechani, Dhuldhoya, & Merchant, 2007). Figure 11 illustrates the chemical structure of guar gum.

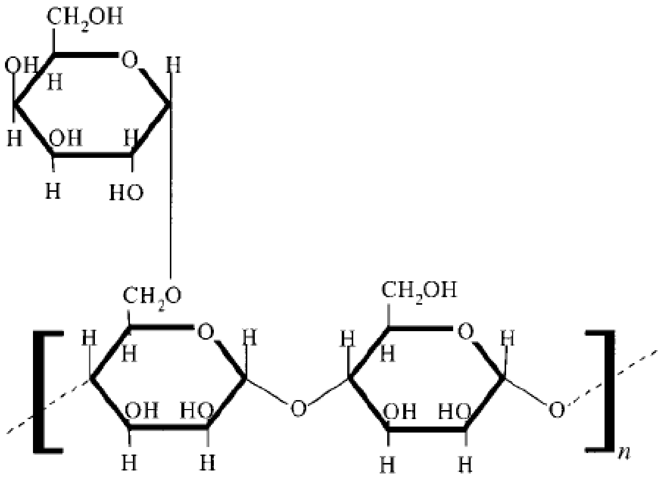


Figure 11: Guar Structure. Source: (Gittings, Cipelletti, Trappe, Weitz, In, & Marques, 2000)

Since a very small quantity of guar gum is needed to dramatically increase the viscosity of solution (Gittings, Cipelletti, Trappe, Weitz, In, & Marques, 2000), guar gum has been used as a thickener, emulsifier, stabilizer, binding agent, natural fiber, flocculant, and fracturing agent (Sharma, Chechani, Dhuldhoya, & Merchant, 2007). Some of the industrial applications for guar gum are food, oil recovery, personal care (Gittings, Cipelletti, Trappe, Weitz, In, & Marques, 2000), textile, pharmaceuticals, paper, explosives, and mining (Sharma, Chechani, Dhuldhoya, & Merchant, 2007).

Chitosan. Chitosan is one of the most common biopolymers found in nature. It is a naturally occurring polysaccharide produced from chitin in the shells of crustaceans, for example, crabs and shrimp (Domard & Domard, 2002). Chitosan is a weak base ($pK_a \approx 6.2$-7); as a result, it is insoluble at neutral and alkaline pH values. However, chitosan forms salts with organic and inorganic acids such as HCl and CH_3COOH. To form a soluble positively charged bioadhesive, chitosan needs to be submerged in an acidic medium. Two factors control the viscosity of chitosan solutions; concentration and temperature. Higher concentrations and lower temperatures give a very viscous chitosan solution (Hejazi & Amiji, 2002). Figure 12 illustrates the chemical structure of chitosan.

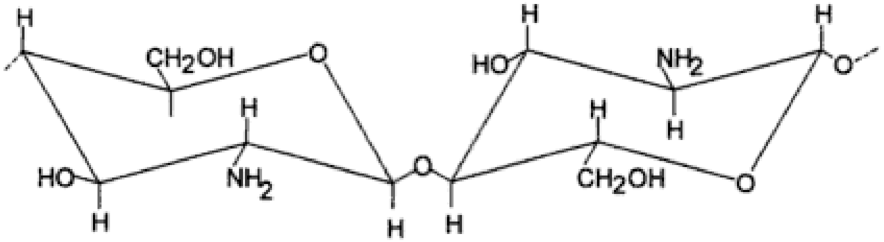
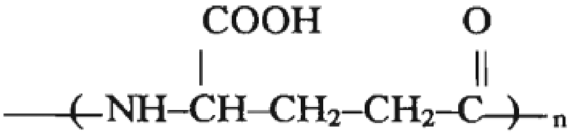


Figure 12: Structure of Chitosan. Source: (Hejazi & Amiji, 2002)

Industrial uses of chitosan include waste water purification, stabilizing oil spills, antibacterial protection for seeds, stabilizes perishable fruits and vegetables, ion exchange media, bacterial immobilizer, cosmetics, and an absorbant for heavy metal removal. Health and nutrition uses of chitosan include absorbtion and binding of fat, promoting wound healing, acting as antacid, and improving calcium absorption (Hennen, 1996).

Polyglutamic acid (PGA). Polyglutamic acid (PGA) is a water soluble, non-toxic, and biodegradable polymer that is produced by several Bacillus species via microbial fermentation. The structure of polyglutamic acid consists of glutamate repeatable units (Richard & Margaritis, 2001). PGA is highly crystalline, has excellent mechanical properties, and has a high rate of degradation (Vroman & Tighzert, 2009). PGA is used in a variety of industrial applications such as thickeners, humectants, and cosmetics and as a drug carrier (Do, Chang, & Lee, 2001). Figure 13, illustrates the structure of polyglutamic acid.



$$-\left(\mathrm{NH-\overset{\overset{COOH}{|}}{C}H-CH_2-CH_2-\overset{\overset{O}{\|}}{C}}\right)_n-$$

Figure 13: Structure of Poly(glutamic) acid. Source: (Richard & Margaritis, 2001)

Polyhydroxy butyrate (PHB). Polyhydroxy butyrate (PHB) is an intracellular substance in bacteria that is aliphatic, semi-crystalline, and biodegradable (Radasch, 2007). PHB is degraded in various environments by bacteria, fungi, and algae (Vroman & Tighzert, 2009). The molecular properties of polyhydroxy butyrate are dependent on the fermentation process. Due to its biocompatibility, it has been approved for use in medical and food applications (Radasch, 2007). Figure 13 show the structure of PHB.

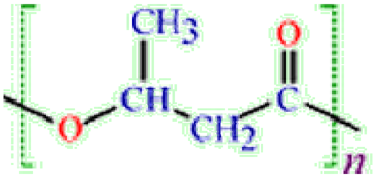


Figure 14: Polyhydroxy Butyrate Structure. Source: (Chemical Industry Education Centre (CIEC))

Biodegradability of Biopolymers

Knowledge about the biodegradability of biopolymers is important since one of the reasons of employing biopolymers is that they are safe to deploy in the environment. Therefore, consideration must be given to “daughter” products created as a biopolymer biodegrades.

It is widely assumed that all biopolymers are biodegradable as they are all from natural compounds as opposed to non-biodegradable synthetic polymers derived from fossil resources. However, the natural origin of biopolymers does not necessarily mean that all biopolymers are readily biodegradable. Most water soluble biopolymers degrade at a high rate, while water insoluble biopolymers degrade drastically slower (i.e., polyphenols and polyisoprenoids). Lignin, which is one of the most abundant biopolymers, is only degraded slowly and only by few organisms like white-rot fungi. This makes some natural compounds, like wood, very stable. Polyisoprenoids (also known as natural rubber) is only degraded by a few Gram-positive bacteria (Steinbuchel, 2005).

U.S. Army Corps of Engineers Dust Control Work

During the 2003 Iraqi war, the United States military suffered from fugitive dust problem resulting from unpaved roads that were trafficked with long convoys of military vehicles in both combat and sustainment roles. The U.S. Marine Corps Systems Command tasked the U.S. Army Engineer Research and Development Center (ERDC) to evaluate commercially available dust palliatives as well as to make recommendations on how to apply them. (Rushing, Moore, Tingle, Mason, & McCaffrey, 2005).

Acrylic polymer emulsions, a polysaccharide biopolymer, calcium chloride, and synthetic fluids were the dust control products evaluated by ERDC in response to this task. Two deployment procedures were employed by ERDC: topical application and admixture stabilization (spray / till / compact / spray). Surtac, the polysaccharide product, exhibited some binding characteristics and prevented major surface deterioration. It was very effective during a 30-day evaluation on all test sections but not as effective during the 80-day evaluation. Its topical application was more effective than the admix procedure. Surtac was also least effective treatment in preventing potholes (Rushing, Moore, Tingle, Mason, & McCaffrey, 2005).

Arizona State University Dust Control Work

Laboratory testing conducted by Kavazanjian, Iglesias, and Karatas (2009) indicated that topical application of biopolymer solutions can significantly increase the resistance of sandy and silty soil to wind erosion. These investigators suggested that the crust formed by the application of biopolymer solutions may be fairly stable for an extended period of time. Similar to ERDC, both topical application and admixture stabilization were deployed. The admixture procedure, though more expensive, achieved similar results to topical application. The biopolymer mixtures appeared to be effective even after sunlight and summer temperatures exposures for periods of up to 7 days. However, extreme temperatures (105 °C) over an extended period of time (7 days) resulted in a loss of stabilization against wind erosion (Kavazanjian, Iglesias, & Karatas, 2009).

Quantitative Measures for Wind Erosion

There are several approaches to wind erosion research. Laboratory and field experiments are used to estimate the threshold friction velocity as a function of particle sizes, sand drift intensity, dust emission mechanisms, and the impact of surface roughness and vegetations on wind erosion. Field monitoring can measure the dust concentration profile and the intensity of sand drift using saltation traps (Shao, 2000).

Tapered Element Oscillating Microbalance (TEOM)

A measurement instrument called the Tapered Element Oscillating Microbalance (TEOM) has been used to monitor PM_{10} and $PM_{2.5}$ emission potentials of non-dispersed soil. The instrument aspirates air at a rate of 16.7 L min^{-1} over the surface of the soil to be evaluated. Suspended particulates are collected with in-line cyclones designed for 50% cut efficiency of either PM particles. A glass fiber filter inside a controlled chamber is used to control aerosols passing through the cyclones. A pressurized air inlet with a desiccant filter is connected to the abrader cone. The cone suspends PM_{10} and $PM_{2.5}$ particles and abrads the larger ones. The accumulated mass in the TEOM device was used to determine the PM percentages (Chandler, Saxtonb, Kjelgaardc, & Busacca, 2002). Figure 15 illustrates this apparatus.

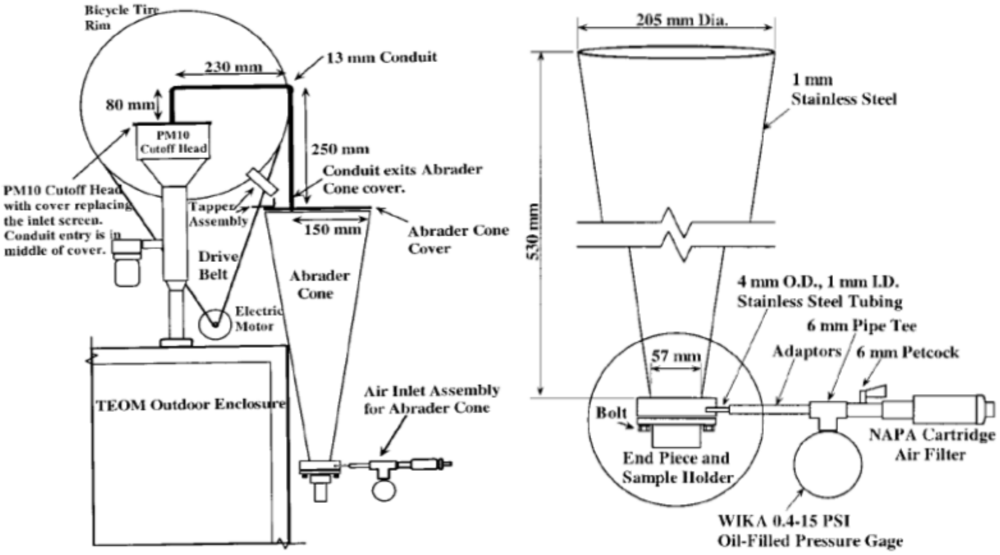


Figure 15: TEOM Instrument and Abrader Cone. Source: (Chandler, Saxtonb, Kjelgaardc, & Busacca, 2002)

Particulate Matter Mass Distribution

Hai et al. (2009) constructed an intrument to measure the change in the shape of a soil surface eroded by wind. The concept of the device is simple: a box with 100 marked rods that measure the falling distance is employed. Under each rod there is a plastic cushion pad to ensure smooth contact upon falling. As shown in figure 16, there is a fixing ring (labeled B9) to keep the rods in place. Three steps are involved in measuring the shape change of the soil surface. First, the box is secured to the ground with nails (labeled B81) and the rods are released. At the end of this stage, the height of each rod is recorded. Second, the box is removed and an artificial wind (13.9 - 17.1 m s^{-1}) is applied for three minutes. Third, step one is repeated.

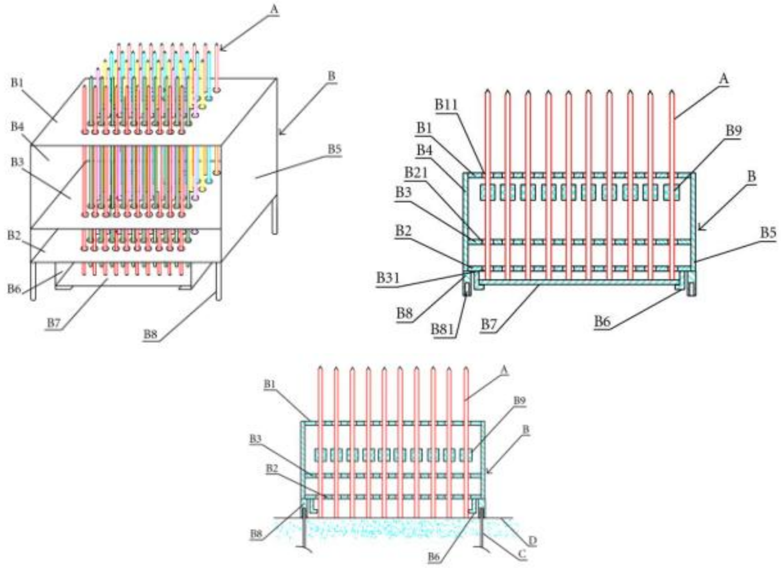


Figure 16: Surface Change Instrument. Source: (Hai, et al., 2009)

PI-SWERL

Another device for measuring wind erosion is DRI's PI-SWERL. PI-SWERL stands for Portable In Situ Wind ERosion Lab. PI-SWERL is a device that measures the potential for wind erosion and dust emission from soil surfaces. The device is composed of an annular ring that rotates 6 cm above the soil surface. Dust concentrations are measured by light scattering. Figure 17 shows a schematic diagram of the device as well as two cross sections (Etyemeziana, et al., 2007).

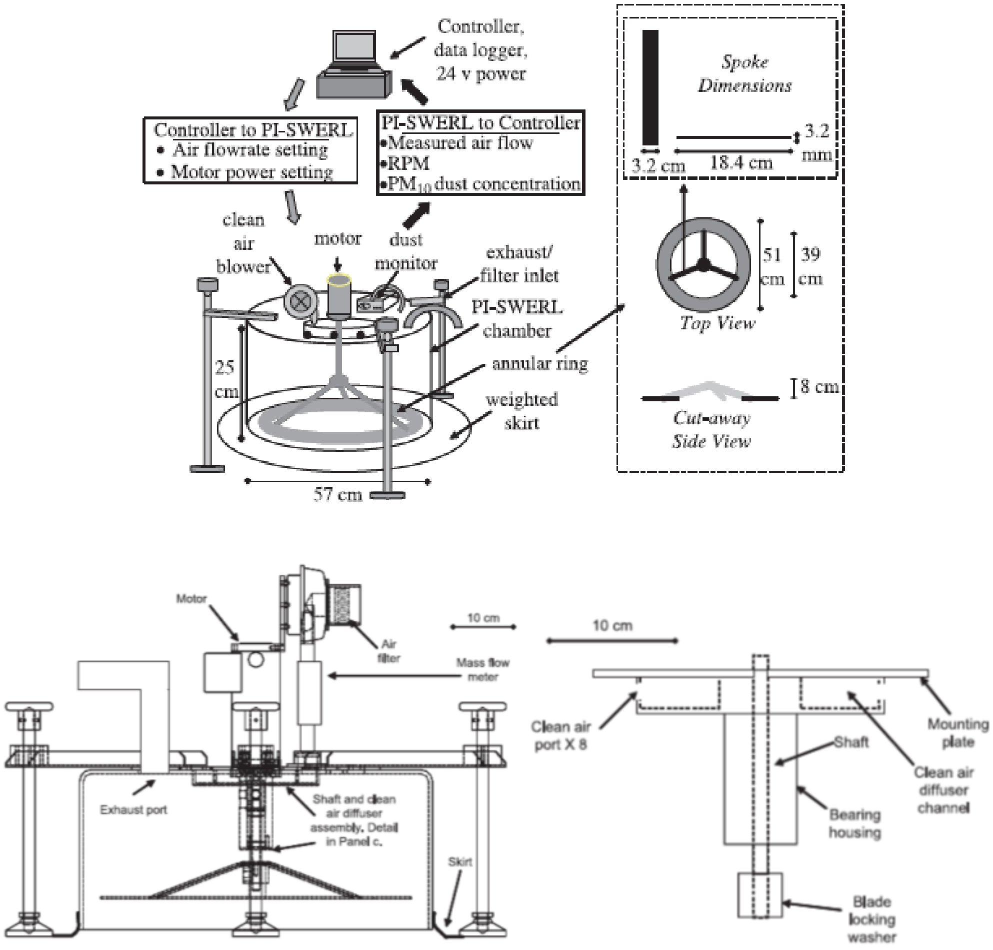


Figure 17: A schematic of PI-SWERL. Source: (Etyemeziana, et al., 2007)

Wind Erosion Equation

Empirical wind erosion modeling can provide a quantitative assessment and prediction of wind erosion (Shao, 2000). Among the different empirical wind erosion models, the most commonly used is Wind Erosion Equation (WEQ) developed in 1965 by Woodruff and

Sidoway. The WEQ was originally developed to estimate the annual average soil loss over a large area. Bondy et at. (1980) and Cole et. al. (1983) modified the WEQ in order to obtain the soil loss over shorter periods than one year. The governing parameters of the WEQ are soil type, vegetation coverage, surface roughness, climate, and field length. Over the years WEQ was further expanded to include more parameters and processes. Gomis and Gerrietts (1994) added planting date, tillage method, and amount of residue of the previous crop to the equation. The Gomis and Gerrietts (1994) equation is called the Revised Wind Erosion Equation (RWEQ) (Shao, 2000).

Recently, a process based simulation system that simulates weather, field conditions, and erosion called the Wind Erosion Prediction System (WEPS) was developed. WEPS is suitable for evaluating soil conservation systems, environmental planning, or assessing wind erosion impacts (Wagner, 1997).

The empirical wind erosion model advocated in this research is the wind erosion equation (WEQ) since it is the most widely model used and employed by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). NRCS designed a computer program called the Management Period Wind employing the WEQ.

In the NRCS program, the estimated annual soil loss, E, is estimated as:

$E = f(IKCLV)$

E = Estimated average annual soil loss expressed in tons per acre per year

I = Soil erodibility factor

K = Soil ridge roughness factor

C = Climatic factor

L = Equivalent unsheltered distance across the field along the prevailing wind erosion direction

V = Equivalent vegetative cover (National Resources Inventory, 2003)

EMIT-PM Emissions Model

The EMIT-PM model is a particle matter emissions model based upon two semi-empirical equations describing horizontal and vertical soil fluxes to estimate the fraction of dust emissions that contribute toward PM_{10} concentrations. The horizontal soil flux is a function of wind energy, soil erodibility, vegetative cover, surface roughness, surface wetting, and crusting. These variables are described by the following horizontal soil flux equation based on extensive wind tunnel and field measurements.

$$Q_t = W_t * EI * \left(e^{-0.05 * SC} * e^{-0.52 * K}\right) * WC$$

Where Q_t is the eroded soil discharge per meter field width per unit time (g m^{-1} width per hour event) and W_t is the erosive wind energy per unit time (m^3 s^{-3} per hour event). EI is the erodibility potential of unprotected soil (g s^3 m^{-3}). SC is the percentage of vegetative soil cover and K is the random roughness. WC is the degree of wetness. The vertical flux is a function of the horizontal soil flux, soil dustiness, wind velocity and the dust constant (C). The vertical PM_{10} flux, F_d, is described by an equation:

$$F_d = C * C_v * u_* * Q_t * (D/100)$$

Where C_v is the unit conversion factor, u_* is the friction velocity (m $s^{-}1$), and D is the soil dustiness index (Sundram, Claiborn, Strand, Lamb, Chandler, & Saxton, 2004).

Simulation of the Breakage of Saltation-Size Aggregates

L. J. Hagen constructed a chamber apparatus to measure the relative breakage fractions of saltation-size aggregates to suspension-size and the fractions of PM_{10} and $PM_{2.5}$. Samples were collected from the upper 1 cm layer of the soil were air-dried in a laboratory greenhouse. After air drying, the samples were sieved and impacted on high volume impaction plates at a velocity of 5.5 m s^{-1} using a calibrated sandblast nozzle. A large cyclone separated the coarse particles from fine particles after the impact. The pre-separator was followed by a four-stage Hi-Vol cascade impactor and a back-up filter to obtain the size distribution of the PM_{10} fraction. The flow rate was 9.4 L per second. The impaction plates' filters were weighed to determine PM_{10} created. $PM_{2.5}$ fraction was calculated from the cumulative size distribution on the filters (Hagen, 2004).

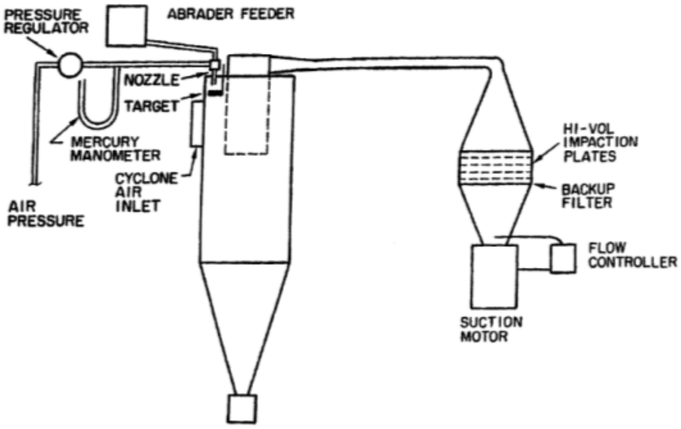


Figure 18: Sandblast Nozzle inside Large Cyclone. Source: (Hagen, 2004)

Chapter 3

RESEARCH PROGRAM

The objective of the research described in this dissertation was to experimentally evaluate the effectiveness of biopolymers for short-term control of fugitive dust (e.g., at construction sites or landfills). The initial Phase of the research consisted of screening available biopolymers to identify candidate biopolymers for experimental evaluation. The subsequent experimental work consisted of three phases:

- Phase 1: Initial "proof of concept" experiments to evaluate the efficacy of candidate biopolymers identified through the screening process and establish appropriate application rates for wind erosion control.
- Phase II: More detailed wind tunnel experiments to evaluate biopolymers identified in Phase I testing as potential wind erosion control agents.
- Phase III: A field experiment to assess the effectiveness and durability of biopolymers for wind erosion control at a landfill site near Phoenix.

Biopolymers Screening

Initial screening to identify candidate biopolymers for use in wind erosion control was done based upon biopolymer characteristics. For instance, some biopolymers are water soluble while others are not, and some biopolymers come in a pure powder while others are aggregated chunks of materials. A biopolymers' water solubility may impact its durability, since water soluble biopolymers can wash away on rainfall or may dissolve due to morning dew and hence lose the intended effectiveness. Furthermore, even though water erosion is not the topic of concern for this dissertation, it is appropriate to address it within the context of this research by testing at least one water insoluble biopolymer, as a biopolymer resistant to both wind and water erosion would be better than a biopolymer that only provided wind resistance alone. Should a wind erosion resistant biopolymer prove to be both durable and resistant when subject to water, it may not be necessary to re-apply the biopolymer after every rain event.

Candidate Biopolymers

Five biopolymers were considered in the preliminary phase of this research as candidates for experimental evaluation: xanthan gum, guar gum, chitosan, polyglutamic acid (PGA), and polyhydroxy butyrate (PHB). The main reasons for selecting these biopolymers was that there was information on their characteristics available in the literature and based upon the information they appeared to have the potential to be effective against wind erosion. As noted above, a secondary goal of this research was that the biopolymer wind erosion control agent be able to resist water erosion (i.e., in a rainfall event). Therefore, both water soluble biopolymers and biopolymers that were not water soluble were considered in selecting the candidate biopolymers. Other consideration included availability, cost, and ease of application.

Xanthan gum was selected as a candidate biopolymer for the following reasons:

1- It is water soluble.
2- It is readily available in the market.
3- Extensive literature on its properties is available.
4- The price per gram compared to other biopolymers is low.
5- It should be easy to apply in the field (no special equipment or mixing technique is needed).

Guar gum was selected as a candidate biopolymer for the following reasons:

1- It is water soluble.
2- It is readily available in the market.

3- Extensive literature on its properties is available.
4- The price per gram compared to other biopolymers is low.
5- It should be easy to apply in the field (no special equipment is needed).

Chitosan was selected as a candidate biopolymer for the following reasons:

1- It is water insoluble.
2- It is readily available in the market.
3- Extensive literature on its properties is available.
4- The price per gram compared to other biopolymers is low.
5- It should be relatively easy to apply in the field (no special equipment is needed).

Polyglutamic acid (PGA) was selected as a candidate biopolymer for the following reasons:

1- It is water soluble.
2- Extensive literature on its properties is available.
3- It should be relatively easy to apply in the field (no special equipment needed).

Polyhydroxy butyrate (PHB) was selected as a candidate biopolymer for the following reasons:

1- It is water insoluble.

2- Extensive literature on its properties is available.

Biopolymer Solution Preparation

Each of the candidate biopolymers would have to be mixed with water so that they could be applied topically (sprayed on) to the soil surface. The method of mixing varied depending on the solubility of the biopolymer.

- Xanthan gum, guar gum, and polyglutamic acid (PGA) are just mixed with water since they are water soluble at room temperature.
- Chitosan needs to be first dissolved in acetic acid (1%) and then mixed with distilled water.
- Polyhydroxy butyrate (PHB) needs to be sonicated (sonication is the act of applying ultrasound to agitate mixture) as follows: 1 g of PHB in 1 liter of water is sonicated 12 times for 30 minutes, with heating for 30 minutes at 50 °C between each sonication episode. Then 5 ml of a 0.05N NaOH solution is added to simulate PHB dispersion and dissolution in water.

Based upon the mixing considerations described above, three biopolymers (xanthan gum, guar gum, and chitosan) were carried forward to the experimental phases of the work.

Candidate Soil

The candidate soil for use in the testing program was selected as a fugitive dust-susceptible soil typical of construction sites in the Phoenix area. In obtaining a candidate soil, consideration was also given to the potential for future testing at the site from which the soil was obtained.

The candidate soil selected for use in this testing program was a silty sand from the Butterfield Station landfill in southwest Maricopa county. Silty sands are very typical of the surficial soils in and around Phoenix. Furthermore, the silt particles in local silty sand are generally of low plasticity and susceptible to wind erosion. Butterfield Station was selected as the site from which to obtain this soil because the landfill operator agreed to cooperate for future field experiments. Geotechnical characteristics of the candidate soil are described in Chapter 4 of this dissertation.

After selecting candidate biopolymers, three phases of experiments were conducted. Below is a description of each of these phases.

Phase I Experiments

Phase I experiments were conducted to prove the concept of biopolymer stabilization for wind erosion control, identify which of the candidate biopolymers were most effective for erosion control for use in Phase II testing, and establish appropriate application rates for Phase II testing. Phase I experiments were conducted in the aluminum duct work set-up described by Kavazanjian, Iglesias, & Karatas (2009) and described subsequently in Chapter 4 of this dissertation.

Phase II Experiments

Biopolymers identified in Phase I as effective in dust suppression (wind erosion control) were subjected to more detailed testing in Phase II. Phase II testing was conducted in the ASU School of Earth and Space Exploration planetary wind tunnel specially developed for wind erosion studies. In Phase II testing, the relationship between biopolymer application rate and the threshold flow velocity for wind-induced soil erosion was investigated.

Phase III Experiments

Phase III experiments were conducted on a soil stockpile at Waste Management's Butterfield Station landfill. The objective of Phase III testing was to evaluate the effectiveness of biopolymer stabilization for wind erosion control under field conditions, both immediately after application and over a period of one or more weeks after application.

Chapter 4

PHASE I: INITIAL PROOF OF CONCEPT EXPERIMENTS

The objective of the Phase I testing program was to prove the concept of using biopolymers for wind erosion (fugitive dust) control. Phase I experiments were conducted to supplement preliminary work described in Kavazanjian, Iglesias, & Karatas (2009).

Candidate Soil

The candidate soil for use in the testing program was selected as a fugitive dust-susceptible soil typical of construction sites in the Phoenix area. In obtaining a candidate soil, consideration was also given to the potential for future testing at the site from which the soil was obtained.

The candidate soil selected for using in this testing program was a silty sand from the Butterfield Station landfill in southwest Maricopa county. Silty sands are very typical of the surficial soils in and around Phoenix. Furthermore, the silt particles are generally of low plasticity and susceptible to wind erosion. Butterfield Station was selected as the site from which to obtain this soil from because the landfill operator agreed to cooperate for future field experiments.

The soil was visually classified as a tan silty sand with low dry strength, a maximum particle size of about 9.5 mm. The grain size curve for the soil, evaluated in accordance with ASTM D422 is presented in Figure 19. The fines classify as ML, low plasticity silt, and the soil classifies as SM, silty sand, in the Unified Soil Classification System (ASTM D2487).

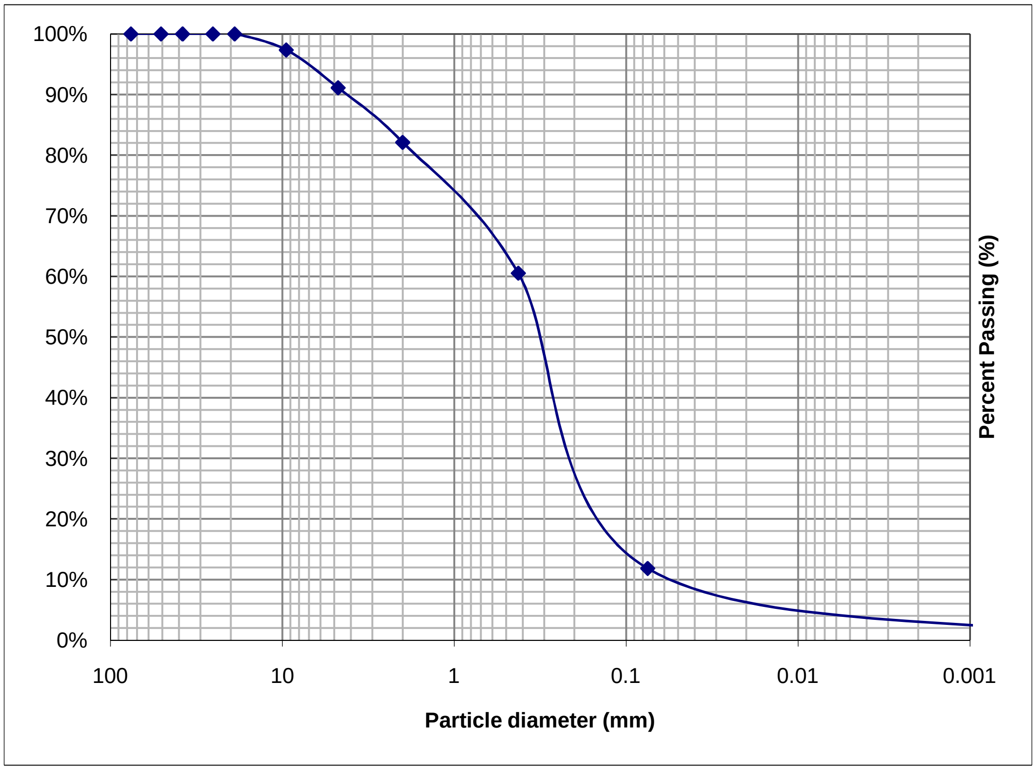


Figure 19: Grain Size Curve

The grain size distribution curve in Figure 19 indicates that approximately 12 percent of the candidate soil, by weight, is silt-sized or smaller (i.e., finer than 0.075 mm). However, the soil was screened through a number 30 (0.6 mm) sieve prior to testing, creating a soil with approximately 18 percent, by weight, particles that were silt-sized or smaller.

Methodology

The equipment used in Phase I testing is shown schematically in Figure 20. The apparatus, including supporting equipment, required for Phase I experiments is listed in Table 5.

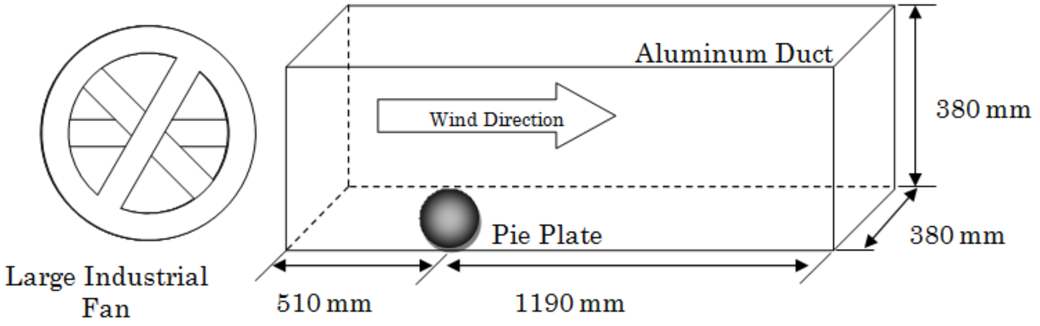


Figure 20: Approximate Sketch of Experiment Set-up

Table 5

Phase I Apparatus

- Aluminum duct work (380 mm x 380 mm x 1190 mm)
- Aluminum pie plate (216 mm diameter and 25.4 mm deep)
- Steel straightedge
- Plastic bottle with a trigger sprayer
- Drying oven
- Sieve shaker
- Large bowl
- Round steel plate (dimensions: 89 mm diameter and 19 mm height, weight: 974 g)
- No. 30 sieve, sieve pan, and sieve cover
- Balance
- Graduated cylinder
- Industrial fan
- High-speed shake blender

Pie plates with untreated soil were placed at different distances from the wind source to find an optimal location for testing (a location at which the untreated soil eroded from the plate in a reasonable period of time); 510 mm from the front edge of the duct appeared to be the optimal location.

Baseline tests were conducted on bare and lightly compacted dry soil specimens as follows (excluding steps 3 to 6 for bare soil):

1. Sieve the soil sample through No. 30 (0.6 mm) sieve with a sieve shaker to create a soil of uniform consistency that is prone to wind-induced erosion.
2. Fill an aluminum pie plate (216 mm diameter and 25.4 mm deep) with the sieved sample and level the surface with a straightedge to obtain the approximate amount of soil needed for the test.
3. Hand mix the soil in a large bowl with 100 ml of water.
4. Place the wet soil into the pie plate to about half the height then tamp it with a round steel plate (89 mm diameter and 974 g mass) using 20 drops from 50.8 mm height.
5. Place the rest of soil into the pie plate to form a second layer and then compact it as Step 4.
6. Oven-dry the soil for 24 hours at 110 °C.
7. Record the weight of the soil sample.
8. Place the pie plate at the designated location inside the aluminum conduit.
9. Operate the industrial fan for 10 minutes.
10. Record the final weight of the pie plate and the soil.

The difference between the weights measured in steps 7 and 10 was recorded as the soil loss and was used as the baseline value to evaluate the effectiveness of the biopolymer stabilized samples.

Biopolymer treated samples were then tested using the following procedure:

1. Sieve the soil sample through No. 30 (0.6 mm) sieve with a sieve shaker.
2. Fill the pie plate with the sieved sample and level the surface with a straightedge.
3. Spray the surface with the desired amount of biopolymer mixture.
4. Leave the pie plate to dry overnight at room temperature.
5. Record the weight of the soil sample.
6. Place the pie plate inside the aluminum conduit.
7. Operate the fan for 10 minutes.
8. Record the final weight.

The difference in weights measured in steps 5 and 8 was recorded as the soil loss and was compared to the soil loss recorded for bare and compacted specimens with biopolymer treated as an index of the effectiveness of biopolymer treatment.

Phase I testing included untreated soil, soil treated with the two biopolymers identified through the screening process, and two synthetic polymer dust control agents. The synthetic polymers used in the testing program were Coherex, manufactured by Pavement Technology, and Dustshield, manufactured by Soil-Loc.

The samples tested in Phase I using the above approach as well as the treatment methods, application rate, and test results in terms of soil loss are summarized in Table 6.

Table 6

Phase I Testing Program

Number of Samples	Treatment Method	Application rates
1	Bare	-
1	Watering	100 ml
1	Tamping with water	100 ml
7	Biopolymer treatment (xanthan gum)	0.2 to 6 g/m^2
1	Coherex	1 L/m^2
1	DustShield	0.25 L/m^2

The application rate presented in Table 6 is the dry weight of biopolymer applied per unit surface area. The biopolymer solutions were applied to the surface of the soil in the pie plate using a plastic sprayer with a hand trigger. To apply the desired application rate, the number of sprays of the trigger required to apply the desired amount was estimated based upon measurements of how many milliliters of liquid was discharged per pull of the trigger (i.e., 2 sprays discharged about 3 ml of liquid) and the concentration of biopolymer in solution. The required amount of solution was then added to the bottle and sprayed onto the soil surface until the sprayer bottle was emptied.

Results and Discussion

Table 7 summarizes the results of the initial test of one of the candidate biopolymers. In this test, 15 ml of solution containing 0.015 g of dry xanthan gum was applied to the surface of the soil in the pie plate, for an application rate of 0.42 g of xanthan gum per square meter of surface area. The initial application rate showed significant effectiveness in reducing soil loss. Only 0.33 percent of the biopolymer-treated soil was lost during the 10 minutes run as compared to 52 percent of the soil in the control test with an untreated specimen. This initial test demonstrated that application of biopolymer is a feasible method of soil stabilization for fugitive dust control.

Table 7

Xanthan Gum Sample

Sand Source	Butterfield Station
Method of treatment	Xanthan Gum
Application rate (g/m^2)	0.42
Weight of dry soil + Biopolymer (g)	1419.23
Weight after 10 minutes in front of the fan (g)	1414.53
Soil loss (g)	4.70
Soil loss percentage (%)	0.33

Table 8 presents the results of the test on a compacted soil specimen. The soil placed in the pie plate was mixed with 100 ml of water and then compacted. A compacted specimen was tested in this phase because it is a good baseline for biopolymer treated specimens, since compaction is the second most common soil stabilization method (after water application).

Table 8

Compacted Sample

Sand Source	Butterfield Station
Method of treatment	Compaction
Weight of dry soil + Water (g)	1457.1
Weight after 10 minutes in front of the fan (g)	1449.8
Soil loss (g)	7.3
Soil loss percentage (%)	0.50

Table 9 shows the results of the test on a watered sample. The preparation of this specimen is identical to the bare soil sample, with the exception of spraying the soil surface with 100 ml of water immediately before testing and conducting the test while the surface of the specimen was still wet.

Table 9

W*atered Sample*

Sand Source	Butterfield Station
Method of treatment	Water application
Weight of dry soil + Water (g)	1403.6
Weight after 10 minutes in front of the fan (g)	1398.7
Soil loss (g)	4.9
Soil loss percentage (%)	0.38

Table 10 and Figure 21 summarize the results of four tests: one test each for untreated soil, soil treated with xanthan gum, soil treated by application of water, and soil compacted after application of water. The summary of results in Table 10 suggests that application of water, soil compaction, and application of xanthan come may be equally effective for controlling wind erosion. About more than half of the sample is lost when the surface is untreated. Applying xanthan gum, wetting the soil surface, and compacting the soil all reduced the loss considerably (by two orders of magnitude, to less than 1%). However, an application rate of 100 ml of water to the surface of the pie plate is a significant amount of water for an area of 0.036 m^2, and water will evaporate quickly in the summer in Phoenix and other arid regions, requiring continual application. Furthermore, compaction of disturbed soil on a construction site is expensive and time consuming and not likely to be cost effective. Therefore, these tests indicate that application of biopolymer may be a cost-effective interim fugitive dust control measure in arid climates.

Table 10

Data Summary

Plate #	Treatment	Soil Loss %
1	Bare	52.16
1A	Xanthan gum (15ml)	0.33
2	Water (100)	0.38
2A	Compaction (100 ml)	0.50

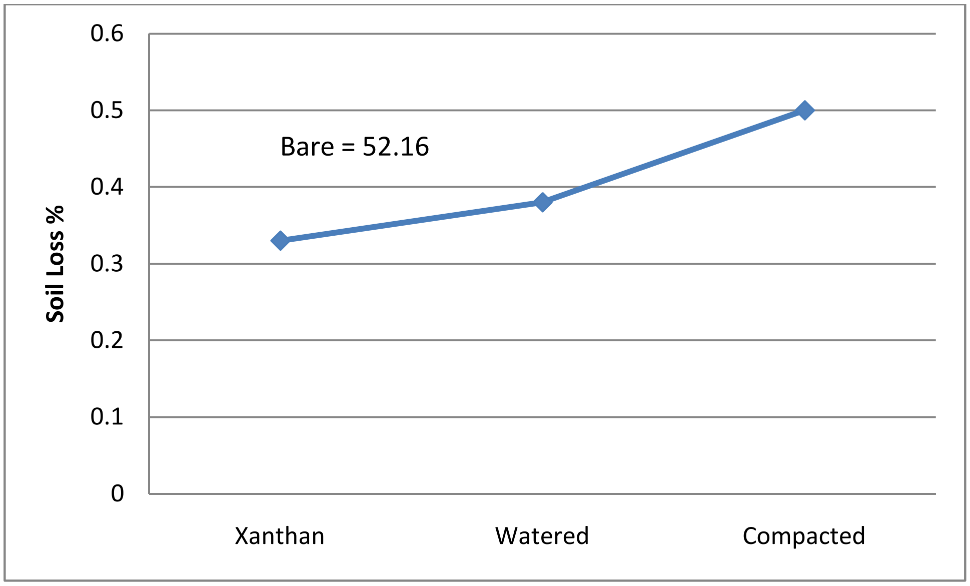


Figure 21: Effectiveness of Different Treatment Methods

Table 11 summarizes a series of tests using xanthan gum in which the application rate was varied from 0.2 g/m^2 to 6 g/m^2. The soil loss in these tests ranges from 16.7 percent at the lowest application rate (plate 3) to practically nothing (plate 9) for application rates in excess of 1 g/m^2. It should be noted that the actual application rate is somewhat less than that reported in the tables presented herein as the spraying process inevitable resulted in some biopolymer being sprayed outside the edges of the pie plate.

The data in Table 11 is summarized in Figure 22. Table 11 and Figure 22 suggest that there may be some optimal application rate for xanthan gum beyond which no immediate benefit is derived in terms of dust suppression. However, there may still be some longer term benefit of higher concentrations in terms of durability. Also, it should be noted that even at the lowest application rate of to 0.5 g/m², there was still substantial benefit of xanthan gum application, as the erosion rate was reduced by approximately 1/3rd from that of bare soil.

Table 11

Application Rate Versus Soil loss Percentage for Treatment with Xanthan Gum

Plate #	Solution Strength g/l	Application rate g/m²	Before Wind (g)	After wind (g)	Soil Loss %
3	0.5	0.2	1383.7	1172.5	16.70225
4	0.5	0.5	1494.4	1491.1	0.240157
5	0.5	1.1	1564.3	1563.9	0.027757
6	2	2.2	1502.2	1502.1	0.007236
7	2	4	1537.7	1537.6	0.007045
8	2	6	1553.3	1553.2	0.006977

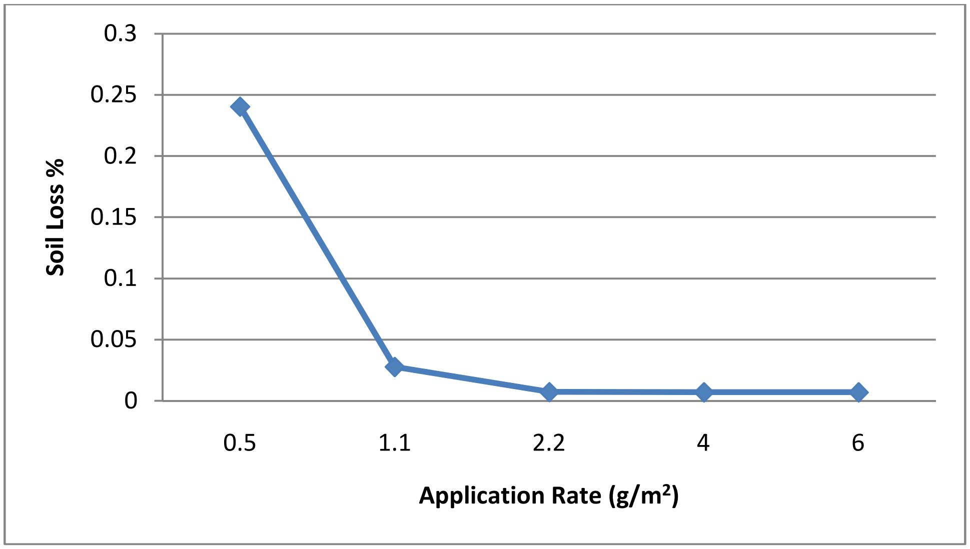


Figure 22: Application Rate Versus Soil loss Percentage

Two synthetic polymer commercial dust palliatives, Coherex and DustShield were tested in Phase I. Soil specimens were treated in accordance with manufacturers' recommendations. Neither of these synthetic polymers showed any loss under this particular experiment setup. To try to induce some erosion with the synthetic polymer-treated specimens, a leaf blower was employed to provide a more powerful wind source. However, soil loss data were not consistent with this device.

The data for chitosan presented in Table 12, was obtained from the study conducted by Kavazanjian, Iglesias, & Karatas (2009). The results of the chitosan test, conducted using the same experimental setup employed in the xanthan gum experiments, are shown in Table 12. Note that Chitosan seemed to require a similar application rates to xanthan gum to attain a high level of dust suppression: a soil loss of 0.35% was achieved with 0.5 g/m^2 of chitosan and a soil loss of 24% was achieved with 0.5 g/m^2 of xanthan gum.

Table 12

Chitosan Data

Solution Strength g/L	Application rate g/m^2	Soil Loss %
1	0.5	0.35

Conclusions from Phase I Testing

The following conclusions may be drawn from the Phase I testing:

1. Biopolymers can be effective as dust suppression agents.
2. Xanthan gum and chitosan can be carried forward for Phase II testing (xanthan gum is water soluble and chitosan is water insoluble).
3. Initial application rates for these biopolymers were established as 0.2 to 6 g/m^2 for xanthan gum and 0.5 g/m^2 for chitosan.

Chapter 5

PHASE II: WIND TUNNEL EXPERIMENTS

Introduction

Phase II experiments were conducted in the Arizona State University School of Earth and Space Exploration (SESE) planetary geology wind tunnel specially designed to investigate wind erosion processes (Figure 23). The objective of Phase II experiments was to determine the effect of soil treatment with biopolymers on the threshold friction velocity (the wind velocity necessary to detach a particle of the candidate soil from the soil surface). The biopolymers tested in Phase II were the biopolymers identified for further testing in Phase I experiments; xanthan gum, and chitosan. In addition to these two biopolymers, a third biopolymer guar gum was tested in Phase II. Guar gum was included in Phase II testing because it is a common and relatively inexpensive biopolymer.

In the Phase II experiments, biopolymer treated specimens were placed in the wind tunnel and the wind velocity was slowly increased until detachment of soil grains from the surface was observed. A special adapter ring was designed and fabricated such that the same pie plates used in the Phase I experiments could be used in Phase II. The equipment and facilities employed in Phase II experiments is listed in Table 12. This equipment and facilities included the wind tunnel, the special adapter ring, two intake rooms, two plexi-glass doors, a fan, a photography system, and a control panel.

Table 13

Phase II Apparatus

Planetary Geology Wind Tunnel	Balance
Adapter Ring (outside diameter 254 mm, inside diameter 222 mm, thickness 6 mm)	Aluminum pie plate (21.6 cm diameter and 2.54 cm deep)
Sieves (No. 10, No. 30, No. 100), sieve pan, and sieve cover	Plastic bottle with a trigger sprayer
Graduated cylinder, beakers, and flasks	Drying oven
Large bowl	Steel straightedge
Sieve shaker	Fume hood
High-speed blender	DSLR camera
Telescope	Flashlight
Paper tape	

Samples Preparation

The specimens for Phase II testing were essentially identical to those employed on Phase I. The same 21.6 cm diameter pie plates were used, the soil was prepared in exactly the same manner, and the dust suppression agents (biopolymer, soil compaction, and water) were applied in exactly the same manner as in Phase I.

SESE Wind Tunnel Characteristics

The School of Earth and Space Exploration planetary wind tunnel, shown in Figure 23, is specifically developed for wind erosion experiments on Earth, Mars, and Venus. The wind flume has a roughened surface and roughness elements (Figure 24) that are designed to trip the air flow to produce the correct wind profile. The wind tunnel has a back-lit observation window. The wind tunnel fan is capable of velocities up to 23 m/s.

It should be noted that the wind tunnel floor is constructed to create a boundary layer flow representative of the flow over a flat soil surface for the specific purpose of measuring threshold friction velocities. The roughened floor of the wind tunnel, designed specifically for this purpose, feels like it has been sprayed with a sand spray paint or covered with coarse sandpaper.

Figure 23: SESE Planetary Geology Wind Tunnel

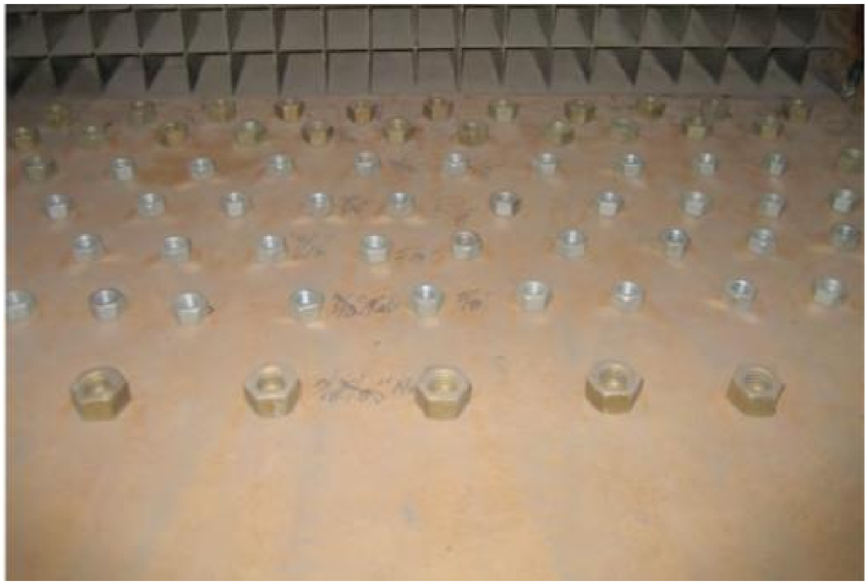


Figure 24: Wind Tunnel Roughness Elements. Source: (Arizona State University)

Modifications for Phase II Testing

To accommodate the aluminum plate inside the wind tunnel flume, an adaptor ring (outside diameter 254 mm, inside diameter 222 mm, thickness 6 mm) was designed to fit into the cut-out space for wind tunnel specimens located in the floor of the flume opposite the observation window. The ring, shown in Figure 25, was designed so that the top edge of the lip of the pie plate and thus the prepared surface of the soil in the plate were perfectly leveled with the floor of the wind tunnel. This configuration was necessary in order to maintain a boundary layer flow with the proper characteristics to measure the threshold friction velocities.

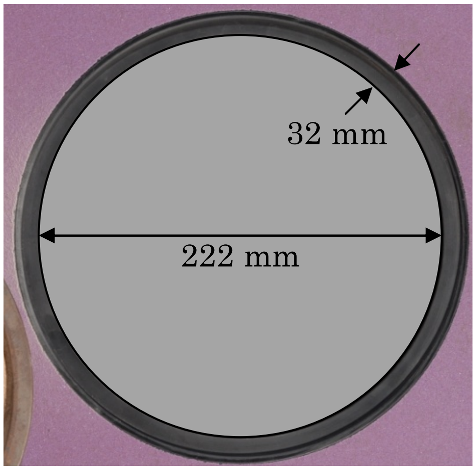


Figure 25: Adapter Ring

Wind Tunnel Operation

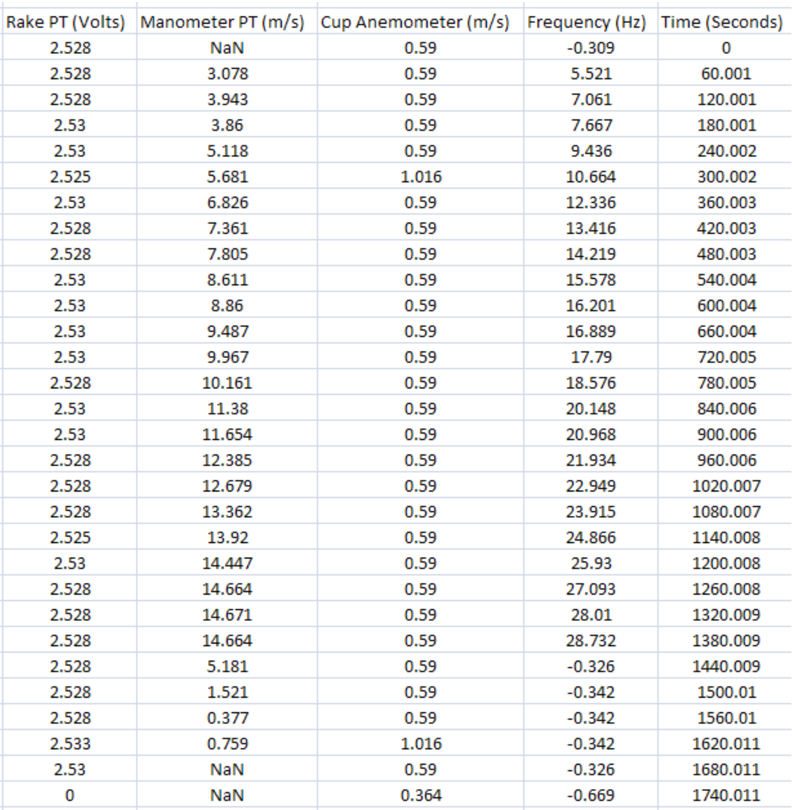
Operation of the wind tunnel involves a three-step process. These steps as described in the Planetary Geology Wind Tunnel Manual (Arizona State University) and detailed in the wind tunnel operation checklist are as follows:

- System setup
    1. Sweep the west and the east intake room of debris prior to the running of experiment.
    2. Set the intake louvers to full open position in both rooms.
    3. Open the exhaust roll door.
    4. Turn on power supply, Stera pressure transducer, Stera array controller and the Variable Frequency Drive (VFD).
    5. Check accuator position.
    6. Initiate LabView monitoring program.
- Preparation for running
    1. Ensure that no debris is present in the north and south of tunnel. This debris may interfere with the experiment
    2. Check the placement of boundary layer roughness elements. See the figure below.
    3. Check water manometer.
    4. Set speed on controller (in Hz)

5. Follow the experimental procedure (shown below) and setup photographic equipment.
6. Press green Start button on the VFD controller.

- System shut down
  1. Press the red “Stop” button on VFD controller to stop the wind tunnel.
  2. Close down the system.
  3. Close the exterior roll door.
  4. Turn off VFD power.
  5. Close all vents in both intake rooms.
  6. Shut off Stera power supply, Stera array controller, and the power supply.

Wind speed was monitored with LabView software, a sample LabView output is shown in Figure 26.



Rake PT (Volts)	Manometer PT (m/s)	Cup Anemometer (m/s)	Frequency (Hz)	Time (Seconds)
2.528	NaN	0.59	-0.309	0
2.528	3.078	0.59	5.521	60.001
2.528	3.943	0.59	7.061	120.001
2.53	3.86	0.59	7.667	180.001
2.53	5.118	0.59	9.436	240.002
2.525	5.681	1.016	10.664	300.002
2.53	6.826	0.59	12.336	360.003
2.528	7.361	0.59	13.416	420.003
2.528	7.805	0.59	14.219	480.003
2.53	8.611	0.59	15.578	540.004
2.53	8.86	0.59	16.201	600.004
2.53	9.487	0.59	16.889	660.004
2.53	9.967	0.59	17.79	720.005
2.528	10.161	0.59	18.576	780.005
2.53	11.38	0.59	20.148	840.006
2.53	11.654	0.59	20.968	900.006
2.528	12.385	0.59	21.934	960.006
2.528	12.679	0.59	22.949	1020.007
2.528	13.362	0.59	23.915	1080.007
2.525	13.92	0.59	24.866	1140.008
2.53	14.447	0.59	25.93	1200.008
2.528	14.664	0.59	27.093	1260.008
2.528	14.671	0.59	28.01	1320.009
2.528	14.664	0.59	28.732	1380.009
2.528	5.181	0.59	-0.326	1440.009
2.528	1.521	0.59	-0.342	1500.01
2.528	0.377	0.59	-0.342	1560.01
2.533	0.759	1.016	-0.342	1620.011
2.53	NaN	0.59	-0.326	1680.011
0	NaN	0.364	-0.669	1740.011

Figure 26: Sample LabView Output

Experimental Procedure

Following preparation of specimens, the wind tunnel tests were conducted in the following manner:

1. Open the wind tunnel Plexiglas doors (Figure 27).
2. Insert the adapter ring into the tunnel floor.
3. Place the pie plate inside the adapter ring.
4. Tape the sides of the plate (a safety measure to avoid losing the plate on higher speeds and damaging the wind tunnel fan).

5. Close the Plexiglas doors, insert the upper clamp first then the lower clamp (make sure both clamps are firmly in place and tightened).

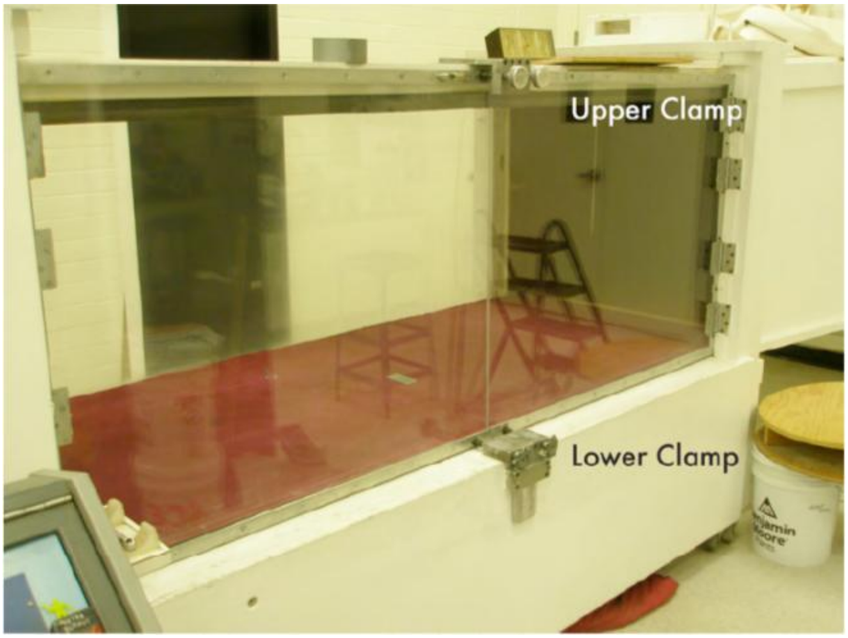


Figure 27: Wind Tunnel Plexiglas Doors in the Closed Position with Both Clamps Inserted. Source: (Arizona State University)

6. Turn on the fan. The fan works by suction instead of blowing.
7. Visually monitor the sample for saltation. This step involves turning the lights off and holding the flashlight at 45 degrees to eye-level (Figure 28).
8. Increase the velocity gradually until saltation/erosion is observed.
9. Record the threshold friction velocity.

10. Turn off the fan.
11. Take the weight of the sample as necessary. The before and after weights of pie plates were helpful especially when TFVs were not observed, i.e., at 23 m/s.

Figure 28: Observing Threshold Friction Velocities.

Observations during Testing

The following pertinent observations were made during the wind tunnel tests

- Very loose particles are usually blown away at the beginning of the wind tunnel run at low velocities (5 m/s and below). Soil detachment at this speed is neglected.

- Soil loss accelerates drastically just moments after the threshold friction velocity is observed.
- Soil loss usually takes the form of grooves in the soil surface, wherein the soil crust protects loose particles. Once the crust breaks loose, the underlying loose particles are exposed, and they are lost.

Phase II testing included testing of dry uncompacted soil surfaces, testing of wetted uncompacted soil surfaces, testing of dry compacted soil surfaces, testing of uncompacted soil surfaces treated with bioploymers, and testing of bare soil surfaces with topographic relief. The testing program for Phase II experiments is shown in Table 14.

Table 14

Phase II Testing Program

Number of Samples	Treatment Method	Application rates	Notes
1	Bare	-	-
3	Tamped	-	Bare, dried, and wetted
2	Xanthan gum	0.320 g/m^2	Sieves No. 10, 30, and 100
5	Xanthan gum	0.063-0.320 g/m^2	-
5	Chitosan	0.063-0.320 g/m^2	-
5	Guar Gum	0.200-1.000 g/m^2	-
2	Wet	5 and 10 ml	-
2	Raised profile	-	Bare and Wet (not allowed to dry)

Results and Discussion

Initial Test Series. The first set of Phase II tests employed soil untreated with biopolymers. All specimens used the candidate soil screened through a No. 30 sieve (maximum particle size 0.6 mm).

Specimen # 1

Specimen # 1 was a bare soil specimen that was untreated by any method (water, biopolymer, or tamping). The objective of this test was to provide a baseline value for untreated soil, i.e., for bare soil at a site disturbed by construction activity. Pictures were taken before the start of the test and every one minute after test initiation to observe changes on the specimen surface. The LabView monitoring program was set-up to run for 30 minutes (reading every minute). The wind tunnel was started at 3 m/s at 12:05 pm, and slowly increased while visually monitoring changes in the soil surface. The rate of velocity increase for this sample was about 0.5 m/s per minute. Initial movement of the soil was seen at 9.01 m/s at 12:18 pm. As the velocity was increased to 11 m/s significant downwind movement of soil particles was observed. After increasing the speed gradually to 15 m/s, the pie plate came loose and the wind tunnel was stopped at 12:28 pm.

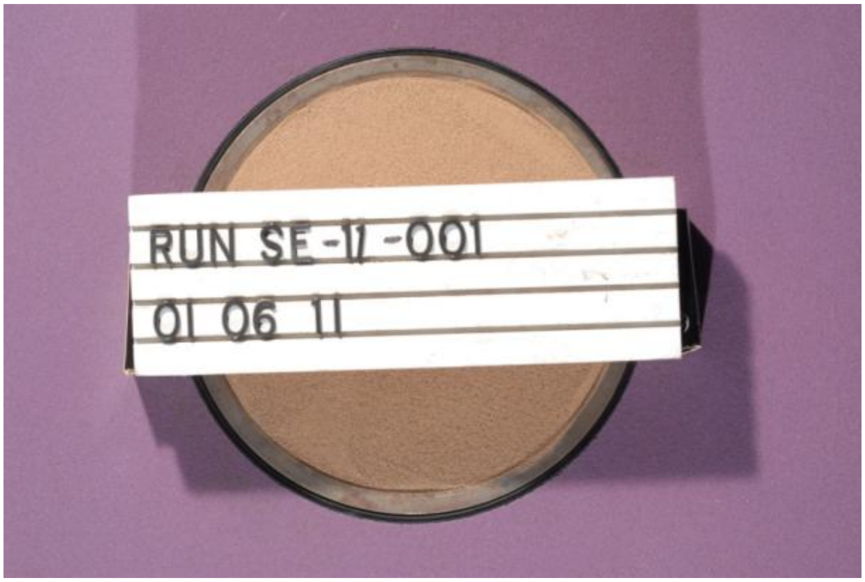


Figure 29: Specimen Prior to Test Initiation

Specimen # 2

Specimen # 2 employed bare soil that was tamped lightly. We increased the speed of the wind at a rate of 1 m/s every minute during this test. A picture was taken every minute. We started the wind tunnel at 10:42 am with a speed of 3 m/s. The first movement of soil particles was noticed at 8.06 m/s at 10:47 am. After the first soil particle movement was observed, the wind tunnel was stopped and a picture of the eroded surface was taken (Figure 30). As the TFV for Specimen 2 was slightly less than that of Specimen 1, the test on Specimen 2 suggested that light tamping has a minimal effect on the wind erosion resistance of the candidate soil.

Figure 30: Eroded Bare Soil Surface

Specimen # 3

Specimen # 3 soil was left in the oven for 24 hours at 105 ˚C. After 24 hours of drying, it was removed from the oven and was tamped lightly. We started the wind tunnel at 9:42 am with a speed of 3 m/s, increasing the speed at rate of 1m/s per minute. The first movement was noticed at 8.78 m/s at 9:47 am. The wind tunnel was stopped. The threshold velocity for Specimen 3 is relatively close to Specimen 2, suggesting that the slight moisture in Specimen 2 has a minimal effect on the TFV.

Specimen # 4

The soil in Specimen # 4 was prepared by mixing the test soil mixed with 100 ml of water in a large bowl. The soil was then placed in the pie plate and the soil surface was leveled by light tamping. The first movement was noticed at 18.46 m/s at 10:40 am. The wind tunnel was stopped. The threshold friction velocity for Specimen 4 is significantly higher than that of Specimens 1, 2, and 3. The test on Specimen 4 suggested that increasing the moisture content could have a significant influence on the wind erosion resistance of the soil.

Table 15 summarizes the results of the first four tests on level, untreated soil samples.

Table 15

Summary of Bare and Tamped Samples Data

Specimen #	Description	TFV m/s
1	Bare	9.01
2	Bare and Tamped	8.06
3	Dried and Tamped	8.78
4	Tamped with 100 ml of Water	18.46

The results of the initial series of Phase II tests, shown in graphically Figure 31, suggests that light tamping and oven-drying does not have a significant effect on the threshold friction velocity. The differences in threshold velocity for specimen 1 through 3 fall within the range expected for experimental scatter. However, adding water and tamping dramatically changed threshold friction velocity(when the specimens was tested without allowing it to dry).

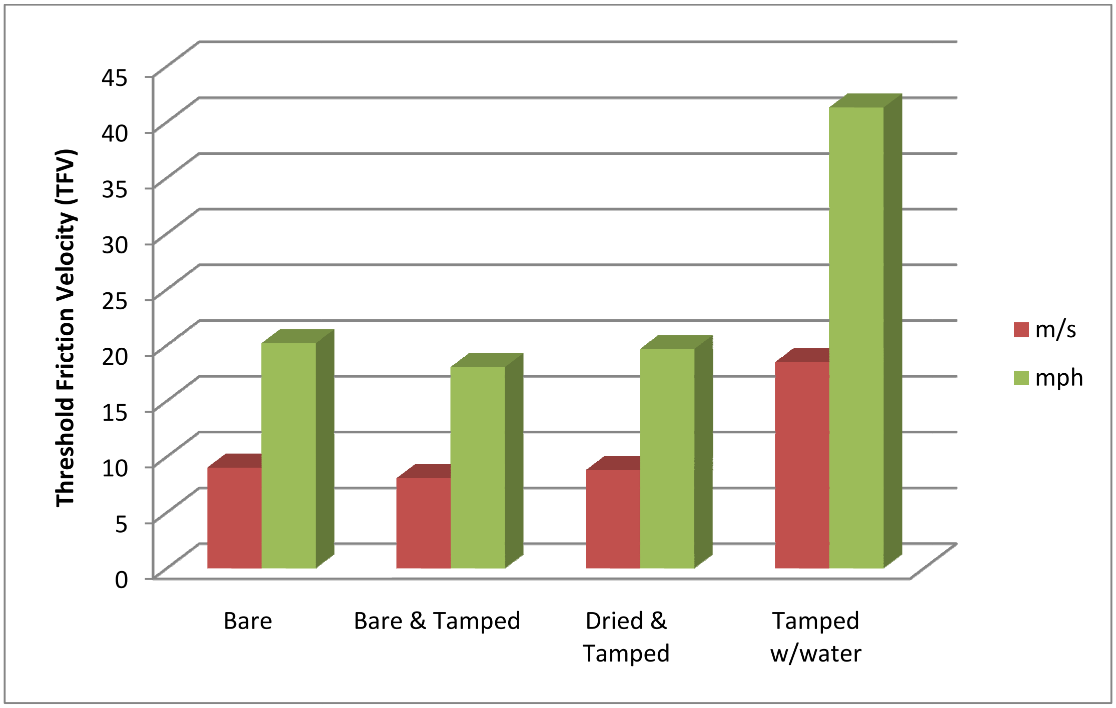


Figure 31: Threshold Friction Velocities for Bare and Tamped Samples (Specimens # 1-4)

Specimens # 5-9

Tests on Biopolymer Treated Specimens. Three biopolymers were tested in the Phase II experiments: xanthan gum, chitosan, and guar gum. To achieve the desired biopolymer concentration, the desired amount of xanthan and guar gum powders were added to 500 ml of water and mixed in a high speed blender until fully dissolved. For chitosan the procedure was slightly different, as a mixture containing 1% acetic acid and 99% water by volume was required to fully dissolve the chitosan powder. The mixing time varied for each mixture; chitosan took the least amount of time whereas xanthan gum took the longest time to thoroughly mix.

Xanthan gum took the longest to mix because it forms clumps of gum upon water contact. To reduce the mixing time, the xanthan gum mixture can be heated or the gum powder can be added gradually in very small quantities while stirring the heated solution.

Table 16 describes the physical characteristics of the biopolymer treated specimens.

Table 16

Biopolymer Mixture Physical Properties

Property	Xanthan Gum	Guar Gum	Chitosan
Mixing time	At least 8 minutes	5 to 6 minutes	3 to 4 minutes
Appearance	Thick and has a lot of bubbles	Light, almost like water	Light with a thick layer of foam
Color	Colorless to Whitish	Colorless	Whitish, maybe due to acetic acid presence
On the surface	Smooth to rough	Rough	Smooth
Surface thickness	1 mm to 1.5 mm	At least 2 mm	1 mm to 1.5 mm

Xanthan Gum. Specimens # 5 through 9 were treated with xanthan gum. The gum mixture was applied by spraying through a mister (commercial spray bottle) at the desired application rate. The required amount of biopolymer was placed in the mister and the spray was applied until the mister was empty. After application of the xanthan gum biopolymer mixture, the soil surface was generally smooth, with a layer of treated soil with a typical thickness of 1 mm to 1.5 mm (based upon visual observations).

Table 17 summarizes the results of the Phase II experiments on specimens treated with the xanthan gum spray.

Table 17

Performance of Xanthan Treated Samples

Specimens #	Application Rate g/m^2	Weight (before) g	Weight (after) g	TFV m/s
5	0.320	1297.18	1296.75	23.00*
6	0.250	1455.00	1446.07	18.24
7	0.125	1494.10	1421.80	15.00
8	0.100	1536.70	1536.27	10.07
9	0.063	1406.00	1406.34	9.23

* For $V_s > 23$ m/s, the before and after weights were used to prove that saltation occurred.

Discussion of xanthan gum test results: The application rate for xanthan gum was proportional to the threshold friction velocity over the range of application rates tested, as shown in Figure 32. At an application rate of 0.063 g/m^2, xanthan gum was somewhat ineffective; its TFV was only slightly higher than that for the bare untreated sample. At an application rate of 0.320 g/m^2, a wind speed of over 23 m/s (the maximum velocity achievable in the wind tunnel) was needed to initiate erosion (this maximum velocity is reported henceforth as 23 m/s). The wind tunnel cannot handle speeds higher than 23 m/s due to the positioning of roughness elements (Figure 25).

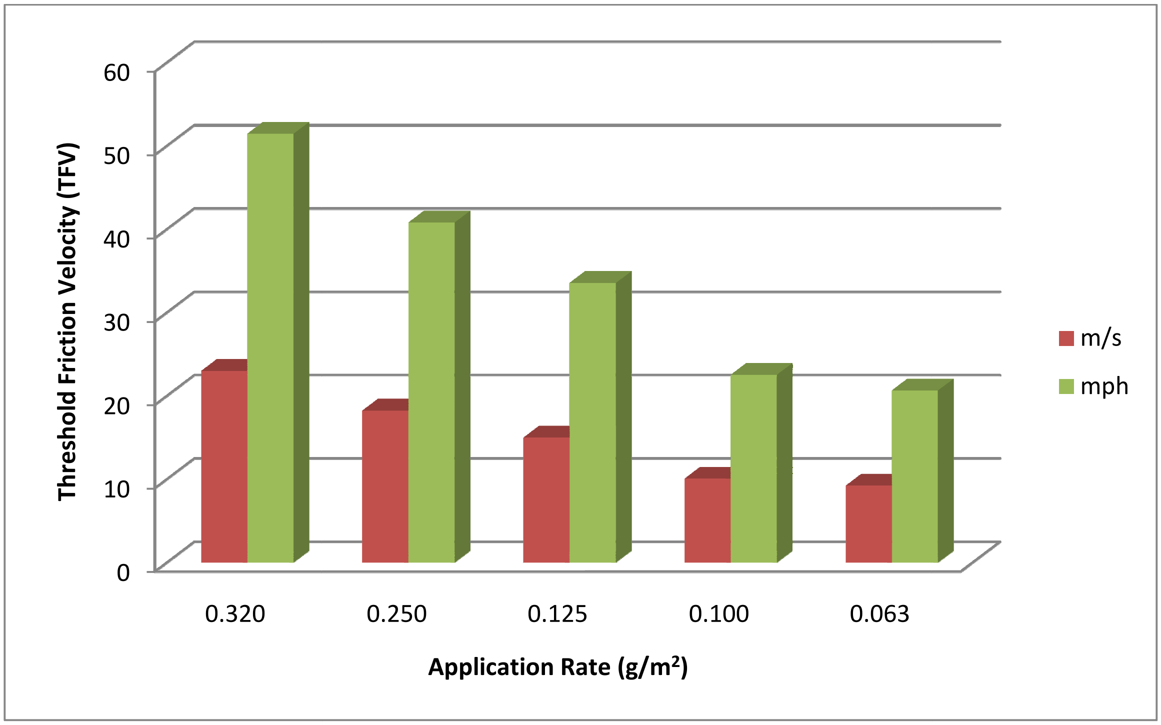


Figure 32: Threshold Friction Velocities for Xanthan Treated Samples (Specimens # 5-9)

The data in Figure 32 show that xanthan gum is effective in stabilizing soil against wind erosion even at low application rates.

Effect of particle size: Two additional xanthan gum treated samples, Specimens 10 and 11, were tested using different soil gradations to evaluate the effect of gradation on wind erosion resistance. These tests were conducted on soil from the same source as the candidate soil but they were sieved through larger and smaller sieves than No. 30 (0.6 mm). The soil for specimen 10 was sieved with a No. 10 (2 mm) screen. The soil for specimen 11 was sieved through a No. 100 (0.150 mm) screen. Specimens 10 and 11 employed the same xanthan gum application rate of 0.320 g/m^2 as specimen 5.

Table 18 and Figure 33 compare the results of Specimens 10 and 11 to Specimen 5. The Specimens that employed soil particles passing the No. 10 and No. 100 sieves both showed lower resistance to wind erosion than the test on the specimen composed of soil passing No. 30 sieve, for the same xanthan gum application rate. Possible reasons for this observation include a decrease in either true cohesion or capillary tension for the coarser soil (specimen 10) and the decreased mass of finer soil particles (specimen 11).

Table 18

Xanthan Treated Samples (Sieves No. 10, 30, and 100)

Specimen #	Sieve No.	Application Rate g/m^2	Weight (before) g	Weight (after) g	TFV m/s
5	30	0.320	1297.18	1296.75	23.00*
10	10	0.320	1345.56	1345.13	12.08
11	100	0.320	1412.99	1412.56	18.46

* For $V_s > 23$ m/s, the before and after weights were used to prove that saltation occurred.

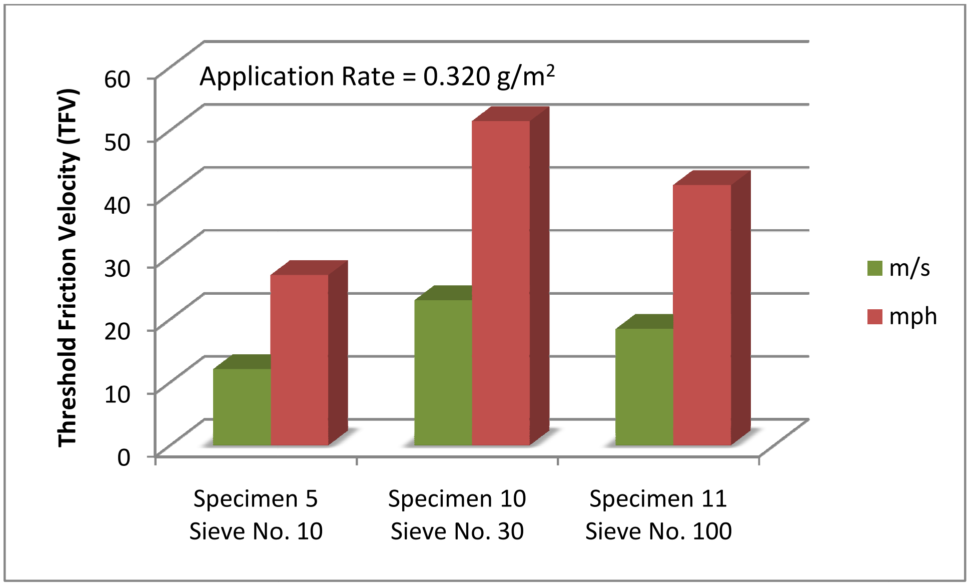


Figure 33: Threshold Friction Velocities for Xanthan Treated Samples of Different Particle Size

Chitosan. Specimens # 12 through 16 were treated with chitosan. The results of the tests on the chitosan treated specimens are shown in Table 19 and Figure 34.

Discussion of chitosan test results: Chitosan powder was added to a solution composed of 1% acetic acid, 99% water by volume. The mixture was light and whitish in color. After the application of chitosan mixture to the soil surface, the soil surface was usually smooth with a thickness of treated soil on the order of 1 mm to 1.5 mm (based upon visual observations).

Table 19

Performance of Chitosan Treated Samples

Specimen #	Application Rate g/m^2	TFV m/s
12	0.320	18.01
13	0.250	17.33
14	0.125	15.86
15	0.100	13.05
16	0.063	8.06

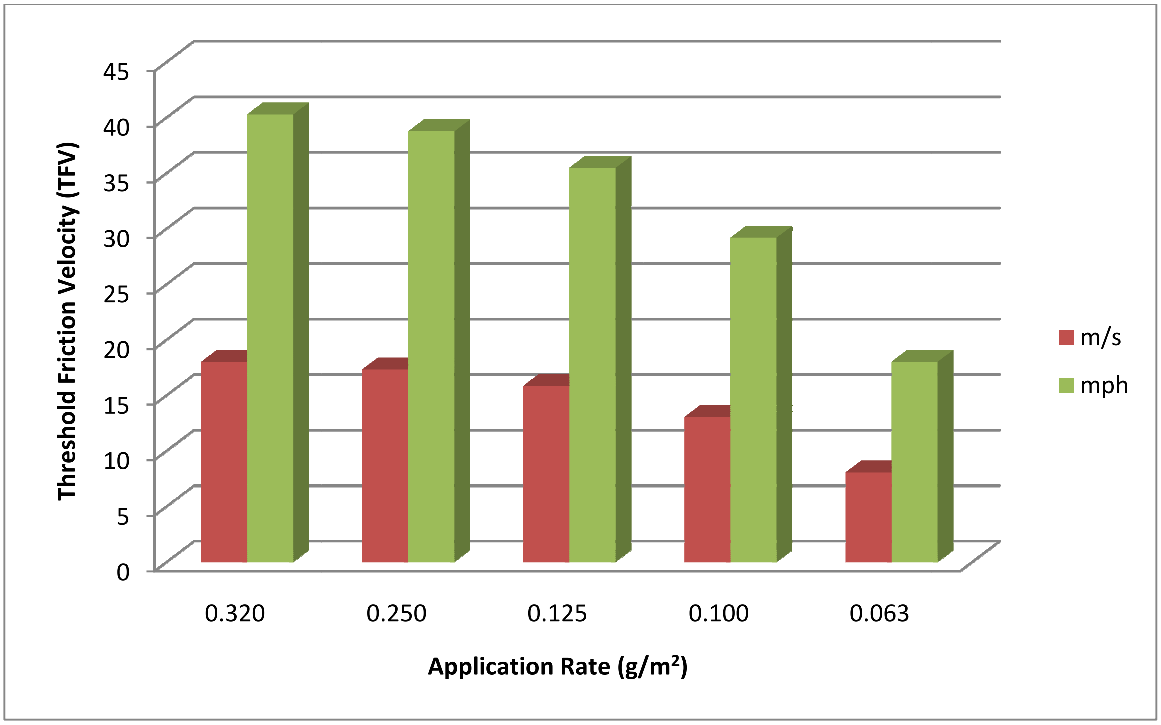


Figure 34: Threshold Friction Velocities for Chitosan Treated Samples (Specimens # 12-16)

The chitosan test data in Table 19 and Figure 34 show that it is effective at application rates of 0.100 g/m^2 and above. As observed for xanthan gum, the relationship between biopolymer application rate and threshold friction velocity appears to be linear.

Guar Gum. Specimens # 17 through 21 were treated with guar gum. The results of the tests on the guar gum treated specimens are presented in Table 20 and Figure 35.

Discussion of guar gum test results: The results of the tests employing guar gum were inconsistent with other biopolymers in that there was no systematic relationship between application rate and effectiveness. This inconsistency could be attributed to the surface roughness of guar gum treated samples. When guar gum solution is sprayed, it forms a thick crust, the thickest among tested biopolymers. The applications rates were used for the guar gum biopolymer were also higher than xanthan gum and chitosan samples. This is because when the guar solution was initially prepared, it looked and felt like water, so higher application rates were used to create a visible coating on the soil surface.

Table 20

Performance of Guar Treated Samples

Specimen #	Application Rate (g/m^2)	Weight (before) g	Weight (after) g	TFV m/s
17	1.000	1397.76	1395.76	17.09
18	0.800	1405.45	1402.77	15.99
19	0.500	1330.84	1330.84	23.00*
20	0.250	1327.07	1325.39	13.05
21	0.200	1507.59	1505.69	15.07

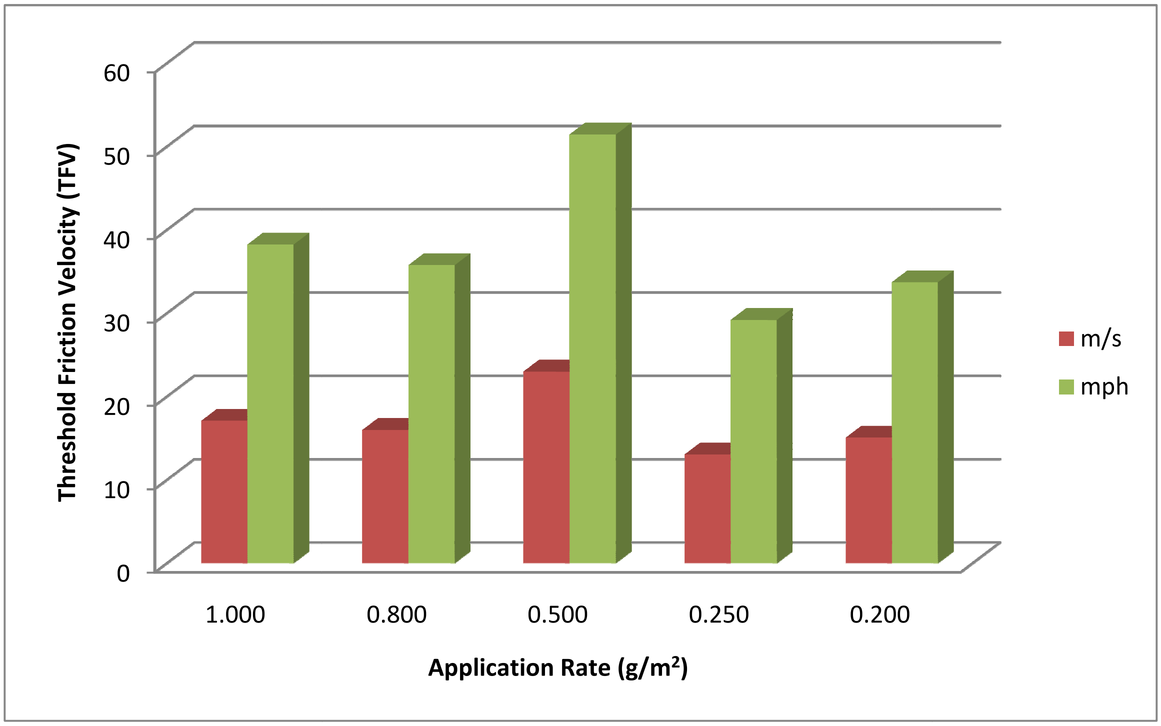


Figure 35: Threshold Friction Velocities for Guar Treated Samples (Specimens # 17-21)

Comparison Among Biopolymers. Figure 36 compares the effectiveness of xanthan gum and chitosan for dust suppression. Figure 36 shows that xanthan gum is less effective at lower application rates but more effective at relatively higher application rates than chitosan. However, in general the effectiveness was of the same order of magnitude for similar concentrations of both biopolymers.

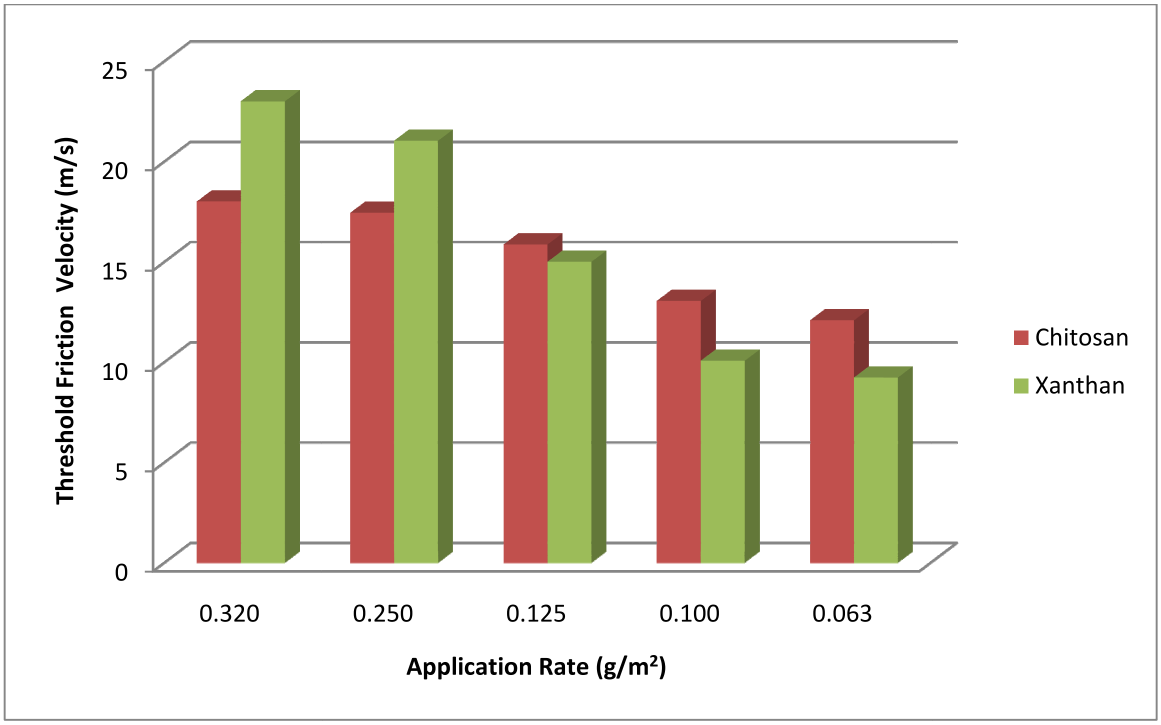


Figure 36: Threshold Friction Velocities for Xanthan Gum and Chitosan Treated Samples

Figure 37 compares the effectiveness of xanthan gum, chitosan, and guar gum at an application rate of 0.250 g/m^2. This data suggests that guar gum is the least effective of the three biopolymers that were tested.

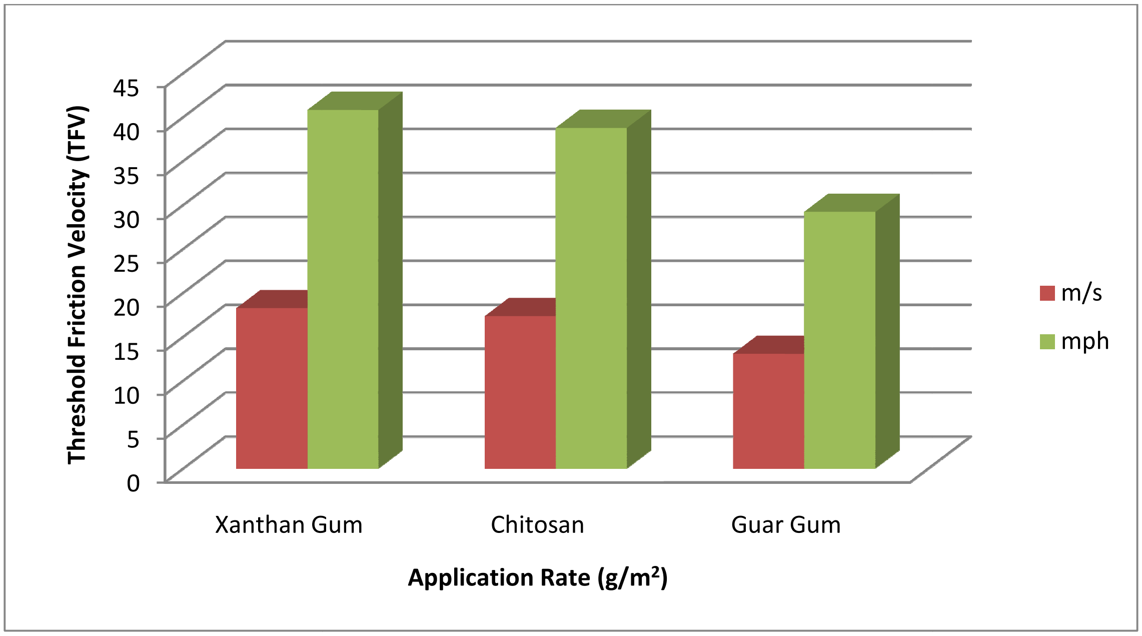


Figure 37: Threshold Friction Velocities for Xanthan Gum, Chitosan, and Guar Gum Treated Samples at an Application Rate of 0.250 g/m^2

Supplemental Testing. A supplemental series of tests, presented in Table 21 and Figure 38, were conducted in which the soil surface was wet and on specimens with a raised profile (with and without wetting).

Specimen # 22 was a specimen that was sprayed with water (5 ml) until the surface glistened and then was tested right after water application. It was not allowed to dry for 24 hours like some of the previous wetted specimens. Specimen 22 showed significant resistance to wind erosion with a TFV equal to that of any of the biopolymer treated specimens. The erosion resistance increased further in

Specimen 23 when twice the amount of water (10 ml) was applied to the specimen.

Specimens 24 and 25 were conducted with slightly raised surfaces (i.e., with surfaces not flush with pie plate lips). The soil in Specimens 24 and 25 was mounded in a dome shape to height of approximately 5 mm above the edges of the pie plate. In Specimen 24, the soil was tested dry and in Specimen 25 water was applied (5 ml) to the surface immediately before testing. Specimen 24 has the lowest threshold friction velocity among the 25 samples tested in the wind tunnel. This is not unexpected, as topographic effects associated with raised surfaces are expected to increase wind velocity and turbulence and thus show raised surfaces will show lower resistance to wind erosion than a level surface of bare dry soil. Application of water to the raised surface increased erosion resistance, as expected.

Table 21

Wet and Raised Samples

Specimen #	Description	TFV m/s
22	Wet	14.8
23	2*Wet	18.89
24	Bare + Raised	6.98
25	Raised + Wet	12.42

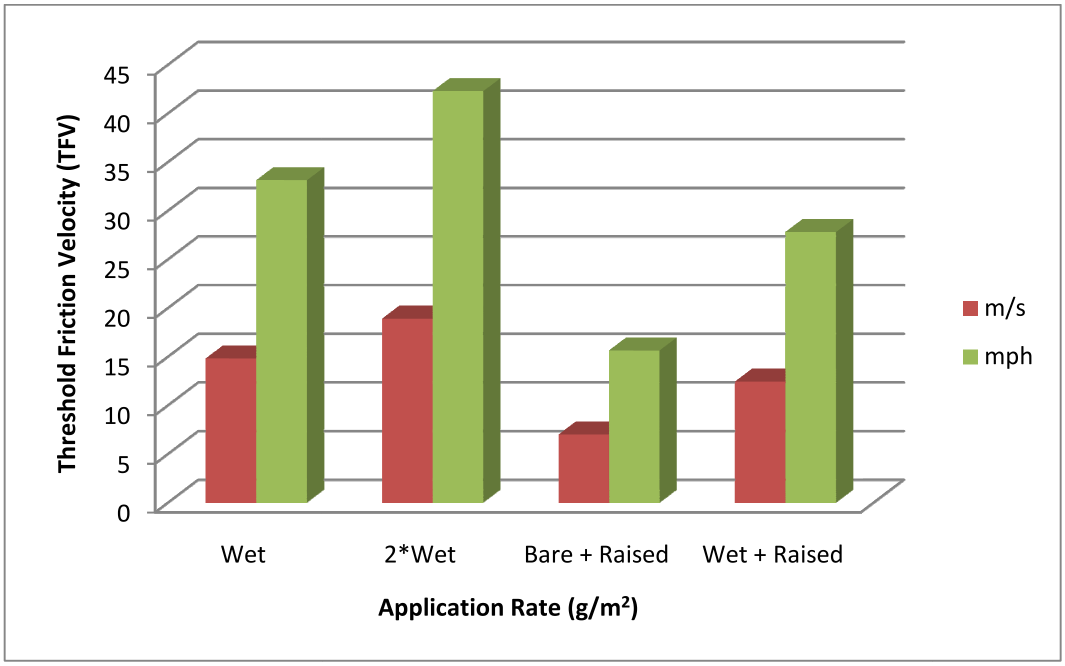


Figure 38: Threshold Friction Velocities for Wet and Raised Samples

Chapter 6

PHASE III: FIELD EXPERIMENT

Introduction

Phase III experiments were conducted to evaluate the effectiveness and durability of biopolymer stabilization for fugitive dust control in the field. Both initial effectiveness and short-term durability were investigated in these experiments. Phase III experiments were conducted at the Butterfield Station landfill (coordinates N33.07, W112.27 and elevation is 1296 ft), on the same soil stockpile from which the soil used in Phases I and II testing was obtained. Six test sections, two each for bare soil and xanthan gum and chitosan stabilized soil, were constructed on the side slope of the stockpile for the Phase III experiments. Each test section was approximately 1.5 m by 1.5 m in dimension.

The test sections were constructed on the side slope of the stockpile in the hope that topographic effects would enhance the potential for wind erosion, and thus help demonstrate the effectiveness of biopolymer stabilization, over the relatively short duration of the field tests. Biopolymer application rates for the test sections were chosen such that some soil erosion was expected over the period during which the test sections were monitored based upon the results of the

Phase II experiments and local climate data on wind speed. The test sections were monitored for wind-induced soil erosion for periods of up to 14 days.

Local Climate Data

In order to determine the optimal orientation of the slope on which the tests sections were to be constructed and the appropriate application rate for the biopolymer stabilization at the test section site, data was collected on the local wind velocity and direction. This data was collected from an Arizona Department of Environmental Quality (ADEQ) monitoring station located at the Cobblestone Farms housing development in the city of Maricopa, approximately 27 km in a northeast direction from the site (coordinates N33.07, W112.04, and the elevation is 1148ft), the nearest climate monitoring station to the landfill. Figure 39 shows the location of the weather station from which the climate data was collected and the Butterfield Station landfill where the test sections were constructed.

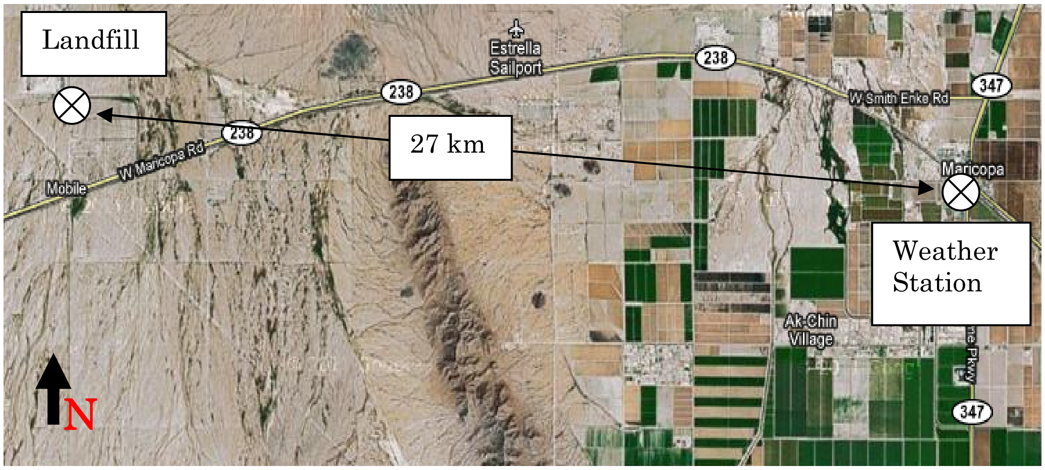


Figure 39: ADEQ Monitoring Station and Butterfield Station Landfill. Source: Google Maps.

Table 22 shows the prevailing wind direction for the months of February and March over a 5 year period from 2007 to 2011. Table 23 shows the maximum wind speed at the monitoring station for the months of February and March over a 4 year period from 2008 to 2011.

Table 22

Average Wind Directions

Year	February (degrees from north)	March (degrees from north)
2007	251	NA
2008	213	246
2009	230	247
2010	222	220
2011	322	-

Source: weather.azkiwis.net

Table 23

Maximum Wind Speed

Year	February (m/s)	March (m/s)
2011	13.9	---
2010	12.9	13.9
2009	17.5	16.0
2008	11.3	12.3
Max	17.5	16.0

Source: weather.azkiwis.net

Based upon these wind conditions, the target threshold velocity for the biopolymer stabilized test sections was on the order of about 15 to 18 m/s such that some wind-induced erosion would be expected on the bare soil test sections. Furthermore, the test sections were placed on a west-southwest facing slope (a slope facing 250 degrees from north) so that the slope was approximately normal to the prevailing winds.

Test Section Program

Based upon Phase II wind tunnel testing, water-soluble xanthan gum and water-insoluble chitosan were selected for Phase III field experiments. An application rate of 0.250 g/m^2 was selected for xanthan gum whereas an application rate of 0.320 g/m^2 was selected for chitosan. These application rates were based upon the Phase II results and the climate data discussed above. A total of six test sections were constructed: two for each biopolymer and two control (bare soil) test sections. The test sections were constructed on a relatively low (≈ 5 m high) approximately 3H:1V slope on a soil stockpile at the Butterfield Station landfill. Figure 40 shows the approximate locations of the test sections.

Figure 40: Aerial View of the Stockpile. Source: Google Maps.

Testing Section Design

Test section design employed a monitoring concept similar to that used by Hai, et al., (2009) as described in chapter 2. Pins deployed from a cross bar were used to measure the relative change in the surface elevation of the test sections. The cross bar was placed across two wooden side rails embedded in the surface of the stockpile. Wooden stakes driven into the soil (4 stakes per test section) were used to secure the side rails. The stakes are made of birch wood with the following dimension: 19 mm in diameter, 305 mm in length and the bottom 40 mm of the stakes is sharpened to a conical point to facilitate penetration into the ground.

Wooden side rails (2 per test section) fabricated from oak were embedded in the ground to provide a reference frame for seating of the cross bar used to make measurements of the change in surface elevation of the test section. A sketch of a rail is shown in Figure 41. The dimensions of each rail was as follows: 38 mm x 89 mm x 1220 mm (Nominal 2 inch x 4 inch), two side holes: 19 mm (64 mm from each side), and three grooves: 25 mm x 64 mm (two of them are 152 mm from the sides and one at the center at 610 mm).

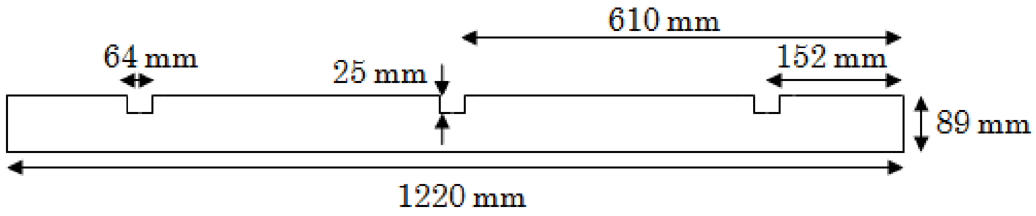


Figure 41: Sketch of the Wooden Side Rail

The cross bar that sat on the wooden rails and from which the measurements of surface elevation change were made was fabricated out of steel. A sketch of the steel cross bar is shown in Figure 42. The cross bar dimensions are as follows: 13 mm x 51 mm x 1220 mm with six grooves: 6 mm x 13 mm (one at every 203 mm).

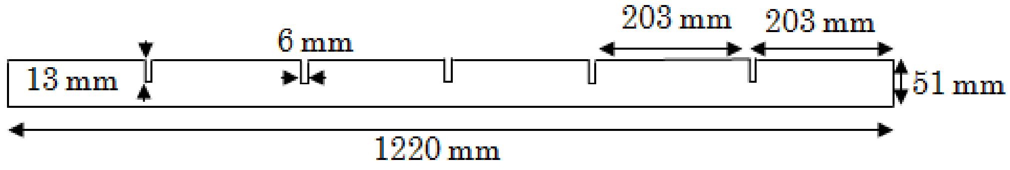


Figure 42: Sketch of the Steel Cross Bar

Measurements of the change in surface elevation were made using a CEN-TECH 8-inch digital caliper (item 47260) with an extendable depth probe at one end. The caliper is shown schematically in Figure 43. The caliper's depth probe was extended through a notch in the steel cross bar and a 19 mm-diameter tack glide was attached to the bottom of the caliper's depth probe. The tack glide, shown schematically in Figure 44, was used to create a more accurate reading when measuring the distance from the steel cross bar to the soil surface. The depth probe with the tack glide attached was extended until the tack glide was seated on the ground surface and a measurement of the distance from the cross bar to the soil surface was recorded. The caliper has a metric display that is accurate to 0.02 mm with 0.0005" resolution.

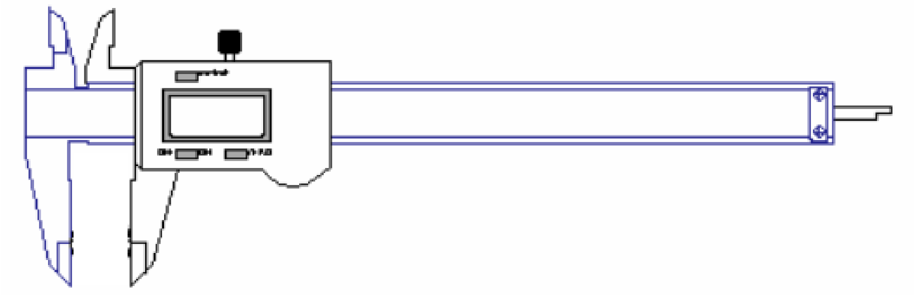


Figure 43: CEN-TECH Digital Caliper

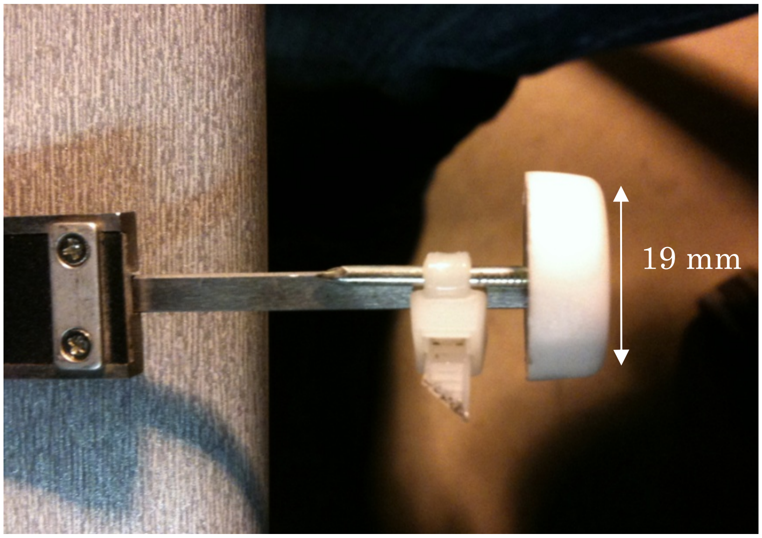


Figure 44: Tack Glide Attachment

Test Sections Installation

The ground at each of the six test section sites was prepared by breaking the crust on the surface of the stockpile with shovels and picks. The prepared area was about 3m x 3m for each section to accommodate for the actual 1.5m x 1.5m testing area. The broken-up soil was then raked to create a smooth surface, free of gravel and large soil aggregates (to as large an extent as practical). The wooden rails for supporting the cross bar were placed approximately 1.5 m apart and then secured in place using the 19 mm diameter stakes driven into the ground. Figure 45 shows one of the wooden rails being installed. Trenches connected to natural gullies were excavated to divert surface water around the test sections. Blue surveyors chalk was dusted on the surface to aid in visual observation of erosion.

Figure 45: Setting Up the Testing Section

Biopolymer Application

The biopolymer was applied to the xanthan gum and chitosan test sections using 2 gallon Flo-Master (Model 1002P) home and garden sprayers purchased at Home Depot. Two options were considered for preparing the biopolymer mixtures. The first option was mixing the biopolymer solution in field inside a 5 gallon bucket with a cordless drill that had a paint mixer attached and then transferring the mixture to the sprayer. The second option was preparing the mixtures in the ASU laboratory (with a high speed blender) in small batches and then transferring each batch into the sprayers and transporting the sprayers to the site.

The advantage of mixing the contents in the field was it would avoid the possible precipitation of the biopolymer from the solution during transport to the site. On the other hand, mixing in the laboratory would create a solution with a better biopolymer distribution, since it could be mixed in batches of 500 milliliters in a high speed blender. It was decided to mix trial batches in the laboratory and observe if there was any precipitation. One batch of xanthan gum and another batch of chitosan were prepared and poured into 200 milliliter beakers. The beakers were observed for three hours, which is approximately the amount of time it takes to transport the mixtures to the field and apply them at the stockpile. Although the color of the mixtures became lighter there was no precipitation observed in either beaker. Therefore, the decision was made to prepare the mixtures in the lab and transport them to the field.

Biopolymer Application in the Field

Biopolymer application rates were selected from Phase II results and wind data obtained from Cobblestone Farms weather station. The Cobblestone Farms wind data is summarized in Table 23. This data indicated a maximum wind speed in the late winter, early fall in the landfill vicinity of between 15 and 18 m/s (35 and 40 mph). Phase II testing indicates that xanthan gum could sustain 18-20 m/s wind at an application rate equal to 0.250 g/m^2 (threshold friction velocity of 18.24 m/s). The Phase II data also indicated that chitosan application rate equal to 0.320 g/m^2 (threshold friction velocity of 18.01 m/s) would be appropriate.

Based upon Phase II testing and the anticipated wind velocity at the site, the xanthan gum mixture was prepared with a concentration of 0.250 g/L and was applied a rate of 0.250 g/m^2. Hence, one liter of the xanthan gum mixture was applied for each square meter of test plot. The chitosan mixture was prepared at a concentration of 0.320 g/L and applied at a rate of 0.320 g/m^2. Hence, one liter of the chitosan mixture was also applied per square meter of test sections.

Test Section Measurements

Figure 46 shows the layout of one of the test sections. The following measurement procedure was employed at each test section:

1. Place the cross bar in the top set of grooves (grooves A in Figure 46).
2. Align the edge of the cross bar with the outside edge of the right-hand rail (looking upslope).
3. Insert the digital caliper into opening 1.
4. Zero the caliper.

5. Extend the depth probe until the foot extension just touches the ground.
6. Record the reading for point A-1.
7. Repeat steps 1 to 6 for the other 4 points on the cross bar.
8. Move the cross bar to the next set of grooves (grooves B) and repeat steps 2-6).
9. Move the cross bar to grooves C and repeat.
10. Move to the other 5 stations and repeat.
11. Take photos of the surveyors chalk.

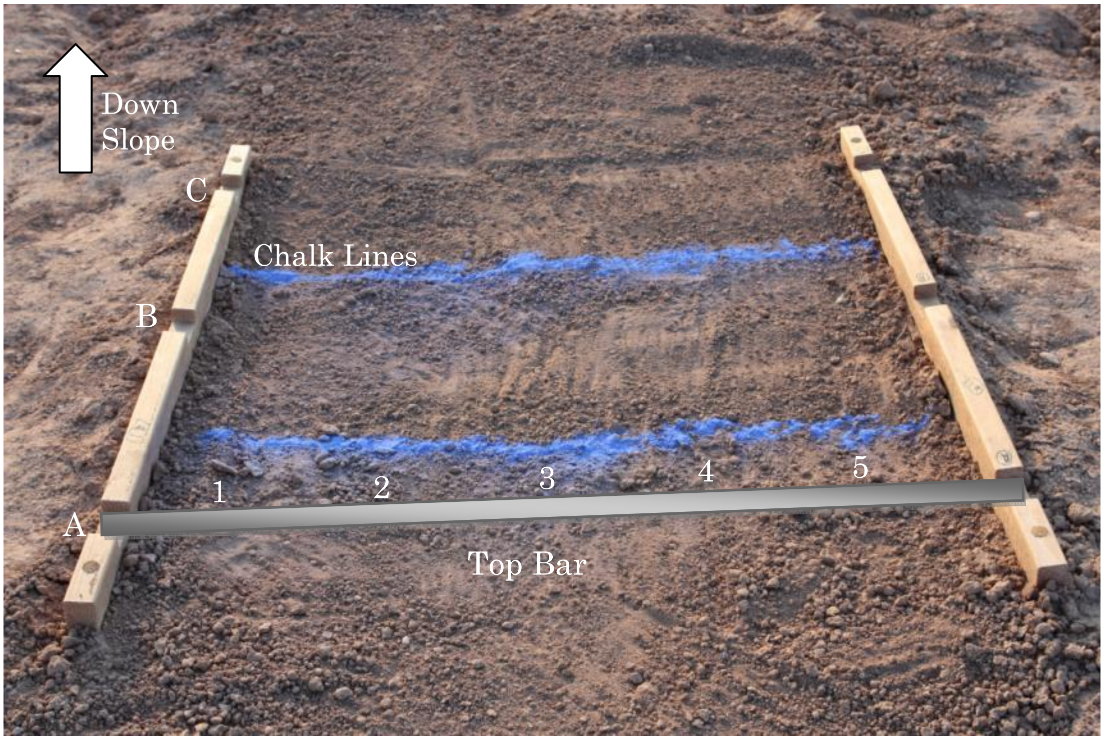


Figure 46: Testing Section Layout

Results and Discussion

Initial installation of the test sections was on February 22nd, 2011. Observations and readings were taken twice a week between the period of February 22nd, 2011 and March 28th, 2011. There were two rain events over this period: one on the 27th of February and another on the 21st of March. After each rain event, the surface of the six test sections was reworked and the biopolymer was reapplied. Therefore, the field testing consisted of three test intervals separated by two rain events. Interval one was only two days in duration and consisted of two sets of measurements, an initial set on February 22 and a second one on February 24. Interval two consisted of 5 sets of readings over a period of 14 days, starting with an initial reading on March 3 and a final reading on March 17. Interval three consisted of 2 sets of readings over a period of 4 days, starting with an initial reading on March 24 and a final reading on March 28.

The first testing interval actually consisted of three sets of readings taken between initial installation of the test sections (February 22) and February 28 (the day after the first rain event). These readings are presented in Table 24. However, only the first two sets of readings are relevant, as the February 28 readings were taken after the first rain event.

Table 24

Test Section 1 (Bare Soil) Readings, First Interval (mm)

Date	Groove	1	2	3	4	5	Average
22-Feb	A	31.85	27.53	35.36	39.42	27.07	32.25
24-Feb		33.14	32.35	37.51	41.13	28.18	34.46
28-Feb		32.96	32.86	36.82	41.20	26.62	34.09
22-Feb	B	34.21	27.94	31.17	34.51	35.52	32.67
24-Feb		35.68	30.77	32.46	36.47	36.61	34.40
28-Feb		34.82	29.18	31.37	35.85	36.37	33.52
22-Feb	C	14.64	10.39	17.78	29.03	20.30	18.43
24-Feb		15.32	16.36	20.28	30.40	22.54	20.98
28-Feb		15.78	16.34	20.29	30.59	21.56	20.91

The values in the above table represent the distance from the cross bar to the soil surface. The difference in the distance to the soil surface is an indicator of how much erosion has occurred. Table 25 presents the processed data showing the difference in the distance to the soil surface from the initial reading of the test interval to the end of the test interval. Zeros refer to the initial readings. Positive values are an indicator of soil erosion. Negative values indicated the ground surface elevation had increased. An increase in ground surface elevation could be due to ground swelling, soil creep, and animal related factors (i.e., footprints and feces) or could be an artifact of the accuracy of the measurements. The increases for the February 28 readings in Table 25 are likely related to the rain event the night before.

Table 26 summarizes the elevation changes between February 22 and February 24 for all six test sections for the first test interval. Table 27 presents a similar summary for the second test interval, from March 3 through March 17, and Table 28 presents the data for the third test interval, from March 24 through March 28. The field data from which these tables were developed are presented in the Appendix. It should be noted that test sections 1, 3, and 5 were not reworked after second rain event (third interval). Their data is excluded from Table 29.

Table 25

Test Section 1 (Bare Soil) Surface Erosion, First Interval (mm)

Date	Groove	1	2	3	4	5	Average
22-Feb	A	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.29	+4.82	+2.15	+1.71	+1.11	2.22
22-Feb	B	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.47	+2.83	+1.29	+1.96	+1.09	1.73
22-Feb	C	0.00	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.68	+5.97	+2.50	+1.37	+2.24	2.55

Table 26

Summary of Ground Surface Elevation Changes, First Test Interval (February 22 through February 24)

Test Section		Ground Surface Elevation Change (mm)					
No.	Type	1	2	3	4	5	Average
1	Bare	+1.15	+4.54	+1.98	+1.68	+1.48	+2.17
2	Bare	+2.23	+3.47	+1.33	+1.06	+1.65	+1.95
3	Xanthan Gum	+0.50	+0.37	+0.84	+3.32	+0.76	+1.16
4	Xanthan Gum	+0.36	+3.24	+1.93	+4.33	+0.56	+2.09
5	Chitosan	+1.23	+0.24	+0.09	+0.11	+1.48	+0.63
6	Chitosan	+0.23	+0.65	+0.26	-0.28	-0.45	+0.08

Table 27

Summary of Ground Surface Elevation Changes, Second Test Interval (March 3 through March 17)

Test Section		Ground Surface Elevation Change (mm)					
No.	Type	1	2	3	4	5	Average
1	Bare	+0.25	+0.24	-0.23	+0.92	+0.35	+0.30
2	Bare	+0.31	+0.41	+0.12	+0.45	+0.35	+0.33
3	Xanthan Gum	+0.24	+0.14	+1.21	+0.29	+0.25	+0.43
4	Xanthan Gum	+0.19	+0.34	+0.28	+0.47	-0.12	+0.23
5	Chitosan	+0.32	+0.52	+0.51	+0.32	+0.39	+0.41
6	Chitosan	+0.27	+0.82	+0.54	+0.43	+0.51	+0.51

Table 28

Summary of Ground Surface Elevation Changes, Third Test Interval (March 24 through March 28)

Test Section		Ground Surface Elevation Change (mm)					
No.	Type	1	2	3	4	5	Average
1	Bare	+0.62	+0.31	+0.22	+0.49	+0.02	+0.33
2	Bare	+0.50	+0.92	-0.28	+0.87	+0.31	+0.46
3	Xanthan Gum	-2.88	-0.28	-0.47	+0.01	+0.44	-0.64
4	Xanthan Gum	+0.24	-0.04	-0.25	+0.47	+0.52	+0.19
5	Chitosan	+0.27	-0.12	+0.27	+0.22	-0.34	+0.06
6	Chitosan	+1.25	+0.63	+1.55	+0.34	+1.01	+0.96

Table 29 shows the average ground surface elevation changes for each type of test sections (bare soil, xanthan gum, chitosan) for the three test intervals. This table presents results obtained by processing the field data in four different ways.

The first method was to use the entire data set without any filtering of the data. In the second approach, the values labeled "three sigma" were obtained by calculating the mean and standard deviation for each data set (i.e. for each type of test section) for each interval and then removing all points more than three standard deviations from the mean. This method of processing the data was based upon the "3-sigma rule" that data points more than three standard deviations from the mean are likely to be outliers for a well-controlled process. The 3-sigma rule is an empirical rule based upon the fact that 99.7% of the points in a normally distributed sample should lie within three standard deviations of the mean. The third method of processing the data was to remove all values indicating an increase in surface elevation (i.e. all negative values) from the data set. Since only positive values represent erosion, the negative values were considered outliers due to migration of soil particles by wind or other means and thus all negative values were removed from the data set and a new average called "positive only" was calculated. The fourth method of processing was to apply the three-sigma rule to the "positive-only" data set.

Table 29

Summary of Ground Surface Elevation Changes (mm)

Interval	Description	Bare	Xanthan	Chitosan
22-Feb to 24-Feb	Entire data	2.06	1.62	0.36
	3-sigma	2.06	1.20	0.36
	Positive only	2.06	1.87	0.90
	Positive/ 3-sigma	2.06	1.41	0.90
3-Mar to 17-Mar	Entire data	0.32	0.33	0.46
	3-sigma	0.31	0.29	0.39
	Positive only	0.58	0.48	0.64
	Positive/ 3-sigma	0.54	0.48	0.59
24-Mar to 28-Mar	Entire data	0.46	0.19	0.96
	3-sigma	0.46	0.19	0.96
	Positive only	0.63	0.43	1.07
	Positive/ 3-sigma	0.63	0.43	1.07

Weather data for the field test period was obtained from the Butterfield Station landfill (the landfill weather station does not retain long-term historical data; but does retain the latest two months of data). Data on the maximum and average wind speed at the site was obtained for the three testing periods. This data is shown in Table 30. Unfortunately, the maximum wind speeds were significantly less than the historical values from Cobblestone Farms reported in Table 30. The relatively low wind speeds for the test period help explain the relatively low erosion rates observed in the field.

Table 30

Butterfield Station Wind Data

Interval	Wind Speed Hourly Average (m/s)	Maximum Speed Hourly Average (m/s)
22-Feb to 24-Feb	0.86	1.94
3-Mar to 17-Mar	1.31	2.79
24-Mar to 28-Mar	1.71	3.67

Interpretation of Results

The xanthan gum averages in Table 29 are less than those of bare soil (i.e., the change in surface elevation is less) in all cases, clearly suggesting that xanthan gum was effective in reducing wind-induced erosion. The chitosan data was somewhat more erratic, as it showed more loss than bare soil for the second and third test intervals. However, the first test interval does indicate that chitosan can be effective at controlling wind-induced erosion. This variability of the chitosan data might be due to some of the factors cited above with respect to the occurrence of negative values in the data set.

A statistical test of whether or not the data showed that the biopolymer treatment was effective at controlling wind erosion is presented in Tables 31 and 32. A paired t-test was conducted on the bare soil and xanthan gum data to determine the degree of confidence with which it can be said that xanthan gum was more effective than untreated bare soil in suppressing wind erosion. Any pair of data with at least one negative value (ground heave) was excluded from the analysis based upon the same reasoning described above for excluding positive values. Table 31 shows the means, variances, and the number of paired observations for bare soil and xanthan gum. Table 32 presents the paired t-test data.

Table 31

Bare Soil and Xanthan Gum Statistical Analysis

Description	Bare Soil	Xanthan Gum
Mean	1.04	0.89
Variance	1.47	3.44
Observations	103	103

Table 32

Paired t-Test Data

Description	Value
Degree of Freedom	102
t_{stat}	0.75
P(T<=t) one-tail	0.23
$t_{critical}$ one-tail	0.68

Statistical analyses were performed for four test sections (2 bare soil and 2 xanthan gum). The statistical analyses used a paired t-distribution for two variables. A statistical hypothesis, two-population test (H_o: $\mu_1 = \mu_2$ {Null Hypothesis} and H_1: $\mu_1 \neq \mu_2$ {Alternative Hypothesis}) were conducted. A significance level of 25% was assumed, and the acceptance criterion for a given hypothesis was when $t_{critical} \leq t_{stat\ \alpha,\upsilon}$ where υ is the degree of freedom. Based upon this analysis, it can be stated that application of the xanthan gum solution suppressed wind-induced erosion with a 75 percent level of confidence.

The blue surveyors chalk lines applied on all of the test sections faded over time, which indicates that soil erosion had occurred at all three locations. In general, the surveyors chalk remained visible for about two weeks. However, no difference was observed among the various test sections based upon the rate at which the surveyors chalk faded, likely due to the very slow rate of erosion at all test sections.

Evaluation of Cost Effectiveness of Biopolymer Stabilization for Wind-Induced Soil Erosion

The potential cost effectiveness of short-term biopolymer stabilization for fugitive dust control using xanthan gum was evaluated by comparing the cost of biopolymer stabilization to the cost of dust control by application of water. Based upon the field testing program, it was assumed that biopolymer stabilization could be effective for a period of up to 2 weeks. In other words, one application of xanthan gum at a rate of 0.250 g/m^2 could replace two weeks of constant water truck use. RS Means 2011 CostWorks® software was used to estimate the cost of renting and operating a water truck for two weeks to control fugitive dust. CostWorks® offers construction cost data that is annually updated. It uses the national cost average for renting and operating equipment. Renting a 23 kL capacity water truck (line# 015433406950) including hourly operation cost for two weeks would cost $10,302 dollars. Assuming the spray truck would cost $1,373 dollars per day (based on 2011 CostWorks®) and 23kL of xanthan solution containing 5750 g (5.75 kg) of xanthan gum powder would be sprayed on the soil at the site, the cost of the xanthan gum powder would have to be less than $1,500 dollars for 1 kg for xanthan gum will be more cost effective than water for dust control.

Unfortunately, costs for bulk purchase of xanthan gum were not available for use in this cost analysis. Furthermore, xanthan gum currently for sale in bulk quantities is for use in food products (and is referred to as food grade xanthan gum). It is our understanding that there may be non-food grade xanthan gum that is currently disposed of by manufacturers of food grade xanthan gum and thus may be available for low cost. Further research is required into the cost of xanthan gum powder to determine its cost effectiveness as a dust control agent.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Results of the experiments conducted for this research indicate that biopolymer mixtures should be considered as a viable soil improvement measure for short-term wind erosion control (e.g., at construction sites and landfills). Proof of concept experiments showed that biopolymer mixtures sprayed on to the soil surface can be effective at suppressing fugitive dust. Wind tunnel experiments showed a strong relationship between threshold friction velocity (TFV) and biopolymer application rate for xanthan gum and chitosan biopolymer solutions.

Field experiments indicated that topically applied biopolymers should be durable for a period of at least one or two weeks in the absence of rain fall. The visual observations showed durability for a week or two. Quantitative measurements data were complicated by down slope movement, rain events, and the very low erosion rates for bare soil over the test period. None the less, statistical evaluation of the field data showed that it can be stated that application of the xanthan gum solution suppressed wind-induced erosion with a 75 percent level of confidence. Large scale field experiments (i.e., 100 m x

100 m) with opacity measurements are needed to overcome the deficiencies associated with the small scale experiments conducted in this research. Furthermore, additional information is required on the cost of obtaining biopolymers in bulk in order to evaluate the cost effectiveness biopolymer stabilization for wind erosion control.

More specific conclusions that can be drawn from the research described herein include:

- Xanthan gum and chitosan application rates are proportional to the threshold friction velocity for the soil type and application rates tested herein. The higher the application rate the higher the TFV.
- Guar gum data did not produce a consistent trend between TFV and application rate. The absence of a consistent trend in the data may be due the surface roughness of the specimens treated with guar gum.
- Biopolymer treated specimens have similar resistance to wind erosion as wetted or compacted soil.
- Field experiments are much harder to control than lab experiments.
- There is a possibility of increased runoff due to biopolymers application due to the plugging effect biopolymers have on soil

particles as mentioned in Khachatoorian, et al. (2003). This effect can only be investigated in a large scale experiment.

Recommendations

Recommendations for future research on the effectiveness of biopolymers for controlling wind-induced soil erosion include:

- To avoid the rain events from altering the testing plots and having to redo them from scratch, the plots could be covered with tarps continuously or just before a rain event (after checking the weather forecast).
- An admixing procedure in which the biopolymer is mixed with the soil and the soil is then compacted might be more effective than a topical application of a biopolymer solution. The procedure would include applying biopolymer, tilling, and then compacting. While this procedure would be more expensive than a topical spray, it might last longer and also be effective at controlling erosion induced by surface water after precipitation.
- To understand the mechanisms by which the biopolymers work, consideration should be given to several additional evaluation tools during field testing. These include but not limited to: stationary dust sampling, mobile dust sampling, and opacity measurement.

- Conducting the field experiments on a flat surface might be advisable to reduce the potential for errors due to down slope movements.
- Extracting bare soil, disturbed soil, and undisturbed cross-sections of biological soil crusts from different sites and exposing them to different velocities in a large scale wind tunnel could be employed to determine the effectiveness of biological soil crusts in controlling wind erosion.
- Large scale field experiments (i.e., on the order of a hectare or more) with opacity measurements could be more effective in evaluating the effectiveness of candidate biopolymers.
- Non-food grade xanthan gum that is currently stockpiled or disposed of by manufacturers of food grade xanthan gum might be available for low cost. Once low cost biopolymer powders become available, biopolymers may be able to several commercial dust palliatives available on the market today.

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APPENDIX A

FIELD EXPERIMENT DATA

Table A1

Test Section 1 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	31.85	27.53	35.36	39.42	27.07
24-Feb		33.14	32.35	37.51	41.13	28.18
28-Feb		32.96	32.86	36.82	41.20	26.62
22-Feb	B	34.21	27.94	31.17	34.51	35.52
24-Feb		35.68	30.77	32.46	36.47	36.61
28-Feb		34.82	29.18	31.37	35.85	36.37
22-Feb	C	14.64	10.39	17.78	29.03	20.30
24-Feb		15.32	16.36	20.28	30.40	22.54
28-Feb		15.78	16.34	20.29	30.59	21.56

Table A2

Test Section 1 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.29	+4.82	+2.15	+1.71	+1.11
28-Feb		-0.18	+0.51	-0.69	+0.07	-1.56
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.47	+2.83	+1.29	+1.96	+1.09
28-Feb		-0.86	-1.59	-1.09	-0.62	-0.24
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.68	+5.97	+2.50	+1.37	+2.24
28-Feb		+0.46	-0.02	+0.01	+0.19	-0.98

Table A3

Test Section 2 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	33.62	41.39	47.38	34.99	29.47
24-Feb		35.05	46.64	49.35	36.41	32.25
28-Feb		34.58	47.15	50.07	35.69	32.05
22-Feb	B	30.13	30.62	27.45	28.84	31.35
24-Feb		34.15	36.48	28.81	28.96	33.03
28-Feb		33.97	36.57	27.59	28.44	33.50
22-Feb	C	22.89	25.00	22.12	19.97	18.34
24-Feb		24.13	24.31	22.79	21.62	18.82
28-Feb		22.94	24.71	22.32	20.61	17.07

Table A4

Test Section 2 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.43	+5.25	+1.97	+1.42	+2.78
28-Feb		-0.47	+0.51	+0.72	-0.72	-0.20
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+4.02	+5.86	+1.36	+0.12	+1.68
28-Feb		-0.18	+0.09	-1.22	-0.52	+0.47
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.24	-0.69	+0.67	+1.65	+0.48
28-Feb		-1.19	+0.40	-0.47	-1.01	-1.75

Table A5

Test Section 3 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	22.18	23.09	24.87	36.60	43.55
24-Feb		22.88	23.51	25.81	35.81	43.75
28-Feb		22.40	23.06	25.32	35.86	42.71
22-Feb	B	33.03	35.85	34.20	23.23	34.53
24-Feb		33.17	36.54	35.05	33.78	35.81
28-Feb		32.55	37.05	35.13	31.75	34.61
22-Feb	C	17.30	10.55	8.69	24.48	27.90
24-Feb		17.96	10.55	9.43	24.67	28.71
28-Feb		17.25	10.80	9.99	23.44	47.86

Table A6

Test Section 3 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.70	+0.42	+0.94	-0.79	+0.20
28-Feb		-0.48	-0.45	-0.49	+0.05	-1.04
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.14	+0.69	+0.85	+10.55	+1.28
28-Feb		-0.62	+0.51	+0.08	-2.03	-1.20
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.66	0.00	+0.74	+0.19	+0.81
28-Feb		-0.71	+1.00	+0.56	-1.23	+19.15

Table A7

Test Section 4 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	37.02	31.52	28.81	24.28	19.55
24-Feb		37.82	34.15	32.45	38.16	19.89
28-Feb		37.09	35.43	32.68	37.76	19.52
22-Feb	B	23.99	21.99	28.61	26.76	24.77
24-Feb		24.03	28.85	30.57	26.10	24.49
28-Feb		24.62	27.99	30.45	25.73	22.80
22-Feb	C	18.57	38.15	32.27	30.08	21.21
24-Feb		18.82	38.39	32.46	29.86	22.83
28-Feb		18.99	37.60	31.96	29.47	21.97

Table A8

Test Section 4 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.80	+2.63	+3.64	+13.88	+0.34
28-Feb		-0.73	+1.28	+0.23	-0.40	-0.37
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.04	+6.86	+1.96	-0.66	-0.28
28-Feb		+0.59	-0.86	-0.12	-0.37	-1.69
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.25	+0.24	+0.19	-0.22	+1.62
28-Feb		+0.17	-0.79	-0.50	-0.39	-0.86

Table A9

Test Section 5 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	24.72	28.28	30.45	30.06	28.48
24-Feb		26.31	28.08	30.21	30.06	30.71
28-Feb		26.86	27.65	29.11	30.00	31.14
22-Feb	B	18.99	27.39	32.76	29.33	36.09
24-Feb		20.17	28.32	33.51	29.63	37.46
28-Feb		19.56	27.43	32.81	29.03	35.58
22-Feb	C	22.41	8.70	5.32	14.67	24.05
24-Feb		23.33	10.20	5.08	14.69	24.88
28-Feb		22.90	9.99	4.66	14.08	24.83

Table A10

Test Section 5 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.59	-0.20	-0.24	0.00	+2.23
28-Feb		+0.55	-0.43	-1.10	-0.06	+0.43
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+1.18	+0.93	+0.75	+0.30	+1.37
28-Feb		-0.61	-0.89	-0.70	-0.60	-1.88
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.92	0.00	-0.24	+0.02	+0.83
28-Feb		-0.43	+1.00	-0.42	-0.61	-0.05

Table A11

Test Section 6 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	24.50	18.20	19.56	25.54	12.63
24-Feb		24.60	20.88	19.63	26.70	11.75
28-Feb		24.12	20.72	20.62	25.23	10.89
22-Feb	B	22.48	21.62	21.44	28.08	19.34
24-Feb		23.05	20.90	23.13	27.78	18.85
28-Feb		22.96	21.00	22.69	26.97	17.93
22-Feb	C	29.91	32.21	39.19	38.99	22.22
24-Feb		29.93	30.87	38.21	37.29	22.24
28-Feb		30.31	30.20	37.55	36.12	22.22

Table A12

Test Section 6 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
22-Feb	A	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.10	+2.68	+0.07	+1.16	-0.88
28-Feb		-0.48	-0.16	+0.99	-1.47	-0.86
22-Feb	B	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.57	-0.72	+1.69	-0.30	-0.49
28-Feb		-0.09	+0.10	-0.44	-0.81	-0.92
22-Feb	C	0.00	0.00	0.00	0.00	0.00
24-Feb		+0.02	0.00	-0.98	-1.70	+0.02
28-Feb		+0.38	+1.00	-0.66	-1.17	-0.02

Table A13

Test Section 1 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	42.64	52.11	57.94	50.36	43.12
7-Mar		41.63	53.14	58.06	52.12	43.34
10-Mar		42.99	53.73	58.15	51.57	43.15
14-Mar		42.24	53.71	58.84	52.76	43.20
17-Mar		42.51	53.75	56.73	52.63	43.21
3-Mar	B	45.66	45.13	51.74	54.57	49.23
7-Mar		47.09	44.46	52.68	55.41	50.01
10-Mar		46.64	44.87	53.43	55.51	50.11
14-Mar		47.70	45.00	50.22	60.42	50.35
17-Mar		47.66	45.08	50.40	61.03	50.72
3-Mar	C	20.18	29.16	31.61	39.10	33.51
7-Mar		20.41	29.88	31.57	39.72	35.06
10-Mar		20.22	29.73	31.77	40.36	35.44
14-Mar		20.99	29.91	31.41	40.74	36.11
17-Mar		21.26	30.45	31.35	41.40	36.12

Table A14

Test Section 1 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		-1.01	+1.03	+0.12	+1.76	+0.22
10-Mar		+1.36	+0.59	+0.09	-0.55	-0.19
14-Mar		-0.75	-0.02	+0.69	+1.19	+0.05
17-Mar		+0.27	+0.04	-2.11	-0.13	+0.01
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+1.43	-0.67	+0.94	+0.84	+0.78
10-Mar		-0.45	+0.41	+0.75	+0.10	+0.10
14-Mar		+1.06	+0.13	-3.21	+4.91	+0.24
17-Mar		-0.04	+0.08	+0.18	+0.61	+0.37
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.23	+0.72	-0.04	+0.62	+1.55
10-Mar		-0.19	-0.15	+0.20	+0.64	+0.38
14-Mar		+0.77	+0.18	-0.36	+0.38	+0.67
17-Mar		+0.27	+0.54	-0.06	+0.66	+0.01

Table A15

Test Section 2 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	59.03	64.14	61.65	49.96	41.80
7-Mar		60.95	64.91	61.90	50.62	42.08
10-Mar		59.19	63.89	61.22	50.72	42.22
14-Mar		59.03	64.02	62.51	50.94	42.70
17-Mar		59.62	64.02	62.28	52.65	42.98
3-Mar	B	40.99	42.11	41.91	39.52	42.52
7-Mar		42.26	44.12	42.47	40.15	43.77
10-Mar		42.00	44.37	41.58	40.00	43.94
14-Mar		42.31	44.61	42.26	40.52	44.15
17-Mar		43.03	45.03	42.63	40.99	44.44
3-Mar	C	28.54	23.59	21.45	20.74	23.72
7-Mar		29.06	24.27	21.96	21.40	24.01
10-Mar		29.27	25.15	20.84	21.71	23.88
14-Mar		29.39	25.55	20.96	22.13	24.58
17-Mar		29.67	25.69	21.52	22.02	24.81

Table A16

Test Section 2 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		+1.92	+0.77	+0.25	+0.66	+0.28
10-Mar		-1.76	-1.02	-0.68	+0.10	+0.14
14-Mar		-0.16	+0.13	+1.29	+0.22	+0.48
17-Mar		+0.59	0.00	-0.23	+1.71	+0.28
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+1.27	+2.01	+0.56	+0.63	+1.25
10-Mar		-0.26	+0.25	-0.89	-0.15	+0.17
14-Mar		+0.31	+0.24	+0.68	+0.52	+0.21
17-Mar		+0.72	+0.42	+0.37	+0.47	+0.29
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.52	+0.68	+0.51	+0.66	+0.29
10-Mar		+0.21	+0.88	-1.12	+0.31	-0.13
14-Mar		+0.12	+0.40	+0.12	+0.42	+0.70
17-Mar		+0.28	+0.14	+0.56	-0.11	+0.23

Table A17

Test Section 3 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	33.93	39.54	37.14	36.08	38.51
7-Mar		33.98	39.75	38.24	37.60	39.00
10-Mar		34.47	39.95	38.43	37.64	39.20
14-Mar		34.69	40.04	38.31	38.71	39.37
17-Mar		34.46	39.73	38.65	38.38	39.94
3-Mar	B	47.48	45.17	43.13	40.88	42.77
7-Mar		48.03	45.83	43.57	40.85	42.88
10-Mar		48.32	45.63	43.71	39.69	43.28
14-Mar		48.58	45.93	43.99	41.10	43.63
17-Mar		49.10	46.19	44.82	40.73	43.62
3-Mar	C	30.38	20.97	24.36	30.29	41.62
7-Mar		29.52	21.58	25.05	30.92	41.96
10-Mar		30.69	21.76	25.06	31.15	41.66
14-Mar		30.92	21.26	24.99	31.13	42.20
17-Mar		31.06	21.45	25.73	31.65	42.29

Table A18

Test Section 3 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.05	+0.21	+1.10	+1.52	+0.49
10-Mar		+0.49	+0.20	+0.41	+0.04	+0.20
14-Mar		+0.22	+0.09	+4.70	+1.07	+0.17
17-Mar		-0.23	-0.31	+5.26	-0.33	+0.57
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.55	+0.66	+0.44	-0.03	+0.11
10-Mar		+0.29	-0.20	+0.14	-1.16	+0.40
14-Mar		+0.26	+0.30	+0.28	+1.41	+0.35
17-Mar		+0.52	+0.26	+0.83	-0.37	-0.01
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		-0.86	+0.61	+0.69	+0.63	+0.34
10-Mar		+1.17	+0.18	+0.01	+0.23	-0.30
14-Mar		+0.23	-0.50	-0.07	-0.02	+0.54
17-Mar		+0.14	+0.19	+0.74	+0.52	+0.09

Table A19

Test Section 4 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	37.09	35.24	37.43	35.40	19.57
7-Mar		37.27	35.76	37.85	35.43	20.33
10-Mar		38.15	35.01	37.97	36.31	20.58
14-Mar		38.64	36.42	38.59	36.30	20.98
17-Mar		38.46	36.37	38.34	36.58	21.02
3-Mar	B	28.88	37.10	41.05	42.46	38.11
7-Mar		29.84	37.55	41.48	42.28	37.22
10-Mar		29.64	38.25	41.37	42.84	38.33
14-Mar		29.85	37.97	41.77	43.28	38.38
17-Mar		29.73	38.74	42.20	43.61	38.76
3-Mar	C	26.70	33.26	35.03	30.48	23.91
7-Mar		27.30	33.53	35.47	31.66	19.27
10-Mar		26.88	34.45	36.15	31.41	19.74
14-Mar		27.24	34.59	35.97	32.50	19.63
17-Mar		26.72	34.59	36.28	33.77	20.33

Table A20

Test Section 4 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.18	+0.52	+0.42	+0.03	+0.76
10-Mar		+0.88	-0.75	+0.12	+0.88	+0.25
14-Mar		+0.49	+1.41	+0.62	-0.01	+0.40
17-Mar		-0.18	-0.05	-0.25	+0.28	+0.04
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.96	+0.45	+0.43	-0.18	-0.89
10-Mar		-0.20	+0.70	-0.11	+0.56	+1.11
14-Mar		+0.21	-0.28	+0.40	+0.44	+0.05
17-Mar		-0.12	+0.77	+0.43	+0.33	+0.38
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.60	+0.27	+0.44	+1.18	-4.64
10-Mar		-0.42	+0.92	+0.68	-0.25	+0.47
14-Mar		+0.36	+0.14	-0.18	+1.09	-0.11
17-Mar		-0.52	0.00	+0.31	+1.27	+0.70

Table A21

Test Section 5 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	35.17	30.81	33.43	43.87	38.73
7-Mar		35.96	30.91	34.14	44.32	40.03
10-Mar		36.09	31.23	34.08	44.63	39.77
14-Mar		35.77	30.78	34.11	44.27	39.79
17-Mar		35.29	29.36	34.52	44.74	39.30
3-Mar	B	38.87	33.97	37.24	35.75	33.92
7-Mar		39.71	35.16	38.33	35.96	34.16
10-Mar		39.69	35.83	39.02	36.19	35.47
14-Mar		39.37	35.74	39.15	36.54	35.62
17-Mar		40.67	35.70	40.37	37.42	36.46
3-Mar	C	29.02	19.51	18.50	23.18	28.04
7-Mar		29.04	20.29	19.29	23.70	28.54
10-Mar		29.46	20.72	19.05	23.41	27.98
14-Mar		30.21	20.63	19.77	24.39	28.29
17-Mar		30.92	21.66	20.45	24.51	29.59

Table A22

Test Section 5 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.79	+0.10	+0.71	+0.45	+1.30
10-Mar		+0.13	+0.32	-0.06	+0.31	-0.26
14-Mar		-0.32	-0.45	+0.03	-0.36	+0.02
17-Mar		-0.48	-1.42	+0.41	+0.47	-0.49
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.84	+1.19	+1.09	+0.21	+0.24
10-Mar		-0.02	+0.67	+0.69	+0.23	+1.31
14-Mar		-0.32	-0.09	+0.13	+0.35	+0.15
17-Mar		+1.30	-0.04	+1.22	+0.88	+0.84
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.02	0.00	+0.79	+0.52	+0.50
10-Mar		+0.42	+1.00	-0.24	-0.29	-0.56
14-Mar		+0.75	+2.00	+0.72	+0.98	+0.31
17-Mar		+0.71	+3.00	+0.68	+0.12	+1.30

Table A23

Test Section 6 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	29.17	25.00	22.49	22.29	12.72
7-Mar		29.46	24.97	23.08	22.37	13.17
10-Mar		29.44	25.63	23.83	22.57	13.89
14-Mar		29.24	26.27	23.63	22.88	14.10
17-Mar		30.01	26.73	24.77	22.90	14.56
3-Mar	B	24.73	25.98	22.44	21.18	20.10
7-Mar		24.82	26.76	23.29	22.12	20.75
10-Mar		25.12	27.02	23.56	22.39	21.58
14-Mar		25.56	28.30	24.87	23.52	22.10
17-Mar		25.75	28.04	24.77	23.96	22.42
3-Mar	C	34.70	39.91	41.34	36.01	26.14
7-Mar		34.15	40.25	42.50	36.39	26.23
10-Mar		35.49	41.37	42.56	36.44	26.80
14-Mar		35.48	41.16	42.82	37.45	27.36
17-Mar		36.13	41.86	43.16	37.81	28.06

Table A24

Test Section 6 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
3-Mar	A	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.29	-0.03	+0.59	+0.08	+0.45
10-Mar		-0.02	+0.66	+0.75	+0.20	+0.72
14-Mar		-0.20	+0.64	-0.20	+0.31	+0.21
17-Mar		+0.77	+0.46	+1.14	+0.02	+0.46
3-Mar	B	0.00	0.00	0.00	0.00	0.00
7-Mar		+0.09	+0.78	+0.85	+0.94	+0.65
10-Mar		+0.30	+0.26	+0.27	+0.27	+0.83
14-Mar		+0.44	+1.28	+1.31	+1.13	+0.52
17-Mar		+0.19	-0.26	-0.10	+0.44	+0.32
3-Mar	C	0.00	0.00	0.00	0.00	0.00
7-Mar		-0.55	0.00	+1.16	+0.38	+0.09
10-Mar		+1.34	+1.00	+0.06	+0.05	+0.57
14-Mar		-0.01	+2.00	+0.26	+1.01	+0.56
17-Mar		+0.65	+3.00	+0.34	+0.36	+0.70

Table A25

Test Section 1 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	42.36	53.65	55.79	52.07	42.53
28-Mar		42.32	53.74	56.15	52.71	42.69
24-Mar	B	45.31	44.37	48.98	59.22	50.54
28-Mar		46.77	44.81	49.49	59.73	50.42
24-Mar	C	18.97	26.76	30.95	40.10	35.38
28-Mar		19.41	27.16	30.75	40.41	35.41

Table A26

Test Section 1 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		-0.04	+0.09	+0.36	+0.64	+0.16
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		+1.46	+0.44	+0.51	+0.51	-0.12
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.44	+0.40	-0.20	+0.31	+0.03

Table A27

Test Section 2 (Bare) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	64.54	64.22	64.50	56.12	53.67
28-Mar		65.14	64.72	63.44	56.82	54.20
24-Mar	B	42.08	38.89	44.79	47.79	43.82
28-Mar		42.71	40.59	45.16	48.68	44.08
24-Mar	C	27.94	23.97	21.44	27.03	29.16
28-Mar		28.20	24.53	21.28	28.05	29.30

Table A28

Test Section 2 (Bare) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.60	+0.50	-1.06	+0.70	+0.53
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.63	+1.70	+0.37	+0.89	+0.26
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.26	+0.56	-0.16	+1.02	+0.14

Table A29

Test Section 3 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	34.13	39.82	38.40	38.11	38.75
28-Mar		33.36	39.52	37.16	38.01	39.52
24-Mar	B	48.49	46.14	43.52	40.82	43.54
28-Mar		48.43	46.17	43.47	40.62	43.69
24-Mar	C	38.13	21.34	25.63	31.21	41.66
28-Mar		30.33	20.76	25.50	31.53	42.07

Table A30

Test Section 3 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		-0.77	-0.30	-1.24	-0.10	+0.77
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		-0.06	+0.03	-0.05	-0.20	+0.15
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		-7.80	-0.58	-0.13	+0.32	+0.41

Table A31

Test Section 4 (Xanthan Gum) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	47.40	43.47	37.65	38.64	28.26
28-Mar		47.18	43.69	37.85	39.45	29.17
24-Mar	B	34.14	44.38	45.78	38.34	37.84
28-Mar		34.77	44.04	45.14	38.72	38.04
24-Mar	C	13.96	26.49	32.84	35.65	32.63
28-Mar		14.26	26.48	32.52	35.88	33.07

Table A32

Test Section 4 (Xanthan Gum) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		-0.22	+0.22	+0.20	+0.81	+0.91
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.63	-0.34	-0.64	+0.38	+0.20
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.30	-0.01	-0.32	+0.23	+0.44

Table A33

Test Section 5 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	35.68	31.40	34.11	43.34	39.62
28-Mar		35.41	31.43	33.72	43.05	37.94
24-Mar	B	39.26	36.18	36.13	36.51	34.87
28-Mar		40.00	35.79	37.64	36.36	35.42
24-Mar	C	29.70	21.50	19.86	23.58	28.84
28-Mar		30.04	21.05	19.55	24.68	28.95

Table A34

Test Section 5 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		-0.27	+0.03	-0.39	-0.29	-1.68
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.74	-0.39	+1.51	-0.15	+0.55
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.34	0.00	-0.31	+1.10	+0.11

Table A35

Test Section 6 (Chitosan) Actual Readings (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	38.89	38.32	29.62	20.15	20.93
28-Mar		39.72	38.87	31.61	20.81	21.61
24-Mar	B	37.54	33.81	28.21	28.01	24.68
28-Mar		38.91	35.16	29.50	27.84	26.40
24-Mar	C	16.17	28.04	32.99	40.59	36.77
28-Mar		17.73	28.43	34.37	41.13	37.41

Table A36

Test Section 6 (Chitosan) Surface Height Differences (mm)

Date	Groove	1	2	3	4	5
24-Mar	A	0.00	0.00	0.00	0.00	0.00
28-Mar		+0.83	+0.55	+1.99	+0.66	+0.68
24-Mar	B	0.00	0.00	0.00	0.00	0.00
28-Mar		+1.37	+1.35	+1.29	-0.17	+1.72
24-Mar	C	0.00	0.00	0.00	0.00	0.00
28-Mar		+1.56	0.00	+1.38	+0.54	+0.64

Figure A1: Test Plots Location

Figure A2: Applying Biopolymer Mixtures

Figure A3: Recording Height Readings

Figure A4: Ground Swelling After Heavy Rain Event

Figure A5: A Test Plot Surrounded be Ditches to Divert Rain Water

Figure A6: The Slope after Installing the Test Sections

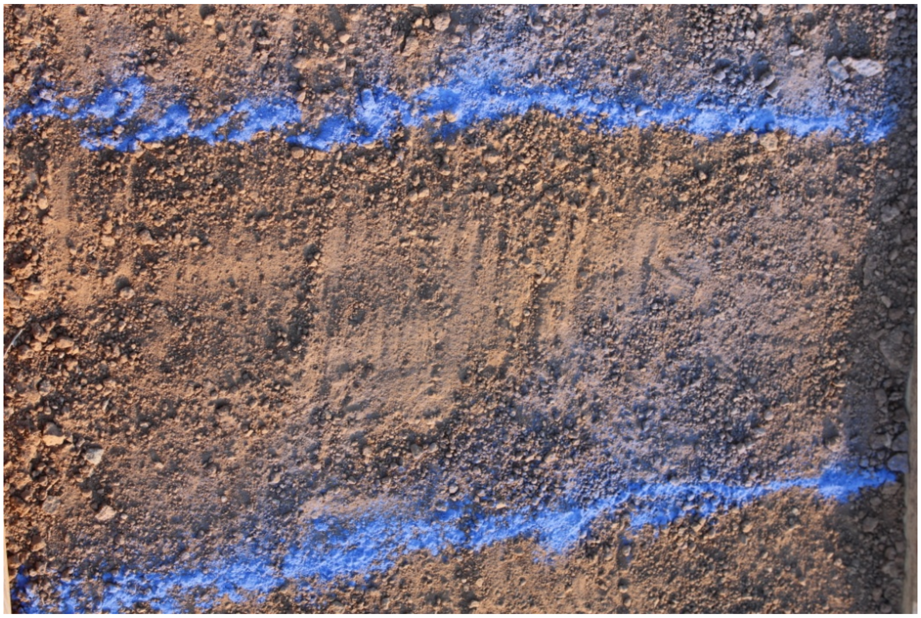

Figure A7: Test Section 1 (Bare) Chalk Lines on 3-3-2011

Figure A8: Test Section 1 (Bare) Chalk Lines on 3-17-2011

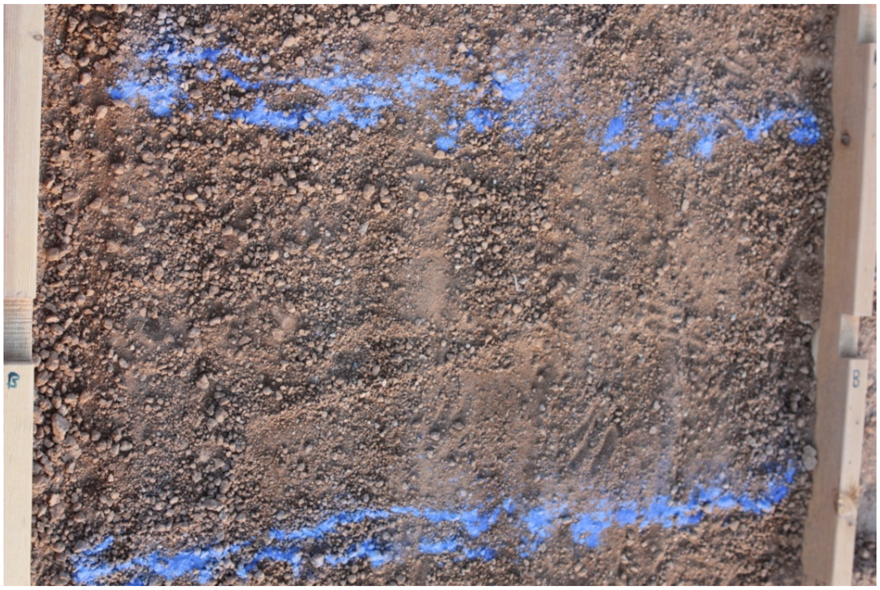

Figure A9: Test Section 3 (Xanthan) Chalk Lines on 3-3-2011

Figure A10: Test Section 3 (Xanthan) Chalk Lines on 3-17-2011

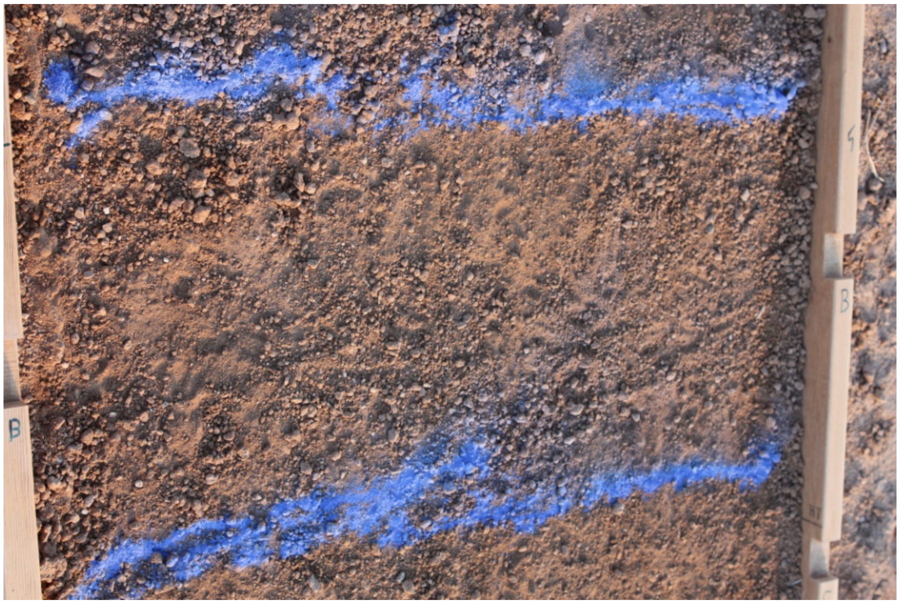

Figure A11: Test Section 5 (Chitosan) Chalk Lines on 3-17-2011

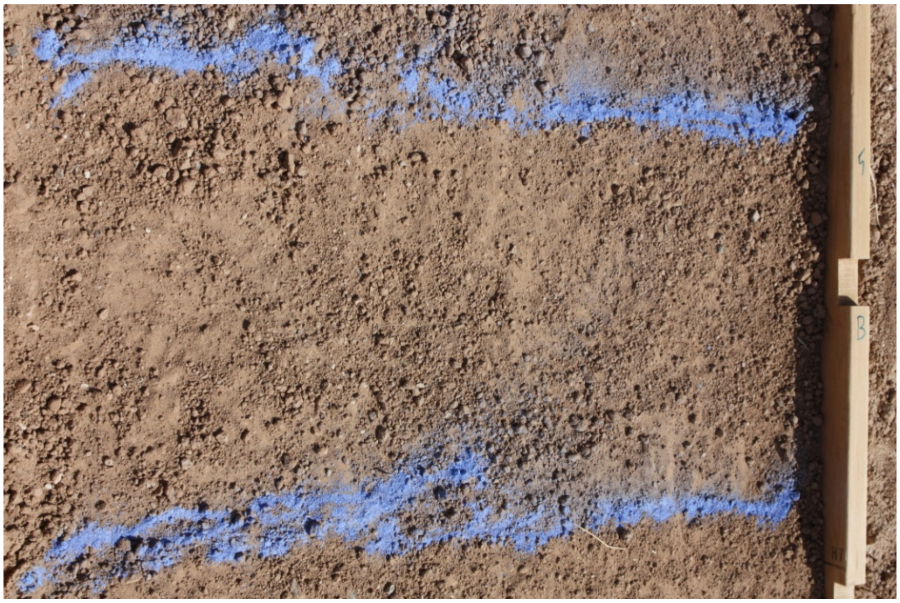

Figure A12: Test Section 5 (Chitosan) Chalk Lines on 3-17-2011

APPENDIX B

WIND TUNNEL PHOTOS

Figure B1: Adapter Ring

Figure B2: Sample Run-board

Figure B3: Bare Soil Sample before the Wind Tunnel Run

Figure B4: Bare Soil Sample after the Wind Tunnel Run

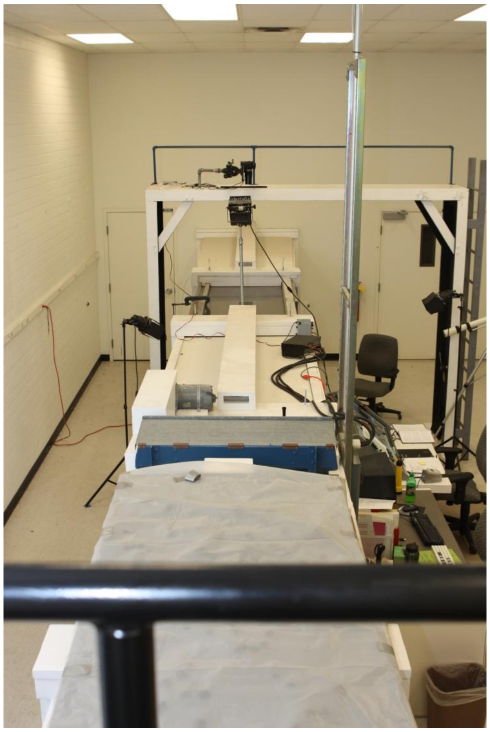

Figure B5: A Top View of the Main Tunnel

Figure B6: Intake Rooms with Louvers Open

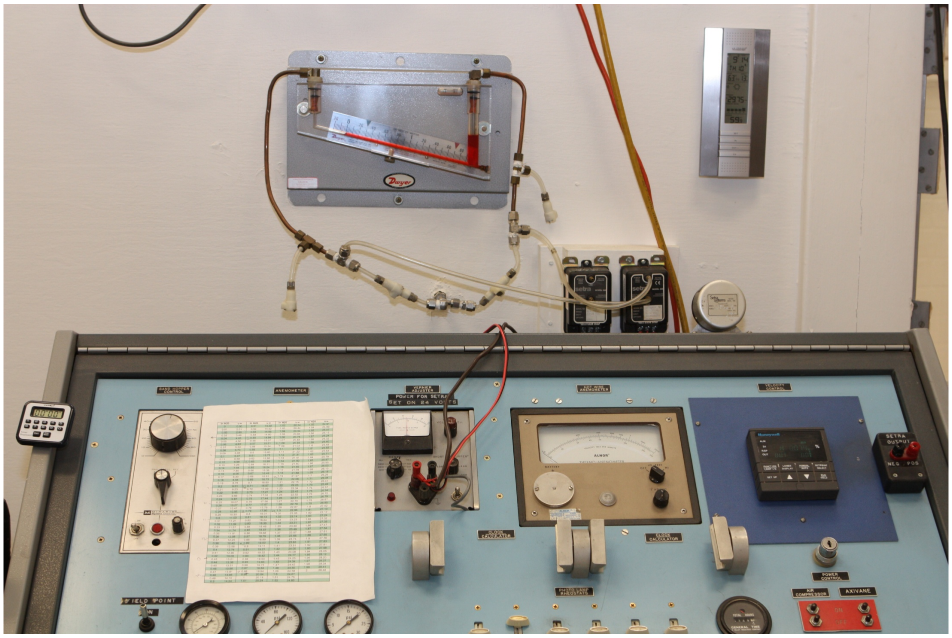

Figure B6: Control Panel

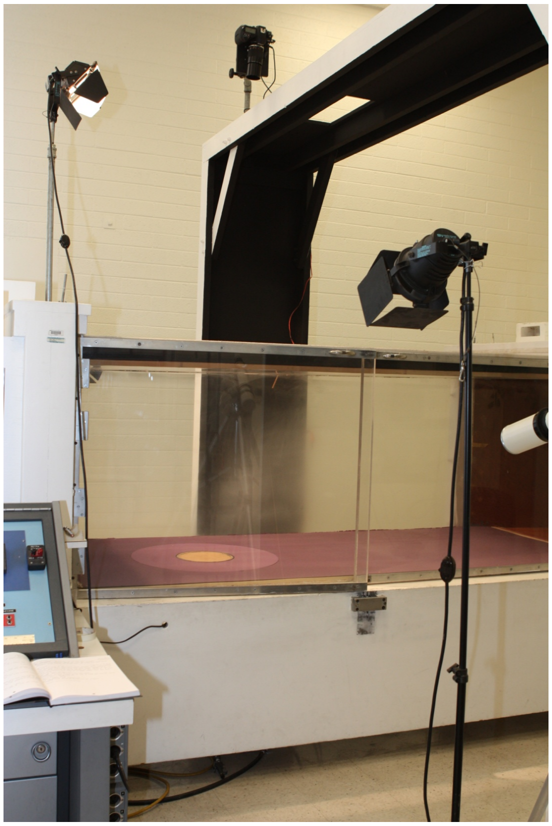

Figure B7: Pie Plate and Camera Setting

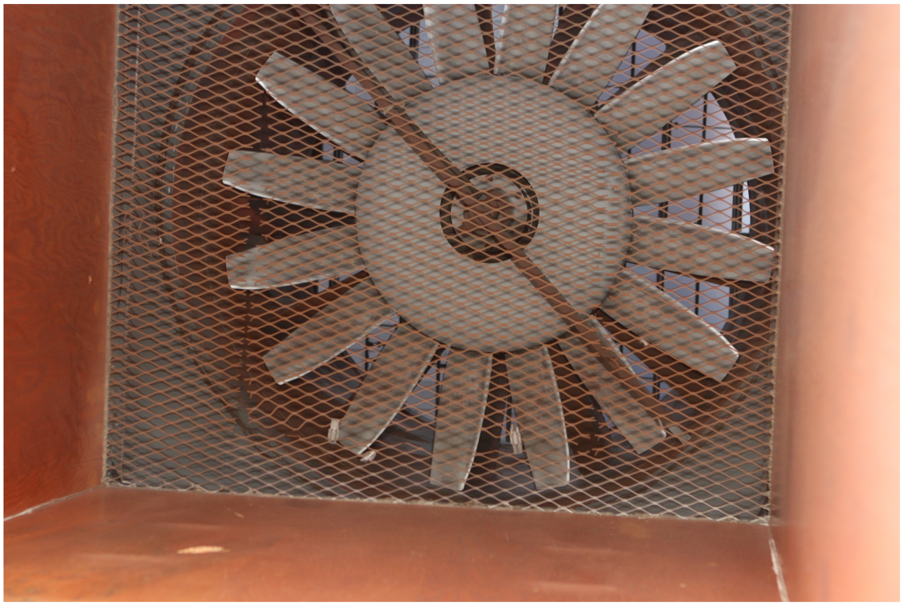

Figure B8: Main Fan

Figure B9: Outlet Room

APPENDIX C

DUST PALLIATIVES

Reports Data

Since watering is expensive and only effective on short time frames (i.e., less than a day), dust suppressing agents may be more cost effective, durable, and require less labor (Public Works Department, 2008). Most of the below products are taken from a report published by the public works department/environmental regulation section in the town of Buckeye Arizona. The manufacturer descriptions are taken from the manufacturer’s website.

Table C1

Salts

Product	Manufacturer	Manufacturer Description
DUST-OFF	Cargill	Intended for use as a dust control agent on unimproved roads. Consists primarily of 'liquid bitterns,' a naturally low corrosive product produced by the evaporation of seawater. Helps in soil compaction and in improving road stabilization.
DOWFLAKE 77-80% calcium chloride	DOW	Calcium chloride meets ASTM D 98 and AASHTO M144 requirements for calcium chloride purity. DOWFLAKE 77-80% calcium chloride is primarily used for dust control of unpaved roads and parking lots, and as a deicer.
DUST FYGHTER Chloride Dust Suppressant	MIDWEST INDUSTRIAL SUPPLY, INC.	Dust Fyghter® chloride dust suppressant continuously absorbs moisture from the air and locks it into the dust surfaces, thereby suppressing the dust. The result is a hard-packed, dust-free dirt road.
DustGard®	North American Salt Company	DustGard - Magnesium Chloride Dust Suppressant & Road Base Stabilizer is used for both dust and erosion control. The hygroscopic (attracts moisture) characteristics gives it the ability to maintain natural surfaces for months at a time with a single application. http://www.nasalt.com/products/magchloride/dustgard/dustgard.htm

Table C2

Petroleum Emulsions

Product	Manufacturer	Manufacturer Description
Coherex®	REJUVTEC	Coherex® dust retardant provides a clean and economical dust control. Coherex® creates cohesive membranes that attach themselves to adjacent particles resulting in “agglomerates” too heavy to be dislodged by wind.
Pennz Suppress®	American Refining Group®	PennzSuppress® D is a unique, environmentally safe, emulsified petroleum resin that helps suppress dust and stabilize soil.
Road Pro NT	MIDWEST INDUSTRIAL SUPPLY, INC.	Road Pro NT® is a polymer modified asphalt emulsion that reduces the human health risk and environmental exposure to polynuclear aromatic hydrocarbons (PAH’s). The polymers enhance the weather-ability of the treated surface, and help to “lock-in-place” the hazardous constituents in the asphalt.

Table C3

Environmentally Friendly Emulsions & Polymers

Product	Manufacturer	Manufacturer Description
ArenaPro	DUSTKILL™ The Leader in Bio-Based Dust Control	ArenaPro is an organic dust suppressant derived from a unique blend of natural oils. It is completely biodegradable and environmentally safe. ArenaPro is applied to the arena surface and worked into the footing. It is a straight oil and does not mix with water at the time of application. The proprietary blend of oils and surfactants coat and condition the arena floor.
Entac	enssolutions environmental stabilization	Entac is 100% organic emulsion and is comprised of Tall Oil Pitch (TOP) which is a distillation product of Crude Tall Oil (CTO). Tall Oil is an adaption of the Swedish word Talloja, which means pine oil.
EC-46®	SynTech® Products	Polymer emulsion used for stabilization. Nonvolatile & environmentally safe. Excellent choice for sealing piles, ash ponds, and open areas. Cures to a water resistant surface. Applies white, dries clear.
Soil-Sement® Dust and Erosion Control Agent	MIDWEST INDUSTRIAL SUPPLY, INC.	Soil Sement will significantly reduce particulate matter (PM_{10} & $PM_{2.5}$). Environmentally safe, non-toxic, non-corrosive, non-flammable and does not pollute ground water. It Creates a stabilized surface which will resist shifting, breaking up or sink failures. Offers maximum weather-ability to wind, rain ultraviolet light.

Table C4

Other Emulsions

Product	Manufacturer	Manufacturer Description
PetroTac®	SynTech® Products	Nonvolatile, environmentally safe specialized emulsion. Manufactured only with virgin materials. Excellent non-leaching characteristics. Does not contain PCB's or any other harmful contaminants. Saturates, penetrates and bonds dust and aggregate. Improves and stabilizes unpaved road surfaces. Engineered to be applied as a topical palliative. Cures to a water resistant surface that will not re-emulsify.

Table C5

Polymers

Product	Manufacturer	Manufacturer Description
DirtGlue	DirtGlue® ENTERPRISES	DirtGlue Polymer Emulsions are powerful, high-tech bonding agents specifically engineered and formulated to bond soil particles together. Applied to the surface of the soil. DirtGlue Polymer Emulsions form a protective, flexible film that eliminates dust, prevents mud and controls erosion thereby providing a solution to today's challenging dust and erosion control requirements.
PolyPavement	PolyPavement™ The Natural Soil Pavement	PolyPavement is a liquid soil solidifier. The grounds-maintenance crew or a landscape contractor installs it. The existing natural soil or decorative soils such as decomposed granite or suitable fine particle sand may be used. PolyPavement does not change the color of the soil. Natural Soil Pavement is more than two times stronger than asphalt. It is not damaged by rain. It supports heavy vehicles.
LDC +12™	ENVIROSEAL CORPORATION	LDC+12™ is an environmentally safe, low cost chemical solution which is mixed with water and applied to soil with results of up to 100%dust control and elimination of problems associated with soil and wind erosion. As a barrier against moisture, LDC+12™ is so effective that when used in sufficient concentration, it forms an impenetrable liner. This liner can be used for a pond or chemical pit to prevent seepage into the groundwater.

Table C6

Surfactants

Product	Manufacturer	Manufacturer’s Description
Haul Road Dust Control®	MIDWEST INDUSTRIAL SUPPLY, INC.	Haul Road Dust Control® is a blend of special surfactants which increases the ability of water to wet and suppress road dust. Haul Road Dust Control® Increases the wetting and penetration ability of water a minimum of 100%. It causes a deep moisture penetration into dust and the roadbed. It Reduces water's tension which causes water to spread in much smaller droplets. It contains non-volatile materials which attract both dust particles and water. Haul Road Dust Control® continuously improves the effectiveness of your watering program. There is a cumulative benefit from every application. Haul Road Dust Control® has a cumulative effect in suppressing dust. Each new application of treated water receives a boost from the residual materials of the previous application.

Table C7

Lignin Sulfonate

Product	Manufacturer	Manufacturer's Description
Dust Suppressant	Borregaard LignoTech	The binding property of lignosulphonates has been utilized for dust control, dust suppression, dust palliative treatment, road stabilization and many other dust binding applications since the beginning of the 20th century. The lignin molecule functions by adsorbing on the substrate and the binding effect results from intermolecular forces between the lignin molecule and the substrate. This forms an inactive film binding system.
Calbinder	CALIFORNIA-FRESNO SINCE 1901	Calbinder acts as a dust palliative and soil stabilizer. It is a glue that bonds the soil particles together. This is particularly true in that the wood sugars and lignin polymer are both bonding agents. However, the wood sugars are also hygroscopic and both attract and retain moisture in the road surface. This builds a flexible, hard, relatively dust free surface. This ability is very important when the lignin is "top shot" on the roadway.

Table C8

Other Chemical suppressants

Product	Manufacturer	Manufacturer's Description
SOYKILL	SOYsolv® Industrial Solvents and Cleaners	Provides dust control for a variety of situations especially gravel roads and lots. It forms water resistant crust onto gravel surface, provides long term control, reduces frequent re-applications, environmentally friendly, biodegradable, does not migrate into ground water when used at suggested levels, and does not harm agricultural crops.
	PETRO-CANADA	Petro-Canada Dust Suppressant Fluid DSF 65 is a safe, non-toxic fluid designed to reduce the generation of airborne particulate matter on roads, fields, vehicles and industrial applications. Odorless and colorless, Dust Suppressant
DURASOIL®	SOILWORKS®, LLC	Durasoil® is distinctively crystal clear, odorless and is applied neat and simple, without the need for water dilution. This technologically advanced fluid does not cure, allowing for immediate use upon its application. Furthermore, Durasoil® has the unique ability to be reworked and still maintain its dust controlling properties. Any equipment capable of spraying water can safely be used to apply Durasoil®, without any mess or damage to the equipment.