AGING EFFECTS OF ENVIRONMENTAL FACTORS ON ROLLED EROSION CONTROL PRODUCTS

A Thesis

by

SUMEE KHANNA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Ming-Han Li
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ABSTRACT

Aging Effects of Environmental Factors on Rolled Erosion Control Products.
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This thesis presents a study made on erosion control blankets with respect to their aging and longevity. Erosion control blankets have been relied upon increasingly in recent times replacing the old and traditional methods for protecting areas from erosion by storm water and other factors. But what can be an estimated duration for which a given set of blankets can be functional in channel erosion control. This research is done with the ultimate aim of understanding whether these erosion control blankets can stay in place and be conducive to some vegetation growth, which is said to be the most reliable measure for long-lasting erosion control.

Seven erosion control blankets, consisting of natural, synthetic and composite types, were put to actual use for erosion control for 3 years in a field. After 3 years these used materials were cut from the field for conducting the tests. Unused blankets of the same brands were obtained. Index tests were conducted on both used and unused material specimens to measure the erosion control properties. All materials experienced a significant amount of strength loss after use. The natural materials show 80% strength loss, while the composite and synthetic materials were tested to have around 50% strength losses after being put to use for 3 years. Thus it can be observed that the composite and synthetic materials have a decent amount of life where erosion control is concerned. Other tests also proved that composite materials can be relied upon for erosion control to a reasonable extent, and the research goal was achieved.

To my parents

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CHAPTER I

INTRODUCTION

For centuries, many areas of the world have been victims of some natural as well as imprudent human activities causing baneful widespread soil erosion. There are many adverse effects of soil erosion, such as flooding, landslides, loss of valuable soil cover etc. The perpetual increase in erosion and its harmful effects has led to development of many government and private agencies focusing on erosion control.

The US Environmental Protection Agency (EPA) is one of these agencies. Due to the advances in the US EPA Clean Water Act (CWA), the erosion and sediment control industry is experiencing tremendous growth recently (Theisen 2005). The National Pollutant Discharge Elimination System (NPDES) Phase II permit coverage initiated by the CWA helps EPA to conserve and protect the nation's water resources from sediment-laden storm water runoff. One of the important features of storm water discharge management controls known as "best management practices" (BMPs) is erosion control.

There are various methods involving attempts to control erosion. Stabilizing disturbed land through the addition of vegetation is among the most effective ways to prevent erosion and sedimentation. Rolled erosion control product (RECPs) are extremely efficient in facilitating the growth of natural vegetation on bare sites. There has been a lot of study in the field of erosion control in general and methods of erosion control involving blankets or RECPs in particular, which is outlined in Chapter II, Literature Review.

The duration of the effectiveness of these erosion control methods is an important factor. Once an erosion control method is installed, it takes some time for the vegetation to develop to ensure long-lasting control over the area. RECP, a common erosion control method, is defined as a temporary or long-term non-degradable erosion control material

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which is used to reduce soil erosion and help in the growth, establishment and protection of vegetation. It is evident from the industry surveys that the RECPs are becoming increasingly popular. They have confirmed that the usage of RECPs has more than tripled since 1996 leading to the development of more sophisticated and higher performing RECPs. However, functional longevity of these RECPs is a very important feature (Theisen 2005). Although most manufacturers claim that their RECPs have an average life duration of 3 years, which is sufficient to ensure the growth of vegetation, an in-depth study is needed to investigate this.

The goal of this study is to investigate the longevity of these erosion control blankets or RECPs by studying the change in their erosion control properties and quantifying the strength loss in the blankets after their use in erosion control for the earlier stated period of 3 years. This will help in investigating the validity of using these products which are so heavily relied upon for the important application of erosion control.

The chapters of the study consist of this chapter, which is chapter. I, Introduction, chapter II, Literature Review, which is an outline and study of the previous work done in this field; chapter III, Hypothesis of the Study, the need for this study and the hypothesis involving different erosion control properties; chapter IV., Methodology consisting of different materials and testing methods used for the study, chapter V, Results and Discussion, consisting of the results of the tests, analysis of the results and discussions; and finally, chapter VI, Conclusion and Recommendations, consisting of the conclusions from the study and the recommendations for future study.

CHAPTER II

LITERATURE REVIEW

2.1 Channel Erosion

A channel is a concentrated flow path for water leaving a field or watershed. The channels can be either permanent waterways or may be plowed across. Erosion in channels is usually caused by downward scour due to excessive flow shear stress.

Erosion is basically a two part process; initially the soil particles are loosened and subsequently, they are transported by flowing water. Soil particles could be loosened due to the rainfall impact (Free 1960). As the raindrop hits the ground, the kinetic energy of the falling water works to dislodge exposed soil particles. Freezing-and-thawing and wetting-and-drying cycles also ruin the soil structure and loosen soil particles subject to erosion.

Erosion process is a part of the hydrologic cycle. Soils that have high permeability also have high infiltration capacities. This reduces the runoff and erosion potential. Water that infiltrates the soil pores will eventually enter the ground water and flow down and wash out into the river channel as subsurface storm flow. This water will then enter the river at a low velocity with a low peak discharge. Water also collects as depression storage in depressions in uneven ground surfaces. As soon as the infiltration capacities and depression storage capacities are exceeded, the water flows across land surfaces. This shallow and sheet-like flow is called Horton overland flow (Horton 1945). Sheet flow transports particles that have been detached by raindrops in shallow flow across the ground. The flow concentrates in the imperfections in the ground in low spots and erodes tiny channels in the form of rills. Rill erosion creates channels that are only a few centimeters (inches) deep, but rills are often in a very large number in a small area (Gilley et al. 1990). When many rills combine to form a larger channel, gully erosion occurs. Large chunks of gully walls fall into the flow and are transported downstream along with it. Channel erosion occurs when bank vegetation is altered or the flow levels are elevated. Common points where channel erosion occurs are at bends or curves or where structures such as bridges restrict the flow. Landslides that are capable of changing the entire morphology of a river channel can occur due to erosion. They often extend only partially into the channel constricting the flow at some point and increasing the water velocity, thereby increasing erosion and deepening of the river channel.

2.1.1 Mechanism

The process of channel erosion is similar to the basic erosion in which the causes, processes and effects are similar. Channel erosion is the type of erosion that results from increased volume, velocity and/or duration of the flow, and it is accrued with the removal of vegetation. Channel erosion occurs in places where tributaries, storm drains and/or culverts flow into unprotected channels (Lane 1957).

The mechanism of channel erosion can be explained by introducing stream power and critical power. Stream power is defined by Bagnold (1977) as ability of the stream to do work by sustaining the fluid flow against flow resistance and by carrying bed-load along with it. It constitutes the energy available to transport the sediment. Critical power is the amount of energy needed to transport sediment load added to the given stream reach. As long as stream power remains greater than critical power, there is a tendency for channel erosion (Bull 1979; Chang 1979). During the channel erosion, the stream energy performs mechanical work in two forms:

1. Work against friction at the channel boundary
2. Work in eroding the channel boundary

In a stream, channel erosion consists of soil removal from stream banks and/or sediment scour along channel bottom. The part where the erosion will occur depends upon the type of stream. Small streams undergo bed erosion; whereas large streams mainly exhibit bank erosion. In both the cases there is a balance maintained between the materials eroded and the material deposited along a particular reach of stream. The several processes acting along streams that are responsible for channel erosion (Keown 1977) are:

1. Toe undercutting: Attack at the toe of an underwater slope, causing bank failure and erosion.
2. Bank erosion: Erosion of bank material by current or wave action.
3. Bank sloughing: Sinking of saturated, cohesive banks incapable of free drainage during rapid drawdown.
4. Flow slides: Liquefaction of banks in saturated, silty and sandy soils.
5. Piping: Bank erosion by seepage of ground water.

From the view-point of fluvial geomorphology (Leopold et al. 1964), there are two main mechanisms in the process of channel erosion:

1. Deepening: degradation or scouring of channel bottom caused by increased flows.
2. Sinuosity change: bank loss causes change in stream meander configurations. It is usually accompanied by bank accretion somewhere along the affected stretch thus causing the formation of a meander.

Thus, it can be said that channels remain straight if there is little or no erosion, whereas meandering occurs due to localized bank erosion (Leopold and Wolman 1957).

Channel erosion occurs in both intermittent as well as permanent waterways and streams, which includes both stream bank and stream bed erosion (Chang 1986). Again, the causes of channel erosion may be summarized as increased runoff, removal of natural vegetation along the waterway and channel alterations resulting from construction activities.

A special type of channel erosion is concentrated channel flow erosion. In this type, the channels can erode by three mechanisms (Schumm et al. 1984):

1. Channel bed degradation due to shear
2. Channel wall failure
3. Knick point (headwall) advance

One characteristic of the concentrated flow channels is that there is no smooth transition from a wide shallow flow to an incised channel with a deeper flow (Schumm et al. 1984). The transition occurs abruptly at a knick point or headwall. Many such transitions may occur in a concentrated flow channel. Finally the knick points merge, making one incised channel.

Harvey et al. (1985) summarized their work on channel erosion by describing the following features:

1. The same evolutionary trend is followed by all incised channels: initiation, headwall migration, channel widening, channel slope reduction, reduction of bank angle, sediment deposition, and vegetation establishment.
2. The nature of sediment eroded and transported affects the morphology of the channel and the channel adjustment.

In general, channel erosion estimates are highly empirical and rely on the field surveys. Channel erosion may often occur as chunk or blowout type erosion. Also, a channel bank may not erode for a period of years when no major runoff events occur.

According to Horton (1945), Channel initiation is also a product of channel erosion mechanism, a kind of threshold phenomenon. While moving downwards, the overland flow exerts a shear stress (τ) on the surface given by:

$$\tau = \gamma \times d \times \sin\theta \tag{1}$$

where γ : specific weight of water; d: mean depth of flow; and θ : local slope angle.

As the flow depth increases down-slope along with a constant or increasing gradient, shear stress and the potential for erosion also increase. At some critical point, applied stress equals the surface resistance to give a ‘belt of no erosion’ upslope and a zone of potential sheet wash erosion down-slope. Once the overland flow becomes erosive, Horton (1945) believed it to be inherently unstable causing a flow capable of incision. Horton (1945) regarded critical distance from the start of that particular flow, as the most important factor controlling the setting of a physically defined spatial limit on channel initiation. However, it was subsequently proved that the onset of channelization requires another threshold to be crossed, possibly related to critical conditions of slope geometry (angle, length and curvature) and flow dynamics. Along with the critical length criteria, a critical area has to be defined, because the channel initiation requires an accumulation of sufficient runoff, which is area related. While according to the Horton (1945) model, channel initiation reflects the exceedence of an erosional threshold, a more elaborate model by Willgoose et al. (1991) demonstrates that channelization occurs where sediment transport rate defined in terms of the product of discharge and slope increases rapidly producing necessary incision.

2.1.2 Components

Channel erosion comprises of the following components:

1. Rill erosion: it occurs as runoff concentrates in very small channels and the shearing force of flowing water detaches additional soil particles. It is characterized by uniform spacing of eroded parallel channels (Robinson et al. 2000).

2. Gully Erosion: when the small rivulets present in rill erosion combine to form larger channels, the erosive force of the water increases, and gully erosion occurs. Gully erosion forms deep defined channels (Robinson et al. 2000).

Channel Erosion: this is the last level of erosion which occurs in watercourse channels and streams. The initially stable streams that have adapted to a particular peak rate of runoff may become unstable when the prevailing peak rate of runoff increases in reaction to changes to runoff rates within the upstream watershed (Meyer and Monke 1965). The instability is due to inadequate hydraulic capacity to carry increased volume of runoff generated and inadequate bed and bank linings for the higher velocities (Fortier and Scobey 1926) developed. The size and the quantity of material that can be eroded and transported increase when the velocity (Fortier and Scobey 1926) and volume of runoff exceed.

2.1.3 Effects of Channel Erosion: Need for Channel Erosion Control

Channel erosion can cause loss of vital soil cover and hamper the agricultural activities in a particular area and at the same time raise the sediment levels by depositing this soil in some other area making it vulnerable to flooding and inundation. Also, it can create unstable conditions which can cause heavy mass movements ultimately leading to landslides. Un-eroded land has very little surface runoff because most of the rainfall soaks into the top soil and evapotranspirates or migrates slowly through the soil mantle as an interflow to the stream (Roesner et al. 2001). But once the thresholds are exceeded and channel erosion is initiated, the process is self sustaining and the runoff continues to erode and carry soil unless stopped by human intervention. Eroded sediments are also efficient carriers of contaminants such as pesticides and heavy metals which might destroy the native habitat.

The following are the three points describing the reasons for the need of channel erosion control:

1. To control the loss of useful soil cover critical for agricultural and other activities;
2. To prevent change in landform causing unstable soil conditions like reduction of soil material causing weakening of soil mass (e.g. landslides);
3. To prevent floods caused due to increment in plain elevation because of the material deposited after erosion.

The next part describes the various ways of controlling channel erosion, relevant to this study.

2.2 Natural Methods of Channel Erosion Control

Various methods can be used to control channel erosion. The natural methods of erosion control are explained here. These comprise of herbaceous and woody vegetation which can be established in the channel to restrict the erosion. In general, vegetation is an essential part of any ecosystem because it acts as armor against surface erosion, decelerating the velocity flow as a check barrier. The vegetation root growth reinforces the upper soil layers increasing the soil shear strength by over 33 % (Bhandari et al. 1998) and the stem helps to retard the flow velocity. Its cover also allows larger pore spaces so that there is more percolation of water in the soil profile, recharging the upper layer with ground water by capillary action and thus substantiating the availability of water for better vegetation yield.

2.2.1 Role of Herbaceous Vegetation

It is observed by Gray (1974) that the herbaceous vegetation has significant effects in controlling the erosion. The following are the processes by which this type of vegetation controls channel erosion:

1. Restraint: The root system binds the soil particles and thus restrains them. The foliage residues, which are above the ground, filter the sediment out of the runoff.
2. Retardation: The foliage residues on the surface increase the surface roughness and reduce the velocity of runoff.
3. Interception: The foliage and plant residues absorb the rainfall energy by intercepting the raindrops and reduce the erosion due to it.
4. Transpiration: Absorption of soil moisture by plants delays the initiation of saturation and runoff.

Grasses, legumes and herbaceous species provide a uniform vegetative cover. Especially, grass is an effective plant type because it regenerates, grows quickly, and often provides a complete ground cover (Samani and Kouwen 2002). Switch grass

(*Panicum Virgatum*) hedges are also potentially effective in resisting gully formations by stopping the incision of stream channels (Dabney et al. 2004).

Turf-grass sod is another new alternative for erosion control because its strong mat of grass blades and roots keeps soil particles from becoming suspended in runoff, which occurs whenever rainfall intensity exceeds the soil infiltration rate.

Natural vegetation buffer strips also act as a barrier, reducing soil movement (Heede 1990). There is a great variability in sediment delivery between different vegetation types. One of the main advantages of buffer strips is that the re-vegetation efforts can be concentrated and, therefore, intensified on relatively narrow areas by applying artificial irrigation, fertilizer and mulch. The study which was conducted in 1987 in Ponderosa Pine, Arizona (Heede 1990) showed that the vegetation strips were effective regardless of the vegetation type and many tree species can be utilized for the purpose of erosion control.

2.2.2 Role of Woody Vegetation

Woody plants also help prevent mass-movement, particularly shallow downward motion in channels. The different parts of woody vegetation or strong trees which take part in the prevention of channel erosion perform the following functions:

1. Roots: The first function of roots is to mechanically reinforce the soil by transferring the shear stresses in the soil to the tensile resistance in the roots (Kassif and Kopelovitz 1968). However, the roots must be long and frictional enough to resist pullout.
2. Stems: Anchored and implanted stems can act as a support in a channel, counteracting shear stresses. The restraint provided by buttressing and soil arching action (Wang and Yen 1974) of the strong trunks of trees gives stability by holding the soil.

3. Foliage: The production of soil moisture stress is controlled by evapo-transpiration and interception in the foliage. The lesser the amount of water in soil, the stronger it is, and less susceptible to erosion.

Stems and foliage also protect stream banks by dissipating the flow energy. They increase the boundary layers along the stream banks thus absorbing the flow energy which may otherwise cause erosion.

The various methods of achieving erosion control through woody vegetation can be listed as contour brush-layering, contour wattling, live staking, reed-trench terracing, brush matting and bare root planting. Land treatment measures like contouring, strip cropping, grassed waterways, rotations, pasture, and woodland improvement also help in controlling erosion by enhancing the vegetal cover. Improved vegetal cover reduces the sealing of surface soil by shielding it against direct impact of raindrops. This, in combination with better soil aggregation from improved agronomic practices, improves the infiltration rate holding back the sediment (Moore and Smith 1968).

2.2.3 Selection of Vegetation for Erosion Control

The main characteristic required in a plant for erosion control is adaptation to the environment. The plant should not be prone to any disease, but should be strong, competitive against less desirable plants and trouble-free. The type of erosion which needs to be controlled also decides the plant depending on the type of roots and top growth (U.S E.P.A 1972). The large woody plants require some time to develop sufficient size to control erosion adequately, the erosion control in the interim period can be provided by grass growth. It should have a strong root development and minimal top growth because top growth may mat and crowd out the more permanent species. A mix of grasses should be used for this purpose because, while long term species can provide assurance of a stand, short-lived species will give the required short-term protection for that time being.

2.2.4 Vegetation for Erosion Control: Advantages and Disadvantages

Though vegetation is sometimes advantageous as it is observed to be self-adjusting and self-repairing to a great deal and vegetative channel protection measures are less expensive than the structural methods (White and Franks 1978), it also suffers from some disadvantages. For example, it is vulnerable to disease, drought, trampling and erosion from wave action and scour. These can however be controlled by selecting the right type of vegetation, planting and maintaining the vegetation appropriately and by using the vegetation in combination with structural and mechanical elements.

The United States Environmental Protection Agency states “Preserving existing vegetation or re-vegetating disturbed soil as soon as possible after construction is the most effective way to control erosion” (U.S.E.P.A 1972). Although it is well known that vegetation plays a critical role in controlling erosion and supports channel stability, little consideration goes into how a sustainable vegetation cover can be attained. Sometimes vegetation is not relied upon for this purpose because the initial establishment is deemed too difficult (Holland 2002). Hence some form of artificial method providing temporary erosion control is resorted to and these methods are explained in the next section.

2.3 Artificial Methods of Channel Erosion Control

In addition to natural methods, there are various artificial ways of erosion control. Traditional erosion control techniques include seeding, mulching (for moderate applications) and hard armor systems such as rock riprap or concrete (for severe applications), however, for environmental and aesthetic reasons, vegetation is the ultimately preferred approach. Sometimes, vegetated systems which consist of a combination of vegetation with other methods of erosion control might be used but their performance depends on the density and type of vegetation as well as the type of soil (Lipscomb et al. 2005). However, some times seed and soil are washed away prior to vegetation establishment and even mature vegetation cannot resist erosive forces associated with some severe applications where expected velocities would exceed 2.1

meters per second (Chow 1959; Nelsen 2005) or shear stresses topping 177 Pascal (Pa) (Chen and Cotton 1988; Nelsen 2005). Hence nowadays rolled erosion control products (RECPs) are used to hold soil and seed in place until vegetation is established and also to permanently reinforce the vegetation. Mostly, RECPs are temporary and used in combination with vegetation. RECPs are also known as Erosion Control Blankets (ECBs, used primarily for slope protection) or Fiber Roving Systems (FRSs) which eventually degrade leaving vegetation as the permanent erosion control measure. For extremely severe applications like very steep slopes, high flow channels and pipe outlets, traditionally, very expensive hard armor systems have been the only solution, but recently, a new genre of RECPs known as turf reinforcement mats (TRMs) are currently being used extensively, thus reducing the cost and extending the use of vegetation into more challenging applications. All those methods which do not involve the growth of vegetation for erosion control on its own, without any support, can be considered as artificial or induced methods. Though there can be many ways of artificial erosion control, the method relevant to this study is the use of the blankets or mats in any of the above described forms, The following are the main types of the mats used for erosion control (Holland 2002).

1. Natural mats: natural blankets/mats made up of short term degradable erosion control materials such as organic ones, usually natural fibers like jute, coir, straw and wood fibers, as explained in natural materials section below.
2. Artificial/synthetic mats: non-degradable synthetic mats made up of fibers consisting of polymer chains with chemical bonds.
3. Composite mats: permanent three dimensional synthetic mats combined with decomposable natural material, help to enhance the shear stress resistance of vegetation by promoting their root and shoot reinforcement. TRMs can be considered as composite mats in some cases.

2.3.1 Natural Mats

Natural erosion control products have an edge over the synthetic ones because of their ability to absorb water and to degrade with time. Natural materials include fibers of coir, jute, straw, wood fibers and some other organic fibrous materials. The following are their inherent advantages (Balan and Rao 1996):

1. Protection against rain splash erosion
2. Capacity to absorb even up to 5 times their own weight
3. Able to reduce velocity and erosive effect of runoff
4. Maintaining humidity in the soil and atmosphere
5. Mitigate the extremes of temperature
6. Adding useful mulch to the soil after biodegradation

An effective erosion control product should closely mimic the function of a vegetative slope cover and these biodegradable erosion control materials will provide ground cover while simulating the rain buffering function of vegetation until the latter is established. This ground cover concept is important because optimum ground cover is directly related to the amount of erosion control which can be offered by the product while maintaining a balance with the light penetration needed to simulate seed germination and allow grass shoots to break through the blankets (Holland 2002).

One of the new abundant natural fiber resources which can be sapped for the erosion control is coconut fiber (coir). Its use in this field is becoming popular due to its durability and wet strength. Santha (1995) studied two widely used coir erosion control products (coir polypropylene netted blankets and woven coir blankets) and analyzed their performance and properties related to erosion. He observed that the woven coir blankets made of bristle fiber coir twines had a very high tensile strength and weight. The tensile strength properties of these fabrics are greater than those of most synthetic blankets and they also provide a cost-benefit.

Geo-jute, being flexible, drapes easily over the surface contours along with being heavy enough to maintain close contact with the soil (Ranganathan 1995). Vegetation grows through it and will not push it up and off the soil surface. Because of its amazing ability to cling to the soil, it is an excellent choice for erosion control in shallow drainage where gradients are gentle and flows are light. The heavy yarn also serves to provide a rough surface, which during water flow, helps to trap sediment, prevents erosion and stabilizes seed so that natural vegetation can become the ultimate erosion control material. Also, it reduces the raindrop impact by its unique ability to absorb water. Jute is almost eight times more flexible than the most flexible synthetic mats and once it absorbs water to capacity, its flexibility is increased approximately 25%, thereby enhancing its ability to maintain intimate soil contact. From the erosion tests, it is proved that the jute retained almost 99.6% of sediment expected to be lost from bare ground (Ranganathan 1995).

Sometimes there is a use of biodegradable materials like compost, straw and mulches to deal with the problem (Haynes 1997). It is observed that the hydro-mulches when used with tackifiers can be quite effective in protecting the channels from rainfall erosion. Agricultural straw is another substance with a high erosion control potential.

2.3.2 Artificial/Synthetic Mats

Artificial mats are made up of synthetic material such as polymers. The ‘polymer’ which forms the basis for the chemical structure of the geosynthetic is the repetition of many chains of monomers. The polymers used in the manufacture of geotextile fibers are made from the following polymeric materials, listed in the order of decreasing use (Koerner 1994):

1. Polypropylene (83%)
2. Polyester (14%)
3. Polyethylene (2%)
4. Polyamide (1%)

Being absolutely synthetic, they lack the advantages which the environmentally-friendly natural methods have because it may take a very long time for certain polymers to break down. They may not play an encouraging role in the vegetation growth and are mostly modified as described in the next part.

2.3.3 Evaluation of Channel Erosion Control by Artificial Methods

There has been a major progress in the products and design methods in the erosion control industry in the last 15 years. Synthetic erosion control products or TRMs are a low cost alternative to concrete ditch linings and also provide flexibility. However, they lose their effectiveness with time where synthetic fibers are subject to slow ultra violet (UV) degradation and organic semi-permanent blankets are subject to slow rate of biodegradation. More studies are needed to evaluate geosynthetics' efficacy in the wide scenario of erosion control.

2.4 Geosynthetics in Channel Erosion Control

According to Sprague and Goodrum (1994), Geosynthetics is a generic term for all synthetic materials used in conjunction with soil, rock, and/or any other civil engineering related material as an integral part of a man-made project, structure or system. The use of geosynthetics in erosion control is to restrict movement and prevent dispersion of soil particles subjected to erosion actions for an infinite period of time. Geotextiles, the type of geosynthetics being used in this study are permeable, polymeric textile products in the form of flexible sheets. They are mostly obtained in four forms, woven, non-woven, knitted and stitch-bonded. They are used in erosion control as they can allow an adequate flow of fluids across their plane while preventing the migration of soil particles along with fluid flow during the projected service period of application under consideration.

Generally, the raw materials for geosynthetics can be polyester, polypropylene, polyethylene, and polyamide, however, as is the case with the geotextiles used in this study, most of them are manufactured from polypropylene because of its low cost and excellent chemical and pH range resistance (Cassidy et al. 1992). Geotextiles are sometimes manufactured from natural biodegradable fibers such as jute, coir, paper, cotton, wool, silk, etc. However, biodegradable geotextiles are usually limited to erosion control applications where natural vegetation will replace the geotextiles' role as it degrades (Greenwood et al. 1996).

2.4.1 RECPs in Erosion Control

RECPs are the usual form in which the geosynthetics are used in erosion control. Sutherland and Ziegler (1996) studied the variation in runoff and erosion from an erodible soil on a 9% field slope covered with ten rolled erosion control products and it was found that time to runoff generation was generally delayed on most RECPs when compared to bare surface treatment. Also, erosion rates for all RECPs when compared were significantly lower than those for the bare soil treatment. The RECPs, most effective in reducing erosion rates, prevented the system from crossing a critical threshold; between inter rill to rill dominated processes (Sutherland and Ziegler 1996). The following observations were made regarding the rolled erosion control system design (Sutherland and Ziegler 1997):

1. Similarly designed systems, composed of the same material, will exhibit higher erosion rates as percent ground cover increases.
2. RECPs with similar open weave designs will display lower erosion rates if fibers are flexible (drapable) and increase and the degree of contact with the soil surface.
3. RECPs composed of randomly distributed fibers are more effective than open weave designs if systems have significant three-dimensionality.

It is observed from the study on the RECPs that significant differences exist between the performances of individual products, whether viewed individually, or within appropriate comparison groupings. The design of RECPs is based on maximum slope, velocity, and shear stresses that are calculated based on site conditions and they are selected based upon these parameters provided by the manufacturer (Smith et al. 2005). Many times, in channel applications, different types of RECPs might meet all the requirements for a particular set of site conditions, but their behavior in this situation is different.

2.4.1.1 Degradable RECPs

Degradable RECPs which have been in existence for nearly 40 years now, are designed to assist in vegetation establishment and to provide temporary erosion protection. They are composed of processed natural or polymer fibers mechanically, structurally or chemically bound together to form a continuous matrix and are generally limited to areas where natural, unreinforced vegetation will eventually provide long-term stabilization and protection. By incorporating various forms of mulch materials into a finished product, the "functional longevity" or desired period of functional performance of these blankets can be changed.

Sometimes these erosion control meshes are used with dry mulches or as a stabilizing underlay for sod reinforcement. The fibers are held in place either by glues or glue strips or by more superior parallel lock stitching by cotton polyester or polyolefin threads. The Biodegradable fiber blankets can be made of straw, excelsior, cotton, coconut, polypropylene or blends, with color varying from clear, tan, green to black and it provides a temporary resistance to flow velocity of up to nearly three meters per second. Also these blankets are environmentally-friendly because, after photo-degradation, the plastic chains are cut into shorter and shorter segments down to plastic sand which becomes a part of the soil (Theisen 1992).

According to Bhandari et al. (1998), wherever practicable and where vegetation needs elementary support for growth, nets made of woven jute or coir fibers may be used for erosion protection of slopes not steeper than 1H: 2V gradient. These nets biodegrade in a period of 2 years at the moistness and provide nutrient to the root mat. However, adequate moisture in the root zone shall be needed to allow the use of such netting for erosion control. These nets are used only initially to hold root mat in soil during germination. Due to degradation with time the reduction of erodibility of soil as a check barrier is not feasible with natural erosion nets.

2.4.1.2 Non-degradable RECPs

According to Theisen (2005), non-degradable RECPs were introduced in Europe in the 1970s when an open three-dimensional thermally fused nylon matrix was designed to reinforce vegetation. This technology remains in use nearly 35 years later and continues to gain momentum. In this system, the ability of plants to protect soil from erosion is enhanced through the use of long-term non-degradable geosynthetic materials. Non-degradable RECPs used in channels are also called TRMs. Details of TRMS are described in section 2.4.3.

These form a type of permanent, “soft armor” alternative to more costly hard armor techniques such as riprap, gabions, fabric formed revetments and concrete liners. They can be designed for permanent and critical hydraulic applications such as drainage channels, roadside ditches, landfill diversion ditches and spillways, where expected discharges result in velocities and tractive shear stresses that exceed the limits of mature, natural vegetation.

2.4.2 Specifications for Geosynthetics Used in Erosion Control

According to Bhandari et al. (1998), the woven nets from natural fibers shall be made from jute or coir and may be treated with polymer or rubber impregnation to increase the life. The net shall be of minimum thickness of 5 mm and minimum aperture size of 15 mm by 20 mm in rectangular shape. The nets of such variety are applicable for slopes up to 7 m length (based on general average plane slipping stability) having mass/unit area of 400 to 600 g/m^2.

Geotextiles used independently for temporary or permanent methods of erosion control shall be made from high density polyethylene (HDPE) or polypropylene (PP) in net form produced by single extrusion process. The general specification required for erosion control shall be as follows (Bhandari et al. 1998):

Material: HDPE or PP polymer/copolymer.

Aperture size: 30 mm (nominal)

Unit weight: 650 gm/m^2 (minimum)

Tensile strength: 4 KN/m at 10 % strain, peak elongation not exceeding 20 %.

2.4.3 Turf Reinforcement Mats

As stated earlier, turf reinforcement mats (TRMs) are the recent genre of erosion control mats used in many application areas. They are geotextiles manufactured from a variety of materials that have been used effectively for over 35 years and are used to improve vegetation's resistance to erosion by increasing the permissible shear stress of the vegetative cover.

The Erosion Control Technology Council (adopted June, 2004) defines a TRM as: "A rolled erosion control product composed of non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, three-dimensional matrix of sufficient thickness." TRMs, which may be supplemented with degradable components, are designed to impart immediate erosion protection, enhance vegetation establishment and provide long-term functionality by permanently reinforcing vegetation during and after maturation.

According to Hewlett et al. (1987), and, Northcutt and McFalls (1998), TRMs are composed of 100% UV stabilized, synthetic materials that do not degrade after vegetation is established. Instead they stay in place combining with the roots and stems to form a synergistic mesh which keeps getting efficient with vegetation growth. This combination can withstand up to twice the erosive forces of the un-reinforced vegetation and can provide erosion resistance comparable to that of a number of hard armor systems during intense storm events. Along with this high performance, they also can provide environmental and aesthetic advantages while continuing to have low installation and maintenance costs. Modern TRMs have thus proven the ability to significantly enhance the erosion resistance of vegetation, supporting their use in areas where high velocities/shear stresses are frequent.

Generally, TRMs should have a non-degradable three-dimensional structure rather than a two-dimensional one, for stem and root reinforcement to further enhance the vegetation's erosion control performance instead of just maintaining it. However, TRMs should not be used under constant, high velocity runoffs or in a land where vegetation cannot exist (Nelsen 2005) because their use is only in combination with vegetation (Sprague 1999). Studies have shown that the geosynthetically reinforced turf is effective only up to 384 Pa (Chen and Cotton 1988). There are three phases of a reinforced vegetative channel lining's development (Lancaster 1996) through which a TRM must provide continuous erosion control and turf reinforcement. During phase 1, the TRM must control soil and seed loss immediately after installation so that a permanent vegetative stand gets developed successfully. Phase 2 is defined as that period of time from seed germination until a mature stand of vegetation is established. During this time, the matting must continue its role by supplementing the erosion protection provided by the vegetation as well as strengthening the developing plants against high shear stress water flows. In phase 3 when the vegetation has become mature, the matting must provide stem reinforcement and root zone protection by formation of mesh.

A TRM which can thus be called a long-term non-degradable geosynthetic material, forms a flexible, three-dimensional matrix which retains seeds and soil, stimulates seed germination, accelerates seedling development and synergistically meshes with developing plant roots and shoots which is its most significant use, giving twice the protection of un-reinforced vegetation (Theisen 1992). TRMs are increasingly becoming popular as “biotechnical composites” that are one third to one half the cost of hard armor, reduce excavation costs, are easier to install, display improved visual aesthetics, promote infiltration and groundwater recharge, reduce water temperatures and help capture and remove sediment and pollutants from run off.

According to Carroll et al. (1992), the first TRM was a three dimensional monofilament nylon fiber mat structure approximately 18 mm (0.75 in) thick, with a highly porous mat which was relatively uniform. It was stiff with excellent resiliency, but problems such as lack of soil filling causing widespread erosion due open structure and stiffness led to development of second synthetic matting called an erosion control and re-vegetation mat (ECRM) which enhanced ground cover and provided good conformity characteristics. Its stiffness is reduced due to use of thick plasticized monofilament and improves the bare soil resistance during moderate flow conditions that can cause erosion beneath a stiff mat. Flexibility and ground cover are very important for the ECRM performance; however, if the stretching characteristic is high, it can be detrimental to the performance when the flow rates are higher. The stretching eliminates the ECRMs’ capability to provide reinforcement to the established turf and at the same time the thinness of the mat significantly reduces its soil holding capacity and its ability to act as a turf reinforcement mat. The stiffness problems of the TRM and the flexibility problems of the ECRM were finally nullified and now we have the newest generation of synthetic blankets, erosion control and revegetation blankets (ECRB), which uses a combination of staple nylon or polypropylene fiber sewn between two nets, which have a longer life than the organic blankets due to UV stabilized fiber. The balance between flexibility and dimensional stability should be achieved because these two criteria are critical to the turf reinforcement application and this is the best achieved form of TRM till date.

According to Hoffman and Adamsky (1980), three dimensional erosion control mats are used to establish a reinforced vegetative surface, or “turf”, in ditches, channels and slopes. The mat entangles with the root and stem network of vegetation to greatly enhance its resistance to flow velocity. Erosion mats used for turf reinforcement have a stable three-dimensional structure with adequate porosity to retain soil while allowing roots and stems to grow through. Correct installation requires pinning the mat to the ground and burying mat edges and ends. Top soil cover may be used to enhance temporary erosion protection and early vegetative growth. The use of flexible porous polymer mats has greatly enhanced our ability to control sheet, gully and rill erosion. These three-dimensional systems are used regularly in channels or ditches and on slopes. Specific application areas include the following:

1. Storm channels
2. Channel banks
3. Slope protection

TRM systems mostly defy a simple physical description. They are in the form of a variety of combinations:-

1. Entangled webbings of a three dimensional structure
2. Open cells of a three dimensional structure
3. Biodegradable paper woven within a loose knit fabric
4. Heavy woven fabrics consisting of thick multifilament fibers
5. Various filler materials within an open netting

Some-times the turf grass mentioned in the previous chapter is established by using TRMs non-woven geotextile mats made of polypropylene which protects the grass seed until germination (Collier et al. 1997).

2.4.4 Channel Calculations in Erosion Control Design by Geosynthetics

There are many approaches for designing the erosion control systems using the geosynthetics. The key to reducing erosion by use of turf reinforcement is to slow down the water velocity by some form of interception and/or impediment. The above listed systems can achieve this and can be evaluated and/or compared through their roughness coefficients for subsequent use in the Manning equation for open channel flow.

$$V = \frac{1.49}{n} R_h^{\frac{2}{3}} S^{\frac{1}{2}} \tag{2}$$

where,

V = average open channel flow velocity

R_h = hydraulic radius

S= slope, or hydraulic gradient

n = roughness coefficient

The higher the roughness coefficient, the lower the flow velocity and the less erosion that will occur. Most non-vegetated, unprotected soils have “n” values from 0.02 to 0.03. The use of turf reinforcement will increase these values by 2 to 5 times, the exact value requiring laboratory flume testing (Theisen 2005).

Thus, geosynthetics if used sensibly may be able to provide a long-term protection against the channel erosion. However, the factors which might affect their application and real-time use must be considered in order to evaluate them for an extended use.

2.5 Factors Affecting Longevity of Channel Erosion Control Geosynthetics

According to Sprague and Goodrum (1994), exposure environment is defined to be characterized by complex atmosphere, soil, and water chemistry as well as unique radiation, hydraulic, and stress-state conditions. The effect of this combination of exposures, over time, is called “aging.” The geosynthetics’ performance depends on the environment to which it is exposed; hence an understanding of all the environmental factors is very essential for the study of its aging process and longevity.

In channels, there are numerous degradation mechanisms which might act on the geosynthetic materials (oxidation, hydrolysis, radioactive, chemical and biological). However, UV light and elevated temperature can be considered to be the most critical ones. The following are the common types of effects of environmental factors mostly seen in practice:

1. Environmental stress cracking is the growth of external or internal cracks in a geosynthetic caused by tensile stresses which are less than the short-time mechanical strength and are accelerated by the exposure environment.
2. Mechanical damage is the localized degradation of the in-service geosynthetic due to the externally applied load.
3. Oxidation is the chemical reaction between oxygen and a specific chemical group in a polymer converting the group into a radical complex, ultimately leading to a molecular scission or cross-linking, thus changing the chemical structure, physical properties and sometimes even the appearance of the polymer. It may take place due to the presence of air and water in the atmosphere.
4. Photo degradation is the change in chemical structure due to the sunlight, resulting in injurious changes to the physical properties and sometimes to the appearance of the polymer as a result of the irradiation of the polymer by exposure to light (primarily UV).
5. Temperature instability, which is the change in the appearance, weight, dimension or any other property of the geosynthetic as a result of low, high, or cyclic temperature exposure, can create very high stress conditions in the structure of the polymer forming the geotextile.
6. Thermal degradation is the alteration in the chemical structure resulting in changes in physical properties and sometimes in the appearance of a polymer caused by exposure to heat alone.

Some-times chemical effect may involve an effect of acid or alkali. It may bring about a change in the pH level of the soil surrounding the erosion control product.

Extreme pH changes can lead to wear and tear of the erosion control product due to breaking of the polymers.

2.5.1 Effect of Ultra-violet Radiation

Geotextiles are mostly protected from UV degradation by either the chemical makeup of the polymer or by addition of additives such as carbon black, but in applications like erosion control where continuous exposure to radiation is involved, it is essential to conduct a study regarding the durability of the product in this respect (Hodge 1987).

Sun's UV light is an important factor affecting the life of the geotextile. The energy of the light photons is greater than or equal to the strength of the chemical bond between the polymers and can break it causing degradation of the fiber. Breaking strength of the geosynthetic fiber is an important factor in the degradation process.

Especially, UV exposure can become the most dominant mechanism due to the chain scission initiated by the nanometer waves of the UV band of radiation penetrating into the polymer along with the elevated temperature (Koerner et al. 2005) and breaking of the chains in the polymer of the structure by the energy of the radiation (Lord and Halse 1989)

When a geosynthetic is installed for erosion control, there is no possibility that it will escape the UV degradation except for in some very rare areas with unique geographical locations. However, the amount of the radiation, to which the geotextiles will be subject to, is decided again by locating the project site accurately and studying the recorded sunlight intensity in that given area. The exact effect of the UV rays and the polymer degradation process initiated by them is explained below:

Sunlight is a dominant degradation factor in the polymers used in geosynthetics. Wavelength of sun's radiation extends from the infra-red (> 700 nm), through the visible spectrum (400-700 nm) and into the UV (< 400 nm), with a cut off at around 300 nm depending on the atmospheric conditions. According to Koerner (1996), UV region is further subdivided into UV-A (400 to 315 nm), which causes some polymer damage; UV-B (315 to 280 nm), which causes severe polymer damage and is considered only some times; and UV-C (280 to 100 nm), which is found only in the outer space. The changes in the intensity and spectrum of sunlight can be observed from summer to winter and the most significant is the loss of the shorter wavelength UV radiation during the winter months. Geographic location, temperature, cloud cover, wind and moisture should also be considered while the study of polymer degradation is performed. As the radiation strikes the polymer surface, photons which have an energy level equal to or higher than the chemical bond strength of the polymer, generate continuous reactions which lead to polymer chain scission and gradual degradation of the polymer properties. The values of energies of 400-300 nm photons are 300 and 390 kJ/mol respectively, where as the strengths of C-C and C-H bonds are 420 and 340 kJ/mol which proves that the UV energy of sunlight is effective in breaking the chemical bonds of the polymers and it gets severe with the shorter wavelengths of light. As oxygen is available in the atmosphere, photo-oxidation may occur.

Chapter IV, Materials, shows that the chemical composition of the geosynthetics consists of either polypropylene or polyamide chains. Table 2.1 shows the wavelength range that can cause photo-degradation in these polymers.

Table 2.1. Range of wavelengths causing photo-degradation

Polymer	Wavelength (nm)
Polypropylene	335-360[a]
Polyamide	<300, 340-400[b]

[a]Zhang et al. (1996)
[b]Hu (1998)

The following is the reaction taking place during the degradation of polypropylene:

$$RH + O_2 + hv \rightarrow R^* + ROO^* + RO^* + OH^* \qquad (3)$$

where, RH is the polymer chain, *hv* is the photon energy with *h* and *v* representing the Planck's constant and wavelength respectively, R *, ROO *, RO *, OH* are the free radical species with R representing the polymer chain. This oxidation reaction initiates chain scission in the polymer yielding a chemical product of carbonyl compound.

The following is the reaction taking place during the degradation of polyamide: Both cross-linking and chain scission can occur in polyamides depending on the UV wavelengths. Cross-linking is the main mechanism acting at short wavelengths (< 300 nm), where as at longer wavelengths, chain scission takes place. The maximum intensity of the UV light is in the mid-June mostly and accordingly the time periods for which the geosynthetics are exposed in this study include this duration.

2.5.2 Degradation due to Temperature

High and cyclic temperatures are most effective in bringing about significant stress changes and adversely affect the stress-strain characteristics of the geotextile reducing its efficiency by bringing wear and tear in the fibers.

Though most of the current geotextiles are relatively stable under normal temperature ranges, certain changes in the mechanical properties might occur, for instance, stress-strain properties (Hodge 1987) at elevated temperatures because of the high energy which the polymer chains are subjected to. In long-term this definitely has an effect on the strength of the blankets and reduces it in most cases.

Cyclic temperature change is the increase in the temperature during the day and the reduction during the night time and also the seasonal temperature variations from winter to summer. This again has a high effect on the mechanical properties of the blankets. The reason might be a small amount of warping caused by the variation of the surrounding temperature conditions.

According to Hsuan and Koerner (1993), high temperature causes all polymer degradation mechanisms to occur at an accelerated rate. The basis of time temperature superposition lifetime prediction techniques (such as Arrhenius modeling, rate process method, etc.) is to test laboratory specimens at high temperatures and extrapolate down to the field anticipated lower temperatures. This high temperature is an acceleration phenomenon acting with some other degradation mechanism like oxidation, hydrolysis, chemical, radiation, biological sunlight, etc.

2.5.3 Degradation due to Water

Water can affect the in-service geotextile in various ways. During the heavy rainfall, sometimes very high stresses might be introduced into the blanket causing mechanical wear and tear. The storm water runoff can induce strains in the fabric. Though the effect of water is very less compared to the UV light and the temperature variation, nevertheless, it needs to be taken into consideration while studying the factors affecting life of a geosynthetic.

The other way, water might affect the geosynthetics is by way of humidity or moisture. The presence of water in this form is continuous and while it promotes the growth of vegetation in the soil to form a permanent vegetative blanket, it might combine with the temperature and light to cause photo-oxidation of the polymers. Sometimes water contains some constituents or contaminants which may react chemically with the polymers in the material and alter its properties.

2.5.4 Difficulties in Measuring Effects of Environmental Factors

There have been several attempts to simulate the environmental factors in the laboratory for the longevity study but when the products are subjected to the real-time conditions by their application in field, the effects of these factors are difficult to quantify. Also, the effect of each factor individually cannot be calculated as the factors act in combination. So how are these factors included in the longevity testing and study of geosynthetic products?

In case of short-term applications, it is necessary to find out how long the product will remain functional and for long-term, non-degradable products it is important to select polymers that will resist the above-mentioned breakdown mechanisms. Theisen (2005) introduced the concept of "consideration factors" that can either be beneficial or detrimental to long term performance of an erosion control blanket. Among these, the one relevant to our study is CFd (consideration factor for durability with respect to biological degradation, UV degradation, chemical degradation). According to Theisen (2005), durability has the direct relation to the functional longevity of a material and material breakdown can take place by microbial activity, UV degradation and chemical degradation.

Though it is difficult to measure durability practically, testing of index properties does allow the comparison of different engineering fabrics. The simple tests that measure a specific property of a material for the purpose of comparing products or monitoring production are called "index tests" and hence the properties measured by these tests are known as index properties (Smart Solutions 2004). The geosynthetics may be exposed to the effects of weathering from a few days, the time it takes for the materials to be installed and covered with the soil in some cases of erosion control to many years for materials used in most cases of erosion control. In terms of the effect of weathering on geosynthetics, the information of importance is the loss in strength and elongation due to the weathering. According to Theisen (2005), some of the projects of erosion control in which these materials are used are critical in nature and the failure of the site on which the material is used may result in property damage and loss or injury to life. Therefore, it is important to be able to accurately measure the effect of weathering. Ultimately, the user of the accelerated test information is looking for an indication of how the materials being tested are going to behave in regards to deterioration due to UV light after installation at a project site but there has been little or no success in relating the results of, for example, the xenon arc testing to actual field performance. The laboratory testing only provides an indication of the tendency of the materials to deteriorate and resultantly, there is a difficulty in attempting to determine the strength of loss over time due to UV exposure of the geosynthetic on a project. This also may lead to an increased cost of the project because of a higher factor of safety being used than what may actually be necessary. When comparing different geosynthetic materials, the variation in time for equivalent degradation to occur varies from days to years. This is another problem in the interpretation of the accelerated test results.

Hence, despite of the recent developments in the accelerated weathering tests, ultimately index testing is the most reliable method till date for the study of effects of the environmental factors on the longevity of the geosynthetic erosion control products and the explanation of the study of these index properties and index tests is given in the next two sections.

2.6 Properties and Testing of Erosion Control Geosynthetics

According to Shukla (2002), durability of a geosynthetic is regarded as its ability to maintain the requisite properties against environmental and other influences over the selected design life while longevity is about how the geosynthetic properties will change over the life of a structure. The durability of geosynthetics has traditionally been assessed on the basis of mechanical property test results. The study of long-term performance of geosynthetics in sunlight can be carried out by exposing them to natural or artificial radiation. Only natural exposure is considered in this study.

The index tests are performed to measure the product integrity, adequacy, continuity and to control quality and are therefore carried out under standardized conditions. They are also used to monitor changes that may occur after a geosynthetic has had some kind of exposure (Shukla 2002). Though durability is an essential requirement for geotextiles, it is difficult to predict this quality by laboratory testing (Hodge 1987). To evaluate the durability of the geotextiles, the best way would be to compare these quality control properties by doing a statistical analysis of the values given by the index tests. The most durability criteria are considered as mechanical properties of the geotextiles. Index parameters describe physical components and characteristics of products such as weight per unit area, thickness, tensile strength, and elongation etc. Among them, values of tensile strength and elongation describe the performance of the product (Driver and Kostielney 1997). Index parameters are examined by various tests on the materials in controlled laboratory conditions according to the American society of testing and materials (ASTM) standards guidelines. The properties studied in relation to longevity and their methods of testing are described below: (Shukla 2002).

2.6.1 Mass per Unit Area

Mass per unit area, also known as “weight” per square yard of a sample, is an important index property. It is a good indicator of cost, physical properties like tensile strength, and also necessary for quality control.

It is measured by weighing a fixed area of the material. The physical properties of different materials can be studied by comparing their masses per unit area.

2.6.2 Thickness

Thickness of geotextiles is measured as the distance between upper and lower surfaces of the material at a specified normal pressure (Driver and Kostielney 1997). As it is one of the basic physical properties of the blanket, its measurement requires rigid control within specified limits, because bulk and warmth properties are often estimated from their thickness values and thickness is also useful in measuring performance characteristics such as before and after abrasion or shrinkage.

In the case of erosion control, the thickness is usually equated with an eventual supportive matrix for root entanglement after vegetative growth. However, thickness is not a critical factor in determining whether or not a product will perform in a given circumstance. Thickness must be accounted for in case the blanket’s ability to perform has to be determined and this is done by the agencies indicating a minimum thickness that is acceptable for products used in their projects.

2.6.3 Tensile Strength

The single most important property of a geotextile is its tensile strength (Koerner 1994). Invariably all geotextile applications rely on this property either as the primary function (as in reinforcement applications) or as a secondary function (as in separation, filtration or drainage). Even in erosion control, this forms an important evaluative property. Tensile strength is an important criterion for selecting a blanket or technique for erosion protection. If the soil is compact, the anticipated flow involved is low and the slope is not severe, the tensile strength required is not very high. However, if the soils are unstable, the flow rates involved are higher and the slopes are steeper, higher tensile strengths are needed. Long-term tensile resistance is the most common property related to durability in geotextiles (Sprague and Goodrum 1994). Tensile strength is a primary quality control property which becomes more important when a RECP is subjected to emergency and recreational vehicular traffic and maintenance such as mowing.

Due to specific geometry and irregular cross-sectional area, tensile strength of geosynthetics cannot be expressed conveniently in terms of stress; hence it is defined as the peak load that can be applied per unit width. To minimize the effects of sample geometry, gripping method, strain rate, temperature, initial preload, conditioning and the amount of any normal confinement applied to the geosynthetics, the test sample should have an aspect ratio of at least two, and the test should be carried out at standard temperature. The minimum strength of the geotextile should be obtained and never exceeded in the practical applications.

The basic idea (Koerner 1994) of the test is to place the geotextile within a set of clamps or jaws, place this assembly in a mechanical testing machine, and stretch the geotextile in tension until failure occurs. Geotextile failures are generally easy to identify. During the extension process, it is customary to measure both load and deformation in such a way that a stress versus strain curve can be generated. From the stress (usually given as load per unit width) versus strain (calculated as deformation divided by original specimen length) curve, four values are obtained:

1. Maximum tensile stress (referred to as geotextiles' strength)
2. Strain at failure (often given as maximum elongation, or simply elongation)
3. Toughness (work done per unit volume before failure, usually taken as the area under the stress-strain curve)
4. Modulus of elasticity (which is slope of the initial portion of the stress versus strain curve), also known as offset/working modulus

Vertical axis is in units of force per unit width of fabric (i.e. in lb. /in or kN/m, which is not a bona-fide stress unit), hence to obtain stress units; this value must be divided by the geotextiles' thickness. This is not conventionally done, since the thickness varies greatly under load and during the extension process and is not easy to determine.

Tensile modulus (Myles and Carswell 1986) is the slope of the geosynthetic stress-strain or load-strain curve, as determined from the tensile test procedures. It indicates the deformation required to develop a given stress (load) in the material. As shown in Fig. 2.1 (Shukla 2002), when the test begins, the load is zero unless a pre-load is used.

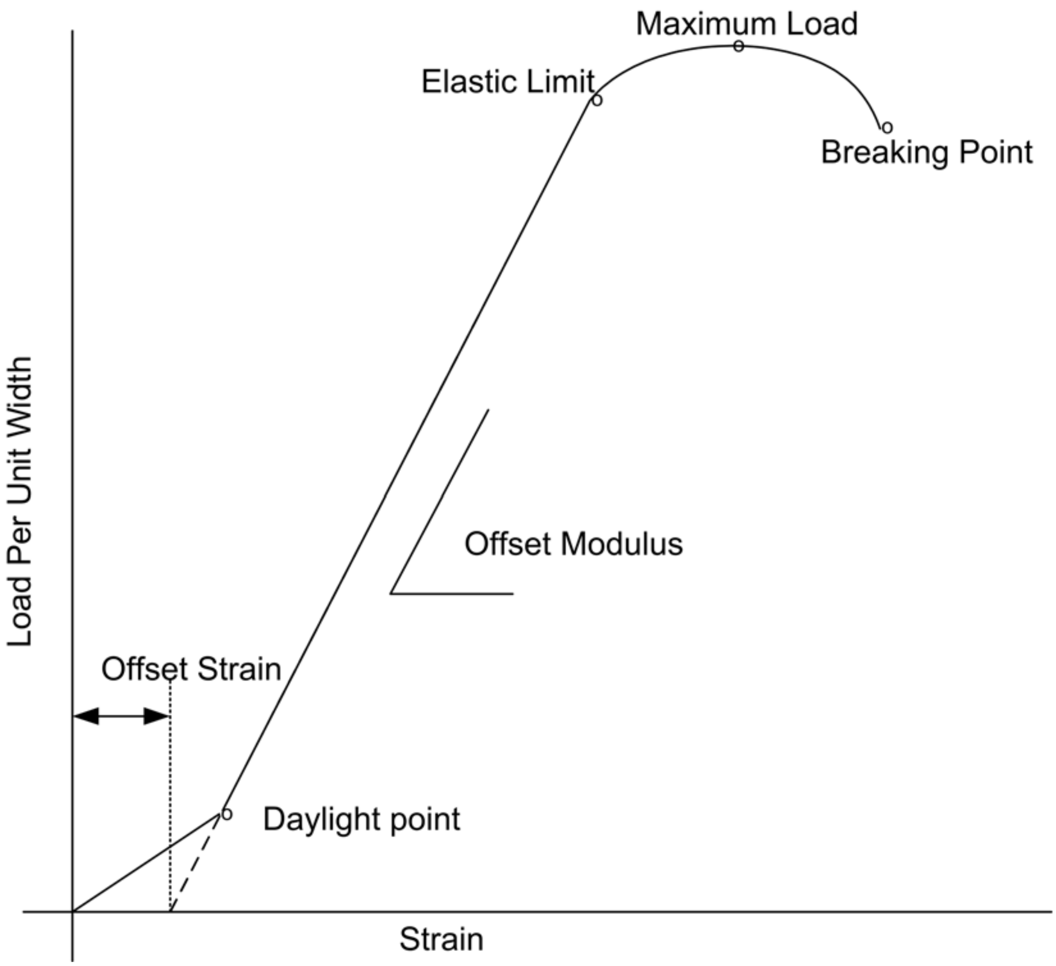

Fig.2.1. Tensile test with a linear range

After the test begins (Shukla 2002), the geotextile strains without loading until it reaches the daylight point (the point where the load extension curve parts from the strain). The offset/working modulus is calculated from the slope of the linear portion of the load-extension data. Offset strain is defined by extending the linear portion of the data back to the zero load line as shown in Fig. 2.1. The unknown strain from the indicated start of the test to the daylight point is eliminated by pre-loading. For geotextiles without a linear range, the modulus is typically defined as the secant modulus at 5 or 10 % strain as shown in the Fig. 2.2.

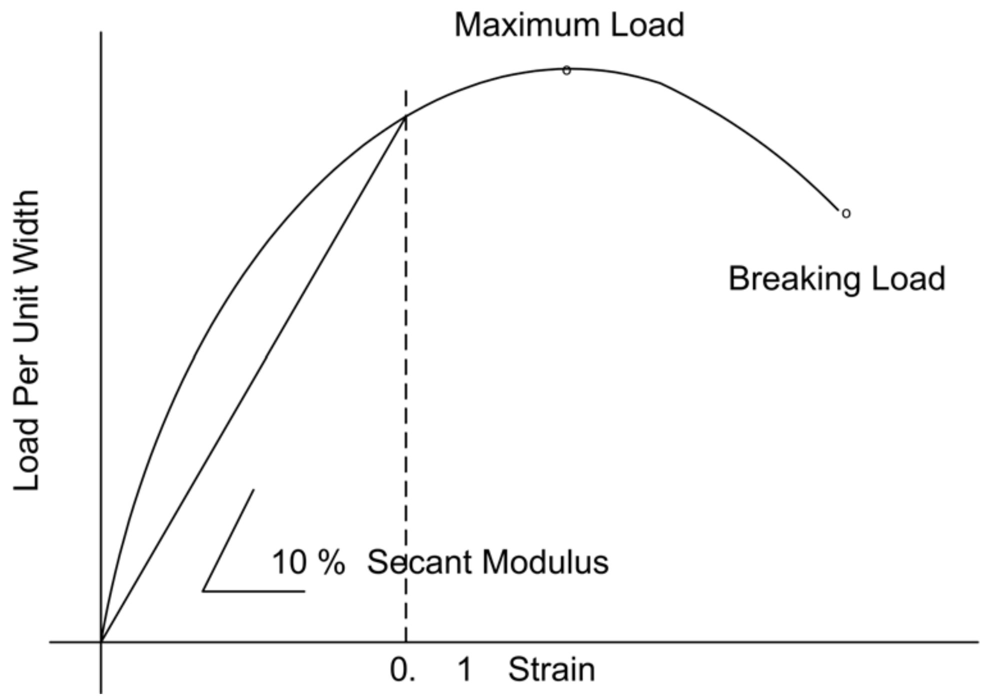

Fig.2.2. Tensile test without a linear range

Mechanically or thermally bonded non-woven geotextiles have the least tensile strength. Geosynthetic confinement within the soil in the field and the resultant interlocking of soil particles with the geosynthetics structure are found to have a significant effect on the stress-strain properties (Shukla 2002). As seen mostly, the modulus of a geosynthetic confined in soil is likely to be higher than when tested in isolation.

Elongation is another property related to the tensile strength. It measures the extent to which a material can be stretched before it breaks (Driver and Kostielney 1997). The appropriate elongation for erosion control product is still being debated. Though certain percentage of elongation is required for the material to be flexible and to conform to the soil surface, too much elongation can allow a material to distort under the pressure of flowing water, heavy rain or unwanted foot traffic, allowing erosion to occur.

American society of testing and materials (ASTM) follows several methods to determine elongation, stretching the material in the tensile testing machine being the basic principle behind it giving elongation factors in two directions, machine and cross.

Tensile strength is determined from the same test procedure as for elongation so that they both can be measured in the same test. In the testing machine, the material breaks after being stretched for a few seconds. The pressure which is applied at the breaking point is recorded and this is the tensile strength of the material.

2.6.4 Stiffness

The stiffness of a RECP is the measure of how much it will deflect under its own weight and the lower the stiffness, the more a product gets flexible making it easy to adapt to the land beneath (Rickson 2002). Thus the lower the stiffness, the more efficiency in the establishment and maintenance of intimate contact with the soil by the blanket increasing its efficiency of erosion control. However, for extremely soft soils, a high stiffness is desirable.

According to Koerner (1994), stiffness or flexibility of a fabric should not be confused with its modulus or the modulus of elasticity which is determined as the initial portion of the stress-versus-strain curve . Stiffness can be measured by its capacity to form a cantilever beam without exceeding a certain amount of downward bending under its own weight (Shukla 2002). Flexibility or stiffness test measures the fabric’s stiffness or resistance to bending (Driver and Kostielney 1997). This test is a measure of the interaction between the fabric weight and fabric stiffness as shown by the way in which a fabric bends under its own weight.

Flexibility is used to evaluate whether a material can conform to the soil surface. If the contact of the erosion product with the soil particles is less than 90%, then the probability of erosion increases (Driver and Kostielney 1997). Flexibility is the stiffness of the material when bent in one plane under the force of gravity. According to Koerner

(1994), to determine it, a fabric strip is slid in a direction parallel to its longer dimension, so that one of its end projects from the edge of a horizontal surface, like a table.

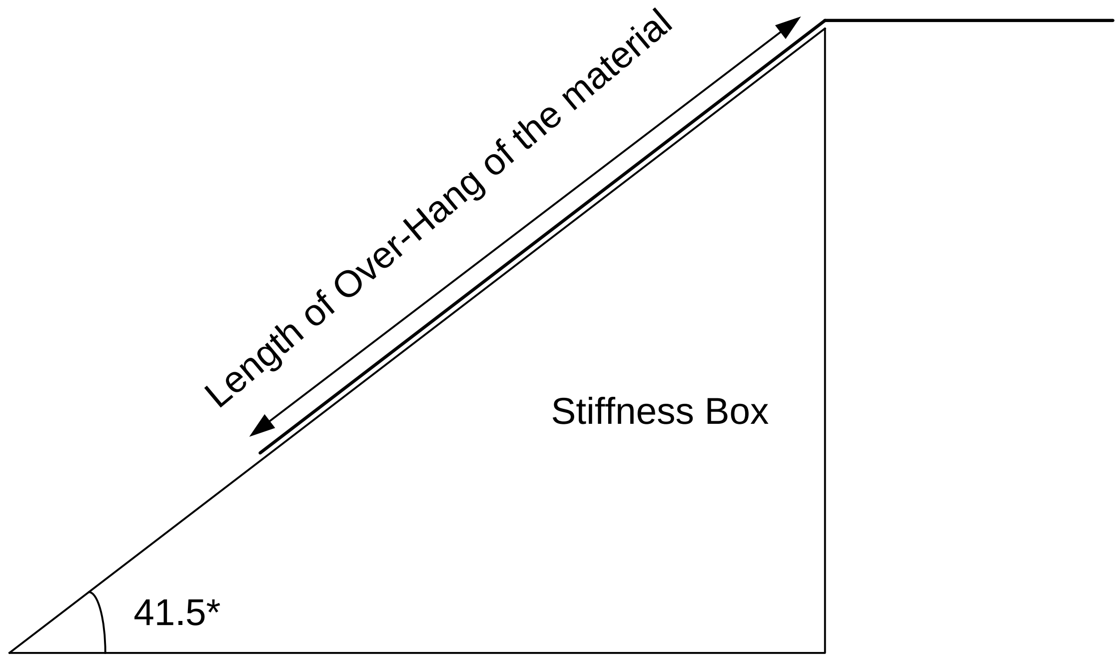

Fig.2.3. Stiffness Test

As shown in Fig. 2.3, the length of the overhang is measured when the tip of the test specimen is depressed under its own weight to the point where the line joining the tip to the edge of the platform makes an angle of 41.5 degrees with the horizontal. One half of this length is the bending length of the specimen. According to Koerner (1994), the cube of this quantity multiplied by the weight per unit area of the fabric is the flexural rigidity. This method which is a preferred method for this test is called the 'cantilever test'. Its test result is stated in mg-cm. The blanket's ability to adapt to the materials beneath it once it is installed is directly related to its flexibility and stiffness. The flexibility rating is given for directions, machine and cross. The higher the flexibility, the better ranked the material will be.

2.6.5 Light Penetration

Light penetration is a property used to quantify the openness of a RECP (Rickson 2002). A light source is placed inside a box on one side of the specimen and the light penetrating through it is measured from the other side. This amount is quantified as a percentage of the amount of light measured, without any specimen, to give a value, which is light penetration. Ground cover is the inverse of light penetration and a balance between these two parameters is necessary for rapid seedling emergence.

It can be understood that denser products have a lower percentage of light penetration than less-denser products (Driver and Kostielney 1997). Since the available light is critical to vegetative germination and growth, and the purpose of the erosion control blanket is to promote adequate vegetation for permanent erosion control, the blanket must be constructed so that adequate light can penetrate the blanket and reach the seeds and plant crowns, and hence higher percentages of light penetration are more desirable than lower percentages.

2.6.6 Resiliency

Resiliency is a measure of impact of cyclic loadings on the thickness of the TRMs. This is relevant to the TRMs' ability to protect the newly developing seed from damage during loading (Rickson 2002). It is described as the erosion control blankets' capacity to spring back into shape in a specified period of time (Driver and Kostielney 1997).

For an efficient three dimensional application of the blanket, a good resiliency value is a desirable factor as after installation; the blankets may be compressed by foot traffic, cows, wild animals or other environmental factors.

2.6.7 Water Absorption

According to Rickson (2002), the significance of water holding capacity for erosion control is because of the effect this parameter has on the weight of the geotextile. As the weight of the product increases due to the wetness, the contact between the geotextile and the soil underneath is enhanced, i.e., their “drapability” with the land increases. This property is very important with respect to erosion control. Natural fiber products have high water holding capacities and can become about five to six times their original weight when wet, however, totally synthetic products have very low water holding capacities and do not gain weight and this may adversely affect their erosion control performance.

Absorptive capacity / water absorption, given by the test in ASTM (D1777) tests the amount of moisture which the erosion control blanket is capable of absorbing (Driver and Kostielney 1997). The erosion control blanket must be able to hold enough moisture for germination and maintenance of seeds and resulting plants, hence the calculation of absorptive capacity helps to choose the blanket also depending upon the type of soil involved, and the average temperatures and wind speeds in the area. Actually, the moisture must be held in the blanket for slow release to the seeds held against the soil beneath the blanket and to growing seedlings once germination has occurred. Without adequate moisture, the seeds will perish, no vegetation will become established, and the channel is once again at risk of eroding and hence higher percentages of water absorption are more desirable than lower ones.

2.6.8 Swell

Swell is a property of the blanket related to water absorption and also resulting from it (Rickson 2002). Swell test (Driver and Kostielney 1997) is similar to the water absorption; where the lower the percentage of swell, the better is the performance. This is because if the blanket swells greatly, the moisture may be at the risk of easily being blown away by the high or dry winds, or of reducing the ability of light to penetrate to assist germination and growth. If the swell is less, the blanket will be able to keep the moisture closer to the soil and the seeds where it is most essential.

2.6.9 Specific Gravity

Specific gravity is the unit weight of the material when compared to that of water (Rickson 2002). It is measured with the procedure in accordance to ASTM D792. It is a property used in a way similar to mass per unit area and thickness when comparing the different TRMs.

2.6.10 Smolder Resistance

Smolder resistance is an evaluation of the organic material's resistance to ignition by a smoldering cigarette (Rickson 2002). It is determined by allowing a cigarette to completely burn on the top of the blanket sample in a fume hood (Driver and Kostielney 1997). This is an issue because degradable erosion control blankets are susceptible to flammability by cigarettes. The distance from the cigarette ashes to the maximum reach of the smolder is measured. Lower numbers are more desirable for this test than the higher numbers because the smolder resistance is higher if these numbers are lower.

Finally, the properties related to longevity can be classified in the table 1.2 with respect to their specific function:

Table 2.2. Index properties (Rickson 2002)

Specific purpose served by the index property	Property related to quality control	General index property
Soil-Protection- Retention	Mass/Area	Stiffness, Light Penetration
Vegetation growth	Thickness	Water absorption, Swell
Stability under flow		Specific gravity
Survivability	Tensile strength	Resiliency, Smolder resistance

The quantification of change in the properties is a good indicator of the longevity properties of the geosynthetics. In a study conducted by Schneider and Groh (1987), it was seen that after nine years of use as erosion protection, polypropylene geotextiles showed 8% loss in strength and 18% loss in elongation.

2.7 Concluding Remarks

2.7.1 Current State of Erosion Control Technology

The erosion control industry is experiencing growth due to the continuously developing technologies. The RECP manufacturers are encouraging the specifiers and designers to use the test data currently available to assist in selecting the best management practice (BMP) for their individual projects. The available results of the various index and performance tests provide a better scope for judgment to decide what could be the longest lasting product for their application (Driver and Kostielney 1997).

The product specified and used, should be able to withstand the stress of installation, provide adequate time for the vegetation to become established, control soil loss, and promote the establishment of vegetation. Ultimately, permanent erosion control is best achieved through permanent vegetation and hence TRMs which are the best supporters of vegetation are being used extensively in this respect.

2.7.2 Need for Study of Longer Lasting Erosion Control Mats

As water quality regulations continue to become more stringent, the demands placed on manufacturers of TRMs or other erosion control geosynthetics and engineers designing the erosion control systems with them, are in transition from a process of qualifying a TRM reinforced vegetative channel lining’s performance to the quantification of how well the reinforced vegetated lining will work and for how long (Nelsen 2005).

There are various design methodologies widely available for designing channels using vegetation or hard armor but these methods provide little information on the use of geosynthetically reinforced vegetation which is slowly becoming the life-line of erosion control. The life of these geosynthetics plays a very important role in this design. Recent development of standardized research methods have also allowed TRM manufacturers the ability to establish quantifiable performance with respect to durability and other hydraulic values for mattings and reinforced vegetation to meet the needs of the engineering community. This data can in turn be used with previously available and accepted design methods to assess the overall effectiveness of reinforced vegetation for erosion control (Nelsen 2005).

The growing recommendations for use of vegetation clearly point out that the progress of erosion control industry is now resting upon the shoulders of a durable TRM or any other erosion control mat which supports the vegetation to a decent extent (Nelsen 2005). Hence the need to conduct the study in this direction cannot be overlooked.

2.7.3 Significance of Longevity Study

The exact prediction of the degradation rates of RECPs in the field is very difficult due to environmental factors such as temperature, moisture, shading, and microbial activity. However, the information grows with the increased use of ECBs and TRMs as more and more material testing is conducted on them and combined with field experience in erosion control; it will lead to the most predictable results.

However, when using ECBs or TRMs, it should be understood that vegetation alone will provide the long-term stabilization. ECBs which are newly installed might temporarily increase the erosion resistance, but after they degrade only the established vegetation will persist as the erosion control mechanism. Thus, except in rare instances vegetation is a key component when designing with these geosynthetic materials. In accordance with the policies of the Clean Water Act, the EPA has already designated

TRMs, vegetated swales and vegetated covers as BMPs and as a result RECPs are in a position to realize a significant increase in utilization as more and more construction site operators seek Phase II compliance (Theisen 2005). Thus the use of blankets which guarantee the development of a healthy and permanent growth of vegetation is becoming compulsory. Now the question is, how does one make sure that a particular erosion control geosynthetic will perform and stand up to its expectations? To investigate this and to probe further in the longevity study of erosion control products to achieve a way of permanent erosion control is the goal of this research and thesis.

CHAPTER III

HYPOTHESIS OF THE STUDY

3.1 Hypothesis

In this study, hypothesis is a discussion of the anticipated alterations which will take place in each and every property of the erosion control geosynthetic product after it has served for a certain time period. Deciding this time period is also a critical issue. By industry standards a product which can survive for 36 months in the field conditions qualifies for the term 'permanent' because this time duration more or less takes care of the minimum time required for any type of vegetation to have a growth sufficient for survival. Hence in this study the time duration of field exposure for the products was 3 years or 36 months. The extensive literature survey done in the previous chapter, Literature Review, provides a guide line for making the hypothesis. A general idea regarding all the factors affecting the materials in-service is given in the Section 2.5, Factors affecting longevity of channel erosion control geosynthetics. The factors which are vital to this study are UV light, temperature variation and water effects in the form of storm water or humidity. Also the continuous use of the material in field takes its toll.

The section 2.6 of Chapter II, regarding the properties related to longevity, and the tests carried out to measure these properties, respectively, provide information about the properties being studied and the kind of testing the products are being subject to. The prediction about the effect of a certain environmental factor with time on a particular index property can be made by an in-depth study of the property and its behavior under certain conditions. It can also be made by a general understanding of the material behavior. Some amount of literature review is also responsible for the reasoning given to speculate the changes in the materials.

3.1.1 Mass per Unit Area

The mass per unit area of a material is the basic property of the geotextile. The effect of UV radiation might be that the polymer chains may break, in turn reducing the weight of the material. Heat and storm water runoff may also induce wear and tear of the fabric and this too may be a factor causing the breaking of the fabric which will ultimately reduce its weight. Some material might be lost after weakening by getting washed away with strong runoff. However, some-times soil and foliage residue might get stuck into the geotextile netting. This can increase the mass per unit area to a large extent. Ultimately the balancing of both these effects might show an outcome that the mass per unit area of the mat would not be affected to a large extent. The null hypothesis is that the mass per unit area will increase after the materials are used for erosion control for the period of 3 years.

3.1.2 Thickness

The thickness is a property which will get affected in a way similar to the mass per unit area of the material. The thickness will increase due to the inclusion of soil and organic material into the netting. However, if there is heavy pressure on the mats in the form of continuous water flow or snow etc, the reduction in thickness might take place as a result of cyclic load effect. As above, these two opposing effects acting on the thickness of the blanket will not be able to bring about a significant change in it as they nullify each other. The null hypothesis is that the thickness will decrease after the materials are used for erosion control for the period of 3 years.

3.1.3 Resiliency

In case of resiliency, the entanglement of soil and vegetation residue in the fiber netting and effect of wear and tear will act in combination to reduce the ability of the material to regain its original shape back. As the mass of the material increases, it cannot spring back in a way similar to its previous ability. The null hypothesis is that the resiliency will increase after the materials are used for erosion control for the period of 3 years.

3.1.4 Stiffness

The stiffness of the material will increase as the mass of the material increases due to the inclusion of the soil and vegetation residue in to it. Also the effect of high temperature and sun's direct rays will harden the material to a substantial extent. This will reduce the flexibility of the material and it won't be able to conform to the land beneath it. The null hypothesis is that the stiffness will decrease after the materials are used for erosion control for the period of 3 years.

3.1.5 Tensile Strength

This is the property which will be affected to the maximum extent due to environmental effects and prolonged use. The tensile strength of the material is the most important property because if the strength is reduced, or the applied load exceeds it, the material will go on breaking and finally, there will be no material at all, resulting in absence of erosion control. Other properties may change the physical appearance of the blanket but tensile strength is the key for the structural survival of the material.

As described in the literature review chapter, the environmental factors, especially UV radiation will weaken the polymer bonds in the material making it brittle; while the heavy runoff flow on the material can induce high stress conditions in the fabric. Temperature variation will also act in the same way. In fact, high and low extremes in case of the temperature can be very harmful as the material expands to a minute degree due to continuous heat during day time and then becomes cool again at night. The entanglement of foliage residue and soil in the fibers will not bring about a significant change in the tensile strength. The null hypothesis is that the tensile strength will increase after the materials are used for erosion control for the period of 3 years.

3.1.6 Specific Gravity and Density

The specific gravity of material is the unit weight of the material when compared to that of water. It will increase with time just as in case of mass per unit area and thickness because of the inclusion of the soil and organic residue into it. The density will also increase in the same way. The null hypothesis is that the specific gravity and density will decrease after the materials are used for erosion control for the period of 3 years.

3.1.7 Water Absorption

The water absorption capacity of the material should increase with time. This is because as the material weakens due to all the environmental factors it becomes softer. Also, the vegetation supported by the blanket forms a synergetic mesh with it. This is more porous than the way the blanket is, just at the time of installation. The null hypothesis is that the water absorption will decrease after the materials are used for erosion control for the period of 3 years.

3.1.8 Swell

The swell behaves in a way similar to the water absorption. Hence it should increase due to prolonged use. The null hypothesis is that the swell will decrease after the materials are used for erosion control for the period of 3 years.

3.1.9 Light Penetration

The light penetration will increase with the time. The following are the reasons:

1. Some of the material after weakening or breaking of bonds might get washed away with the heavy storm runoff.
2. The vegetation which develops when the protection is being provided by the mat, will increase with time and exert force on the netting increasing the open space. This is also useful for the further growth of the vegetation because sunlight is essential for the growth of plants.
3. The material expands a bit due to mechanical wear and tear and also due to continuous exposure to heat; this may increase the light penetration to a small extent.

The null hypothesis is that the light penetration will decrease after the materials are used for erosion control for the period of 3 years.

3.1.10 Smolder Resistance

The parameter used to measure this property is smolder area. The smolder resistance will decrease with time because the weakening of material and decrease in its strength will make it more susceptible to the heat energy it is exposed to, during the smolder test which mean the smolder area will increase. However, there is near to impossible chance of the material catching fire when continued to being used in the field. The null hypothesis is that the smolder area will decrease after the materials are used for erosion control for the period of 3 years.

Thus, as seen above, the hypothesis will serve as a torch light for a parallel comparison when the results are discussed and prove a gauging tool to guide if the research is going in the right direction.

3.2 Need for the Proposed Research

3.2.1 Current Scenario

As described previously, the government regulations regarding the storm water runoff are getting more stringent with time. Rigorous action also needs to be taken regarding the safe-guard of the useful soil cover which gets washed away with the storm water runoff. The development in the erosion control industry is phenomenal. The contractors and land developers are realizing the undeniable importance of geosynthetic blankets in general and TRMs in particular.

As described in the literature review chapter, environmentally-friendly application possibility coupled with reduced cost separates this TRM/geosynthetic blanket technology from traditional methods of erosion control placing it at the top in the users' choice. But the question is, is this trend of growing reliability on the erosion control blankets a positive step towards our ultimate aim of achieving permanent erosion control? How long can these mats provide protection, is the issue this whole matter that needs to be addressed.

3.2.2 Need for This Research

The manufacturers of TRMs insist that their products do provide long term protection. Some-times even permanent protection is guaranteed. This is based on the fact that the blankets will ultimately lead a way to vegetation growth, which is by and large a permanent solution to erosion. But then what is the need to conduct a research regarding the life duration of these products?

The reason is that if the products are not going to last for a fair amount of time, the assurance that they will at least survive or remain in place till the growth of vegetation gets started becomes critical. The blankets are not harming the environment in any way and hence there is no problem if they continue to exist even for ever, so the longer they last, the greater is the chance that the vegetation develops.

The manufacturers of erosion control blanket mostly affirm their products to exist for duration of 36 months or 3 years. This duration by and large covers the initiation, growth and full-fledged development of any kind of vegetation. But only survival of erosion control blanket is of no consequence. What is required is that the properties of the blankets do not get changed to such an extent that they are no longer able to perform their expected role.

3.2.3 Problem Statement

The problem statement describes the basic question which prompted the study or the reason for the research. ECBs, TRMs and other materials related to geosynthetics being applied for soil conservation are all artificial ways and cannot replace the natural method of protection by vegetation. However, the efforts to achieve maximum possible protection from these mats never cease. Hence it is detrimental that the properties of the materials do not deviate in large magnitudes so that the mats keep functioning in a consistent manner.

The research goal here is to find out how much the index properties of the blankets will be modified after their use for a standard time period of 36 months, i.e., 3 years. This will provide an insight into whether these materials are fit for use in the first place and if yes what are the possible aspects of their application in light of our ultimate aim to establish long lasting erosion control. The index tests have to be carried out on the products exposed to the environmental degradation and real-time use in field for the earlier specified duration. For the sake of standard or best possible results which will be used for comparison, tests should also be carried out on unused or new products. The statistical analysis of the results of tests on both used and unused blankets will present a better picture of whether the products testify the claims made by the manufacturers and what is their credibility after being used for the standard period of time.

This analysis of index properties will also help in finding which property is most vulnerable to the environmental and aging effects and what kind of product is affected the most which can ultimately help in selecting the most surviving and reliable material within the arena of this study. Thus the research need is justified and will provide a better panorama of the erosion control industry.

CHAPTER IV

METHODOLOGY

4.1 Materials

The materials selected for study here are a specimen of each type of product available currently in the market. These materials represent the industry trends at large.

4.1.1 Classification of Materials Used in This Study

The classification and general description of the materials used in this study is as follows:

4.1.1.1 Natural Geotextiles

These are made of natural materials, such as coconut, jute, straw, mulches, jute fibers and wood/excelsior blankets. These materials are biodegradable and cannot be expected to last longer. However, they can be applied where the erosion control mats are not required to remain in place permanently and vegetation is expected to grow and take over the erosion control role after the material is degraded

These blankets get completely eliminated in long term and if vegetation does not develop before they disappear, erosion may start again. But they have an advantage of being low cost and environmentally-friendly with easy installation. Hence they are preferred over other types in local areas and small scale projects. It is very essential to know their survival period because if they are not going to promote vegetation growth during their service period, they do not satisfy the need of long lasting erosion control and installing them time and again is not an economical or reliable practice.

In this study, natural materials used for testing are Enviromat and Greenfix CFO 72 RR. Their specifications and information is given in the next section.

4.1.1.2 Synthetic Geotextiles

As explained earlier, synthetic blankets are not environmentally-friendly and though they would remain in place for a long time if installed correctly, they do not interact with the environmental components. Though this is good when the effects of environmental factors such as UV radiation, heat and storm water are considered, there are negative aspects to their use. The blankets may not support vegetation growth. Resultantly, there might be no formation of root-geotextile matrix, the soil will not be held in the netting and as water runs off over the blanket, the mat's role may be as good as that of an impervious surface.

The above description may suggest that there is no longevity study required for these blankets, however, actually there are other features which are significantly involved with the durability. What is the exact state of the materials after their use for the standard time period of 3 years and can they be reused? What is the change in the tensile strength of the blankets (this is related to the scission of polymer chains by the UV radiation)? These and other aspects are discussed in the Chapter VI Results, Analysis and Discussion.

The synthetic products used here are Enkamat Composite NPK and Landlok TRM 1060. The chemical structure of the polymers forming these blankets and other information regarding them is given in the next section.

4.1.1.3 Composite Geotextiles

TRMs, which are a form of composite geotextiles are the best possible available geotextiles as of now for erosion control and their use is dependent to a large extent on the time period of their survival. Thus their longevity becomes a critical factor for their efficiency. Whether these materials will function adequately till the vegetation grows is the consideration here.

The composite materials tested in this study are PP5-XCEL, Curlex HD and NAG S-350 and they are detailed in the next section.

4.2 Specifications of Materials

All materials are introduced by their manufacturer, availability, raw material, blanket structure, description, color, properties and application, as well as the references cited. Photographs of fresh materials are also presented for each product.

4.2.1 Natural Geotextiles

4.2.1.1 Enviromat

Fig.4.1. Enviromat

Manufacturer: Enviromat

Availability: No (discontinued)

Raw material: Excelsior

Blanket: Basically fiber structure

Description: Natural soft textured geotextile, very thin excelsior filaments compressed into mat form

Color: Light brown

Properties: The manufacturer claims that it is completely bio-degradable, promotes vegetation and then merges with the soil forming environment-friendly organic residue. Low cost and easy installation

Application: Short term erosion control in channels and slopes, allows vegetation growth, not reliable for long-lasting erosion control by itself unless vegetation develops in the stipulated duration

4.2.2 Purely Synthetic Geotextiles

4.2.2.1 Landlok TRM 1060

Fig.4.2. Landlok TRM 1060

Manufacturer: Synthetic Industries

Availability: Yes

Raw material: Polypropylene fibers

Blanket: Loose structure, heavier weight for long-term ground cover and erosion protection

Description: Consists of a lofty, three dimensional web of black polypropylene fibers positioned between two high-strength, bi-axially oriented nets mechanically bound together by polypropylene stitching to form a dimensionally stable matrix.

Color: Black

Properties: The manufacturer claims that it is uniquely designed for demanding conditions in which soil-filling is specified for maximum performance

Application: It has sufficient thickness and void space, balanced with optimal ground cover, to allow soil filling and/or retention as well as emergence of plants from beneath or within the matrix, may be filled with soil for maximum stability and even quicker vegetation growth

References: Permathene Website (2005) and SI Geo-solutions Website (2005)

4.2.2.2 PP5 XCEL

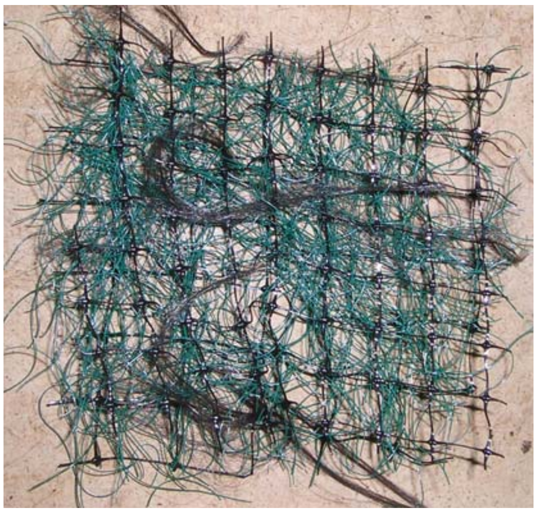

Fig.4.3. PP5 XCEL

Manufacturer: Western Excelsior

Availability: Yes

Raw material: Polypropylene

Blanket: The blanket structure consists of green polypropylene fibers loosely held in place by black polypropylene nest on the top and bottom. As the fibers are loosely held, the blanket needs careful application so that the inside fibers are not lost

Description: It is composed of 100% synthetic products, a matrix of green polypropylene fibers is mechanically (stitch) bound between two UV stabilized heavy duty synthetic nets, stitching is secured on two inch centers using UV stabilized heavy duty polypropylene thread

Color: Black nets and green fibers

Properties: PP5 XCEL provides sufficient thickness and durability to yield functional longevity greater than three years

Application: PP5 is intended to provide immediate erosion control and long term turf reinforcement for the more severe slope and channelized applications

Reference: Western Excelsior Website (2005)

4.2.3 Composite Geotextiles

4.2.3.1 Green Fix CFO 72 RR

Fig.4.4. Greenfix CFO 72 RR

Manufacturer: Greenfix America LLC.

Availability: Yes

Raw material: Coconut/coir, Cotton polyester/polypropylene

Blanket: 100% natural coconut fibers evenly distributed over the entire area with a heavy weight cotton polyester/polypropylene photodegradable top and bottom net on 1.5 inch centers i.e. fibers inside the netting

Description: 0.5 lbs/square yard coconut fiber mats, light weight erosion control blankets

Color: Brownish with dark brown netting on top and bottom

Properties: Bio-degradable, ‘manufacturer claimed life duration’-36 months

Application: The manufacturer claims that it prevents soil loss by temporarily stabilizing and protecting disturbed soil from raindrop impact and surface erosion, to increase infiltration, decrease compaction, soil crusting and to conserve soil moisture, promote vegetation establishment for a permanent erosion control

Reference: Greenfix America Website (2005)

4.2.3.2 Enkamat Composite NPK

(a) (b)

Fig.4.5 (a) Front side of Enkamat NPK and (b) Back side of Enkamat NPK

Manufacturer: Colbond Geosynthetics

Availability: No (discontinued)

Raw material: Polyamide fibers, polypropylene, wood fibers (excelsior)

Blanket: Thick blanket made of uniformly distributed excelsior fibers with polyamide filaments forming a net on one side and polypropylene on other.

Description: Dense and thicker as compared to other products

Color: Brown with black and brown netting

Properties: Manufacturers claim that it supplements nature's own erosion control system by reinforcing plant roots, the excelsior component gives way to the plant after some time while the polymer component stays to strengthen the plant growth

Application: It is mainly used for erosion control in areas with heavy water-flow and steep slopes. Manufacturers claim that Enkamat's tough root-reinforcing system anchors vegetation and protects against hydraulic lift and shear forces created by high-volume discharges

Reference: Colbond Inc. website (2005)

4.2.3.3 Curlex HD

Fig.4.6. Curlex HD

Manufacturer: American Excelsior Company

Availability: Yes

Raw material: Aspen excelsior wood fibers inside the netting, Polypropylene net

Blanket: According to the manufacturers "Heavy duty excelsior Blankets are available in various fiber weights and netting combinations to match the appropriate job site requirements. Eighty percent of the Curlex fibers are six-inches or longer with consistent thickness and are evenly distributed over its entire area. Both the top and bottom side of the blankets are covered with black, heavy-duty, extruded plastic mesh designed to provide strength beyond the service life of standard blankets. Excelsior blankets do not contain any chemical additives, weed seed, or foreign matter."

Description: Curlex blankets are made of unique softly barbed, interlocking, curled, Aspen excelsior fibers. As the length and thickness of fibers is more than the usual found in other brands of blankets, the blanket is not compact and appears uneven

Color: Light green fibers

Properties: Manufacturers claim that curlex excelsior blankets are specifically designed to promote ideal growing conditions for grass seed, while simultaneously protecting topsoil from wind and water erosion. Curlex blankets are designed such that they have a built-in swell factor so that the wet curled excelsior fibers slightly expand in thickness and interlock to form a strong, fiber matrix which allows the fibers to provide intimate contact with local terrain. The roughness of the curled excelsior matrix causes the velocity to slow down to a point where gravity takes over, which allows moisture to slowly seep into the topsoil to promote ideal growing conditions

Application: Manufacturers claim that these blankets have a high range of application right from highway embankments, ditch bottoms and slopes, bridges, approaches and medians, residential, commercial, & industrial developments, urban drainage, stream banks, and waterways, golf course fairways, roughs, waterways, & drop structures, landfill caps, side slopes, and let down structures, pipeline right-of-ways, etc

Reference: Curlex website (2005)

4.2.3.4 NAG-S 350

Fig.4.7. NAG S 350

Manufacturer: North American Green

Availability: Yes (North American Green S350 is currently marketed under the trade name SC250)

Raw material: straw/coconut fiber, polypropylene

Blanket: The blanket consists of straw/coconut fiber matrix which consists of 70% straw and 30% coconut loosely held inside two black UV stabilized polypropylene nets which have an approximate weight of 5lbs/1000ft^2. Also there is one more net inside the blanket between the top net and the straw/coconut matrix which has an approximate weight of 24lbs/1000ft^2. Thus effectively there are four layers in the blanket, three consisting of polypropylene nets and one of straw/coconut matrix

Description: As stated above, it consists of a permanent, high strength three-dimensional matting structure incorporated with a straw/coconut fiber matrix.

Color: brownish yellow inside matrix, black nets

Properties: The manufacturers claim that straw/coconut fiber matrix in the blanket enhances its initial mulching and erosion control performance for up to 24 months. They also claim that it is proven in laboratory and field research that the permanent matting's high strength 3-D structure increases the shear resistance of vegetation up to 10 lbs / ft^2 (480 Pa)

Application: It is designed to provide extended term, pre-vegetated erosion protection and permanent turf reinforcement in a wide variety of applications, including severe slopes, high flow channels and stream banks

Reference: North American Green website (2005)

4.3 Testing Methods

The unused materials are either new ones (for those brands which are still available in the market) or those which have been stored indoors since a long time but not put to use (for those brands which are no more available in the market). The procedures for the index tests which are conducted in the Hydraulics, Sedimentation and

Erosion Control Laboratory (HSECL) of the Texas Transport Institute are described below.

4.3.1 Preparation of Materials for the Index Tests

The materials are in the form of rolls of blankets and need to be cut and preconditioned before the index tests can be performed on them. The RECPs undergo the following procedure before they are ready for the index tests.

4.3.1.1 Sampling of RECPS

RECPS are available in the market in different sizes. Also there are different sizes of specimens that must be cut for different tests and the various sized specimens have different cutting requirements. All specimens are selected from random locations on the product roll. Care is taken to ensure that the same numbers of woven fibers, threads, etc. are used in each of the specimen sets. The following is the standard way of cutting each sized specimen.

- **4"x 4":** These specimens are cut using a standard hydraulic shop Press (HSECL press is an Arcan 20 ton press, model SP-20). Twenty-five different 4"x 4" specimens are cut for the various index tests. Specimens are cut using a 4"x 4" die (manufactured by BT Technology). The die is placed on the RECP and then pressure is exerted on the product using the shop press until the material has been cut. Each specimen is cut by this process.
- **4"x 6":** These specimens are cut with the method similar to the one used for the 4"x 4" specimens except a 4"x 6" die is used in place of the smaller die. Eight 4"x 6"specimens are cut in the cross direction and five in the machine direction.
- **4"x 18":** These specimens are cut using a template of size 4"x 18" and the specimens are cut the size of the template using scissors, shears, or paper cutter.

Four specimens are cut in the cross direction and 4 are cut in the machine direction.

- **8”x 8”:** Three 8” x 8” specimens are required for the index tests which are cut using the hydraulic press and an 8”x 8” die manufactured.
- **11.5”x 11.5”:** Three specimens are hand cut using an 11.5” X 11.5” template
- **12”x 12”:** Three specimens are hand cut using a 12”x12” template.

4.3.1.2 Machine and Cross Direction

The 4” x 6” and 4” x 18” specimens are cut in a machine and cross direction. A cut in the machine direction is such that the long dimension of the cut faces the open end of the roll as it was machined by the manufacturer. In a cross direction cut, the long dimension of the cut faces the cross section or sides of the roll in a direction perpendicular to the open machined end of the roll.

4.3.2 Pre-conditioning of Materials

The temperature and humidity are controlled and the specimen is kept there for some required time, this is known as the pre-conditioning of materials. The preconditioning times and temperatures are set in accordance with the ASTM standard for each index test. The table 4.1 shows the preconditioning temperature and humidity level required for each test and the time for which the cut specimens have to be placed in this atmosphere

Table 4.1. Preconditioning temperature and humidity level required for each test [a]

Roll Products Tests	Hours	Humidity (%)	Temperature (ºC)
Thickness	24	60 (+/-10)	21 (+/-2)
Mass per Unit Area	24	65(+/-5)	21 (+/-2)
Resiliency	24	65(+/-5)	21 (+/-2)

Table 4.1 Continued

Roll Products Tests	Hours	Humidity (%)	Temperature (ºC)
Tensile Properties	24	65(+/-5)	21 (+/-2)
Stiffness	24	65(+/-5)	21 (+/-2)
Light Penetration	24	65(+/-5)	21 (+/-2)
Water Absorption	24	65(+/-5)	21 (+/-2)
Swell	24	65(+/-5)	20 (+/-2)
Specific Gravity & Density	40	50 (+/-5)	23 (+/-2)
Smolder	12	N/A	45
Smolder (after first time period)	2	65(+/-5)	21 (+/-2)

[a] Adopted from HSECL, Texas Transport Institute, College Station, TX

After placing the materials in the specified environment for the required period, the specimens are tested according to the procedures required for the specified test.

4.4 Description of Index Tests on Erosion Control Products

The following is the description of the index tests performed on the preconditioned material specimens:

4.4.1 Mass per Unit Area Index Test

Mass per unit area index test is performed in accordance with ASTM D5261. The following is the equipment and procedure used for it:

Equipment: The mass per unit area of the specimen is determined using a standard platform laboratory scale that weighs in metric units. A Sartorius model LP6200S laboratory scale is used during the tests for this particular research.

Procedure: The specimens used for this test are the same as the ones used for the thickness index test and the resiliency index test. To start with, the scale is zeroed out and specimen 1 is placed on the scale in order to determine and record its mass in grams. Then each of the other specimens is weighed in the same manner as specimen 1. After recording the mass of each specimen the mass per unit area in grams/meter^2 is calculated according to the following formula:

$$Mass\ per\ unit\ area = \frac{Mass\ of\ specimen \times 1000000}{specimen\ area} \tag{4 a}$$

As all the specimens are of size 4” x 4”, the specimen area is constant. The area when converted to square millimeters is 10322.56 mm^2, thus the calculation is:

$$Mass\ per\ unit\ area\ (g/m^2) = \frac{Mass\ of\ specimen\ (g) \times 1000000}{10322.56\ mm^2} \tag{4 b}$$

The average mass per unit area and the standard deviation are calculated and reported after repeating the test procedure for all the specimens. Care is taken to ensure that the specimens are numbered correctly, tested in order, and not mixed up. It is very important to do so since the same specimens used for this test will be used for the thickness and resiliency tests.

4.4.2 Thickness Index Test

Thickness index test is performed in accordance with ASTM D5199. The following is the equipment and procedure used for it.

Equipment: The thickness of twelve 4”x 4” specimens of a rolled erosion control product is determined using a BT technology thickness gauge.

Procedure: The thickness gauge is set to measure the thickness in millimeters. Prior to the testing, it is zeroed out while resting on the aluminum slide plate which is the base plate used to keep the specimens on after the test starts. The test is conducted by placing a specimen on the aluminum slide plate while the thickness gauge is in the raised position. The thickness gauge is then allowed to descend slowly under its own weight until it makes contact with the specimen and after 3-4 seconds of contact with the specimen the thickness is read off of the gauge and recorded.

This procedure is repeated for each specimen until all twelve have been tested and the results have been recorded. The machine is zeroed out prior to measuring each specimen. Care is taken to ensure that the specimens are numbered correctly, tested in order, and not mixed up. It very important to do so as these same specimens are used for the resiliency and mass per unit area tests. Mostly a mark with a permanent marker or white out is placed on the top right corner of the specimen to insure that when measuring the final thickness after the resiliency test, the specimen is placed in the same manner as it was when determining initial thickness. Each specimen is placed on the center of the aluminum slide plate, so that the thickness is read from the center of the 4”x 4” specimen. After recording the thickness for each specimen, the average thickness is calculated and the standard deviation is determined.

4.4.3 Resiliency Index Test

Resiliency index test is performed in accordance with ASTM 5199. The following is the equipment and procedure used for the same.

Equipment: A BT Technology Thickness gauge and a BT Technology Resiliency Press are used to measure the resiliency in this Index Test.

Procedure: Prior to the resiliency test, the same twelve 4”x 4” specimens are used for the thickness index test and the mass per unit area test. These two tests need to be completed before performing the resiliency test on these specimens. The specimen thickness from the thickness index test results are used in this test as the initial thickness taking care that the specimens are numbered correctly, tested in order, and not mixed up from the previous tests. After the initial thickness is recorded the specimens are operated by the resiliency press which subjects each specimen to a cycle of loading under pressure for 1 minute and then applying no pressure for one minute. This cycle is repeated until three one minute pressure and three one minute no pressure periods have been applied to the specimen. The first specimen is placed in the center of the aluminum slide plate on the resiliency press and the resiliency press regulator box and air compressor are turned on. After the air compressor builds full pressure and shuts of automatically, the pressure valve is turned to the on position. After doing this, the machine begins to build pressure and the pressure plate on the resiliency press slowly begins to descend. When the pressure plate makes full contact with the specimen, the one minute time period begins. The pressure readout is 100 psi and this pressure is maintained for 1 minute. After the one minute time period the pressure valve is turned to the off position and the pressure plate immediately rises above from over the specimen. The pressure plate is left in the raised position for 43 seconds, and at 43 seconds the pressure valve is turned again to the on position. After turning the valve to the on position, the machine will build pressure and the pressure plate will again began to descend towards the specimen. It takes exactly 17 seconds from the time the valve is turned on until the pressure plate makes contact with the specimen; therefore the total time in the raised position is 1 minute.

The one minute up, one minute down procedure listed above is repeated until three pressure periods have been applied to the specimen. After this, the specimen is allowed to recover for 30 minutes at room temperature and the final thickness of the specimen is measured using the procedure described for the thickness index test. The above Procedure is repeated for each of the twelve specimens. After the Resiliency test is completed for all the specimens, the average initial thickness, average final thickness, percent recovery for each specimen, average percent recovery and the standard deviation for percent recovery are calculated and reported.

4.4.4 Stiffness Index Test

Stiffness index test is performed in accordance with ASTM D1388. The following is the equipment and procedure used for the same.

Equipment: A stiffness testing box with a 41.5 degree ramp is used for this test. It is used along with a steel weight that is heavy enough to provide good contact with the material, but will allow the material to slide easily at a steady rate.

Procedure: To start with, the mass of each of the 8 specimens is measured and recorded. First machine direction specimen is placed on the flat surface on top of the stiffness testing box with one of the narrow ends facing the ramp, where one of the 4 inch ends will travel down the ramp first. This is considered to be the front edge of the specimen. The steel weight is then placed on the rear portion of the specimen and the specimen is slid smoothly towards the ramp at a rate of 4.75 inches per minute +/- 5 %. The specimen is slid smoothly at this rate until the leading edge of the specimen bends and touches the ramp surface. The overhang length on the ruler provided on the ramp surface is recorded.

Then the specimen is placed back onto the stiffness testing box with its top side still facing up, and the specimen is turned to where the rear narrow (4 inch) edge is now facing the ramp. Then the specimen is tested in the same manner as shown in the previous paragraph and the overhang length is recorded again. Then the specimen is turned over to where its bottom side is now facing up and the front and back of the bottom side are tested according to the procedure shown above. Thus, overall there are four readings per specimen, top/front, top/back, bottom/front, and bottom/back. After obtaining these 4 readings, the entire testing procedure is repeated for each of the remaining machine direction specimens and all of the cross direction specimens. By determining the overhang lengths for each of the specimens, the mass per unit area, bending length, and flexural rigidity are easily calculated according to the following formulas:

$$Mass\ per\ unit\ area\ (mg/cm^2) = \frac{Mass \times 1000}{area\ of\ specimen} \tag{5}$$

As all the specimens are 4” x 18”, the specimen area is constant. Area converted to square centimeters is 464.5152 cm^2, hence the calculation is:

$$Mass\ per\ unit\ area\ (mg/cm^2) = \frac{Mass\ of\ specimen\ (g) \times 1000}{464.5152\ cm^2} \tag{6}$$

$$Bending\ Length = \frac{Length\ of\ overhang}{2} \tag{7}$$

$$Flexural\ Rigidity = Mass\ per\ unit\ area \times (bending\ length)^3 \tag{8}$$

In the end, the average and standard deviation for the bending length and flexural rigidity in both machine and cross direction are calculated and reported.

4.4.5 Tensile Index Test

Tensile index test is performed in accordance with ASTM 5035-95. The following is the equipment and procedure used for the same.

Equipment: A Comten Industries C-TAP model PSB 1000 tensile test machine equipped with a 1000 lb load cell is used. The C-TAP machine is connected to a personal computer in which C-TAP software is installed in order to read and record the data obtained from the test stand.

Procedure: Before starting the test, the equipment is turned on and it is made sure that the C-TAP machine and computer are working properly and that the test parameters for the tensile test are set properly, in accordance with the instructions provided in the Comten industries C-TAP software manual. The following are the general parameters of the tensile test: force limit = 1000 lbs, deflection limit = 40.0 inches, real time data = plot, auto analyze = on, raw data = save, auto results = on. The test specific configuration is as follows: gauge length = 3.00”, width/diameter = 1.00”, cross section area = 1.00”, thickness = 1.00”. Eight 4” x 6” cross direction specimens and five 4” x 6” machine direction specimens are placed near the testing machine. The first cross direction specimen is placed in the clamps of the tensile test stand with its long (6 inch) sides vertical and its narrow (4 inch) sides placed horizontally in the clamps. The specimen is centered in the two clamps where there is an equal amount of specimen being clamped by the top clamp, and an equal amount clamped by the bottom clamp. The clamps are tightened securely making sure that the specimen is held tight and that the specimen is taut between the two clamps. After securing the specimen, the product name, number and specimen direction in the box provided in the computer software for the test. Current temperature and humidity are recorded in the configuration panel and saved. The temperature and humidity are now stored and for the subsequent specimens, only the product name, number and specimen direction are to be entered in the main panel. The tensile test is started by clicking on the START button. After a few seconds, the tensile machine begins to stretch the specimen and collects real time data as to the tensile strength of the specimen. The testing machine stretches the specimen at a slow steady rate until the product breaks, or reaches peak tensile strength without breaking and then falls to 5 % of the peak force. When this occurs, the test automatically stops and the top clamp begins to descend in preparation for the next test. The real time data collection automatically stops when the test stops and the computer screen displays the data in a table and also plots it on a graph. The values for the peak tensile force and the relative % elongation are recorded on the tensile test form and then the data is saved to the appropriate file on the computer. The test is continued with the next specimen following the same method listed above, until all of the specimens have been tested. The average and standard deviation values for the tensile strength and percentage relative elongation for the cross and machine directions are calculated and reported.

4.4.6 Specific Gravity and Density Index Test

This test is conducted in accordance with ASTM D792. The following is the equipment and procedure used for the same.

Equipment: A standard laboratory scale, test clip with wire and weights, specific gravity platform, and de-ionized water are used for this test.

Procedure: Firstly, the two 4” x 4” specimens are weighed on the laboratory scale and their weights are recorded. The specific gravity platform is then placed under the bottom of the scale and the scale is re-leveled to ensure accurate weight readings. After placing the platform under the scale, a 1000 ml beaker is filled with approximately 875-900 ml of de-ionized water. The beaker is placed on the scale directly underneath the hook on the specific gravity platform and the scale is tared out to where the reading is 0.00 grams.

A test clip is then connected to a small wire which holds the standard lead weights whose number varies depending on the amount of weight required to submerse a particular erosion control product. After attaching the test clip to the wire equipped with the lead weights, part of the test clip and the wire with weights are submerged in the de-ionized water and the top of the test clip is attached to the hook on the specific gravity platform. The mass of the suspended wire (with test clip and sinkers) is then recorded. After that the test clip, wire and weights are dried off with a clean rag or towel.

The specimen is then attached to the clip by holding the wire and weights in the center of the specimen, folding the sides of the specimen up around the wire and then clamping the sides of the specimen with the test clip. After that the scale is tarred and the specimen is quickly submerged in the de-ionized water with the test clip being submerged to the same level as before. The top part of the test clip is quickly attached to the hook on the specific gravity platform and the mass of the suspended specimen is instantly recorded. After recording the weight of the suspended specimen, it is removed from the water and discarded. The procedure is repeated for the other specimen. The specific gravity and density are then calculated using the following formulas:

$$Specific\ Gravity = \frac{Dry\ Specimen\ Mass}{(Dry\ Specimen\ Mass + \ Suspended\ Wire\ and\ Sinkers\ Mass - Suspended\ Specimen\ Mass)} \tag{9}$$

$$Density = Specific\ gravity \times 997.6 \tag{10}$$

The average and standard deviation for specific gravity and density are calculated and reported.

4.4.7 Water Absorption Index Test

This procedure is done in accordance with ASTM D1117. The following is the equipment and procedure used for the same.

Equipment: Standard laboratory scale, de-ionized water, and water absorption index test screens are used for this test.

Procedure: Three 8”x 8” specimens are weighed on the laboratory scale and their initial specimen mass in grams is determined. The water absorption index test screens are submersed in de-ionized water and soaked for a minimum of 1 hour in de-ionized water immediately prior to the test. After 1 hour they are removed and allowed to drip dry horizontally for 10 minutes following which the initial mass of each screen is recorded. The three specimens are placed in the water absorption index test screens after that. Each of the screens is labeled with a number and the corresponding specimen is matched to the appropriate test screen. Then each of the screens along with the specimen in it is placed in a vessel containing de-ionized water. The depth of the water is kept adequate to fully submerse each screen and about 1 to 1.5 inches of water is allowed above the top surface of the screens. The time each specimen was placed in the water and the starting water temperature are recorded. The specimens are allowed to soak for a period of 24 hours +/- 15 minutes. After the soaking period, the specimens are removed from the de-ionized water and the time when they are taken out of the water and the ending water temperature are recorded. The specimens are placed on aluminum bars above the water vessels and are allowed to drip dry in a horizontal position for 10 minutes. Finally the total mass of the screens along with the specimens in them is determined for each specimen and is recorded as final total mass.

$$Final\ Specimen\ Mass = Final\ total\ mass - Initial\ screens\ mass \tag{11}$$

$$Total\ amount\ of\ water\ absorbed = Final\ Specimen\ Mass - Initial\ Specimen\ Mass \tag{12}$$

$$Absorption\ Capacity = \frac{Total\ amount\ of\ water\ absorbed}{Initial\ Specimen\ Mass} \tag{13}$$

By using the above formulas, the absorption capacity and total amount of water absorbed for each specimen is calculated and reported. Finally the average and the standard deviation values for absorption capacity for all specimens is calculated and reported.

4.4.8 Swell Index Test

The following is the equipment and procedure used for the same and is performed in accordance with ASTM D1117.

Equipment: A BT technology thickness gauge, de-ionized water and swell index test screens are used to conduct this test.

Procedure: To start with, ten 4" x 4" specimens are placed near the thickness gauge after cutting and preconditioning. The thickness gauge is set to measure the thickness in millimeters and the gauge is zeroed out while resting on the aluminum slide plate prior to testing. The thickness of all the ten specimens is recorded by the procedure described in the thickness index test. After measuring and recording the initial thickness, the specimens are placed in the swell index test screens which are soaked in de-ionized water for a minimum of one hour before the test. Each of the screens is labeled with a number and the corresponding specimen number is matched to the appropriate test screen after which the specimen is placed in it. Then each specimen (enclosed in the swell test screen) is placed in a container of de-ionized water.

The depth of the water is kept adequate to fully submerse each screen and about 1 to 1.5 inches of water is allowed above the top surface of the screens. The time each specimen is placed in the water and the starting water temperature are recorded. The specimens are allowed to soak for a period of 24 hours +/- 15 minutes. After the soaking period, the specimens are removed from the de-ionized water and the time when each specimen is removed out of the water and the ending water temperature are recorded. The specimens are placed on aluminum bars above the water vessels and are allowed to drip dry in a horizontal position for 10 minutes. After allowing the specimens to drip dry for ten minutes, the thickness is again determined according to the procedure described above and the thickness is recorded as final thickness. After determining final thickness the percent swell for each specimen is calculated according to the following formula:

$$Swell = \frac{(Final\ thickness - Initial\ thickness)}{Initial\ thickness} \times 100 \qquad (14)$$

Lastly, the average swell and the standard deviation for swell are calculated and reported.

4.4.9 Light Penetration Index Test

It is performed in accordance with ASTM D6567. The following is the equipment and procedure used for the same.

Equipment: The TTI light penetration box is constructed to satisfy the requirements for the test according to the ASTM D6567. It is the apparatus used for this test and the amount of light penetration is determined by using a GE model 217 light meter.

Procedure: Three 12” x 12” specimens are used for this test. The light penetration box is divided into two sections such that the front and back sections are placed close against each other and the sides of the box are lined up. A black cloth material is wrapped around the area where the two sections of the box come together, so that the light does not go outside the apparatus. The GE model 217 light meter is placed in the slot provided on the front side of the light penetration box. When there is no light entering or leaving the box, the light meter reads zero and the test is started by turning on the light switch for the light penetration box and reinserting the light meter into the front slot. The light intensity value is read in foot candles from the meter and recorded as maximum light intensity on the test form. The first specimen is tested by moving the two sections of the box slightly apart from each other and placing it between the two sections of the box. After the specimen is in place, the two sections of the box back are pushed back together. It is made sure that the specimen is covering the entire area between the two sections of the box, as the light intensity is to be measured through the specimen. All of the sides and corners of the opening are covered by the specimen and there is no place where direct light can enter the box. After making sure that the specimen and box are properly placed, the black cloth material is re-wrapped around the opening area and the specimen light intensity is read and recorded in foot candles. After testing the first specimen, the remaining two specimens are tested in a similar way. After determining light intensity, the percent light penetration for each specimen is determined by the following formula:

$$Light\ Penetration\,(\%) = \frac{Specimen\ light\ intensity}{maximum\ light\ intensity} \times 100 \qquad (15)$$

After determining the percent light penetration for each specimen, the average light penetration and standard deviation are calculated and reported.

4.4.10 Smolder Resistance Index Test

This test is conducted in accordance with ECTC-TASC 00197. The following is the equipment and procedure used for the same.

Equipment: HSECL smolder test box (constructed to satisfy the requirements for the test according to the ECTC-TASC 00197) and Camel unfiltered cigarettes are used to perform this index test.

Procedure: Prior to starting the test, the smolder test box is placed inside the laboratory fume hood. Then the fan is turned on for both the smolder test box and the laboratory fume hood. There are two different conditioning periods for the three 12” x 12” specimens used for this test. After placing the specimens in required conditioning periods, the first specimen is placed on a screen inside the smolder test box. A single Camel unfiltered cigarette is used to test the smolder resistance of the specimen. It is lit and placed in the center of the specimen in the smolder test box such that the lit part of the cigarette faces the fan in the test box. The lid is placed over the top of the smolder test box and the cigarette is allowed to burn until it either extinguishes itself or burns up completely. After the cigarette burns out, the fan on the smolder test box and the fume hood is turned off and the screen is removed from the box. The maximum distance of smolder (in inches) from where the cigarette was resting is measured and recorded. After that the total smolder area in square inches is measured and recorded. After completing the measurements for the first specimen, the above procedure is repeated for the other two specimens. After performing the test on all the specimens, the average maximum distance of smolder, standard deviation for maximum distance of smolder, average total estimated smolder area, and standard deviation for total estimated smolder area are calculated and reported.

CHAPTER V

RESULTS AND DISCUSSION

5.1 Analysis of Results

The analysis is carried out using t-test analysis tools which test the means of different types of populations. The t- Test used for this study is a paired t-test for means of two sample groups. This analysis tool performs a paired two-sample t-test to determine whether two samples' means are distinct. A paired test is used when there is a natural pairing of observations in the samples, such as when a sample group is tested twice, before an experiment and after an experiment. In this case, the paired test is carried out on the following two populations, the results of index tests on RECP blankets tested before their use in erosion control and after it. This t- test is conducted on all the recorded values for each test on each material. The hypothesized mean difference is zero in each case and the alpha (α) level is set to be at a value of 0.05.

The one-tailed probability that the *t* statistic is lower than or equal to the critical *t*-value is calculated. Actually in a paired t-test both one-tailed and two-tailed probabilities that the *t* statistic is lower than or equal to the critical *t*-value is calculated. However, our ultimate aim is to check our hypothesis regarding the various tests. According to section 3.1, Chapter III, the null hypothesis regarding various index tests is that value of some deciding parameter of the index property either increases or decreases. Thus our hypothesis is in the form where we assume the mean of the test results on the used specimens to be either higher or lower than the mean of the test results on unused specimens. In this case only one tailed test can be used. The one-tailed probability values for each test on each material are observed and suppose this probability is P then, if P is less than or equal to 0.05, the null hypothesis mentioned in section 3.1 is rejected and vice versa. These P value is also a decisive factor to determine whether the change in the material property is significant or insignificant. The probability values and the resulting testing of hypothesis are listed in the table below:

Table 5.1. Significant test results

		Mass per unit area	Thickness	Resiliency	Stiffness	Tensile Strength	Specific gravity	Water Absorption	Swell	Light Penetration	Smolder Area
	Null Hypothesis	↑	↓	↑	↓	↑	↓	↓	↓	↓	↓
	Material										
Natural	Enviromat	P=0.04 ↓	P=0.01 ↑		P=0.00 ↑	P=0.0 ↓	P=0.01 ↑	P=0.03 ↑			P=0.02 ↑
Synthetic	Landlok TRM 1060	P= 0.0 ↓	P= 0.0 ↑		P= 0.01 ↑	P= 0.0 ↓		P=0.0 ↑	P=0.01 ↑		
	PP5 XCEL	P= 0.0 ↓	P= 0.0 ↑		P= 0.0 ↑	P= 0.0 ↓	P=0.0 ↑			P=0.04 ↑	
Composite	Greenfix CFO 72RR		P=0.05 ↑		P= 0.0 ↑	P= 0.0 ↓	P=0.05 ↑	P=0.01 ↑	P=0.04 ↑	P=0.0 ↑	
	Enkamat Comp. NPK		P= 0.0 ↑		P= 0.01 ↑	P= 0.0 ↓		P=0.0 ↑			
	Curlex HD	P= 0.0 ↓	P= 0.0 ↑	P= 0.0 ↓	P= 0.0 ↑	P= 0.0 ↓	P=0.04 ↑	P=0.0 ↑		P=0.0 ↑	
	NAG S-350	P= 0.0 ↓	P= 0.0 ↑		P= 0.0 ↑	P= 0.0 ↓	P=0.02 ↑	P=0.02 ↑		P=0.0 ↑	

Decrease =↓, Increase =↑, P=0.0 means infinitesimally less, the blank means values are insignificant for conclusions.

Table 5.2. Insignificant test results

		Mass per unit area	Thickness	Resiliency	Stiffness	Tensile Strength	Specific gravity	Water Absorption	Swell	Light Penetration	Smolder Area
	Null Hypothesis	↑	↓	↑	↓	↑	↓	↓	↓	↓	↓
	Material										
Natural	Enviromat			P=0.44 ↑					P=0.5 ↓	P=0.12 ↓	
Synthetic	Landlok TRM 1060			P=0.34 ↑			P=0.21 ↓			P=0.24 ↓	P=0.36 ↓
Synthetic	PP5 XCEL			P=0.29 ↑				P=0.10 ↓	P=0.16 ↓		P=0.08 ↓
Composite	Greenfix CFO 72RR	P=0.3 ↑		P=0.11 ↑							P=0.1 ↓
Composite	Enkamat Comp. NPK	P=0.12 ↑		P= 0.4 ↑			P=0.17 ↓		P=0.08 ↓	P=0.07 ↓	P=0.19 ↓
Composite	Curlex HD								P=0.38 ↓		P=0.07 ↓
Composite	NAG S-350			P=0.33 ↑					P=0.38 ↓		P=0.07 ↓

The table 5.1 tabulates all the significant changes in the properties while the table 5.2 tabulates the insignificant ones. The significant changes can be used to make conclusions and the insignificant ones help in speculating the odd behavior of the materials. From these two tables, the following can be stated regarding the changes in different properties of different erosion control materials.

1. **Mass per unit area:** For most of the materials mass per unit area undergoes a decrease which may be because the material degrades and is lost while its use for erosion control. For Greenfix and Enkamat, the mass per unit area increases to a very small extent. The reason might be inclusion of soil and organic matter in the mats which exceeds the loss of degradable material in the mats.
2. **Thickness:** For all the materials, the thickness is seen to increase significantly. This is because a lot of organic matter and soil gets included in the mats. Many a times dried leaves and other vegetation matter makes the blanket bulkier.
3. **Resiliency:** This property doesn't show any significant change for any of the materials except for curlex HD for which it decreases. Hence it is not of a great consequence for the study of erosion control.
4. **Stiffness:** For all the materials, the stiffness is seen to increase significantly. The reason might be the inclusion of organic material and soil in the blankets. The continuous sunlight which the blankets are subject to could also increase the stiffness to some extent.
5. **Tensile strength:** The tensile strength is seen to reduce significantly for all the materials. Strength loss is the most expected phenomenon when any material is put to a continuous use. Though the strength loss takes place for all the materials, the amount of loss which takes place can help us decide which material can be used for a longer lasting erosion control.
6. **Specific gravity:** This property increases just like the thickness because of the inclusion of the soil and organic residue in the blanket. For Landlok TRM and Enkamat, it shows insignificant decrease. This may be due to the loss of fibers exceeding the inclusion of any organic material or soil within their blankets.

7. **Water absorption:** This property is seen to increase for all the materials. The presence of organic matter in the blankets causes an increment in water absorption. It only shows a very small decrease for Enkamat; however, since the change is insignificant, this anomaly can be overlooked comfortably.
8. **Swell:** For most of the materials, this property does not show a significant change except for Landlok and Greenfix for which it increases for reason same as those for increase in water absorption. For all other materials an insignificant decrease in swell is observed. This can be related to increase in stiffness which decreases the flexibility to swell.
9. **Light penetration:** This property is seen to increase significantly for all the composite materials. Composite materials are used with the aim that the degradable material inside the mats will decompose giving a way to the vegetation which can serve for a longer lasting erosion control. It is speculated that they may serve this purpose because while other properties do not show much change, it can happen that the increase in light penetration is due to the growing vegetation trying to make a way through the blankets in an upward direction. It shows insignificant decrease for the natural and synthetic materials which shows that these materials might not have promoted the vegetation growth to a large extent.
10. **Smolder resistance:** The parameter used for measuring this property is smolder area. Most materials do not show any significant change in this property after being used for 3 years for erosion control. Only the natural material, Enviromat, shows a significant increase in smolder area which means there is a decrease in smolder resistance. This may be because of inclusion of more organic matter in the material which helps it to smolder to a great extent when subject to high heat. All the synthetic and natural materials show an insignificant decrease in smolder area which means there is an insignificant increase in smolder resistance. This may be due to stiffening of materials.

The above table and discussion shows that tensile strength, stiffness, thickness and water absorption are the index properties which undergo maximum change and they can be used to make stronger conclusions related material longevity concerning erosion control, which is made in the next chapter of conclusions and recommendations.

Tensile strength is one of the most important properties of the material when considering its application for erosion control because it is due to the strength of the material that it can remain in place for the duration till any vegetation growth takes place. If the material does not have sufficient strength, it will undergo wear and tear easily and may disappear even before any vegetation growth for erosion control takes place.

The tensile strength loss for each material is tabulated as follows:

Table 5.3. Tensile strength loss

	Material name	Strength loss in %	Strength loss Comparison
Natural	Enviromat	80.29	Maximum strength loss
Synthetic	Landlok TRM 1060	48.49	Least strength loss
	PP5 XCEL	50.57	
Composite	Greenfix CFO 72 RR	59.33	Medium to less strength loss
	Enkamat Composite NPK	52.20	
	Curlex HD	53.37	
	NAG S 350	52.34	

It can be seen from the above table that natural materials have the maximum strength loss as they degrade with time to the maximum extent. The synthetic materials have the least strength loss, some what lesser than the strength loss for the composite materials.

If the material does not have sufficient strength, it will undergo wear and tear easily and may disappear even before any vegetation growth for erosion control takes place. Thus whether there is any amount of blanket remaining in place for erosion control depends on its tensile strength. Hence tensile strength or its loss is the deciding factor when longevity of erosion control material is evaluated. Tensile strength can be used as a standard to compare the change in other properties. For each material the change in all the other properties is quantified in terms of the loss of mean tensile strength. Suppose X to be the loss in mean tensile strength in % for a given material and Y to be the change in any other property in % for the same material, then the value of X/Y is plotted to show how many times of the loss in tensile strength, a particular property has changed. This graphical representation for each material is shown below in Fig 5.1 - 5.7. A positive value for the ratio shows a decrease in the values of the deciding parameter of the property and vice versa.

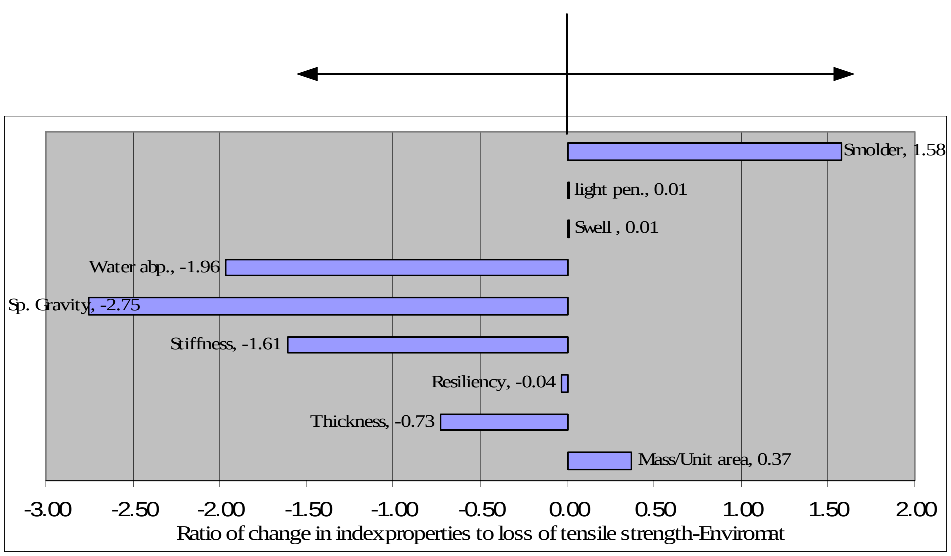

Fig.5.1. Property changes for Enviromat

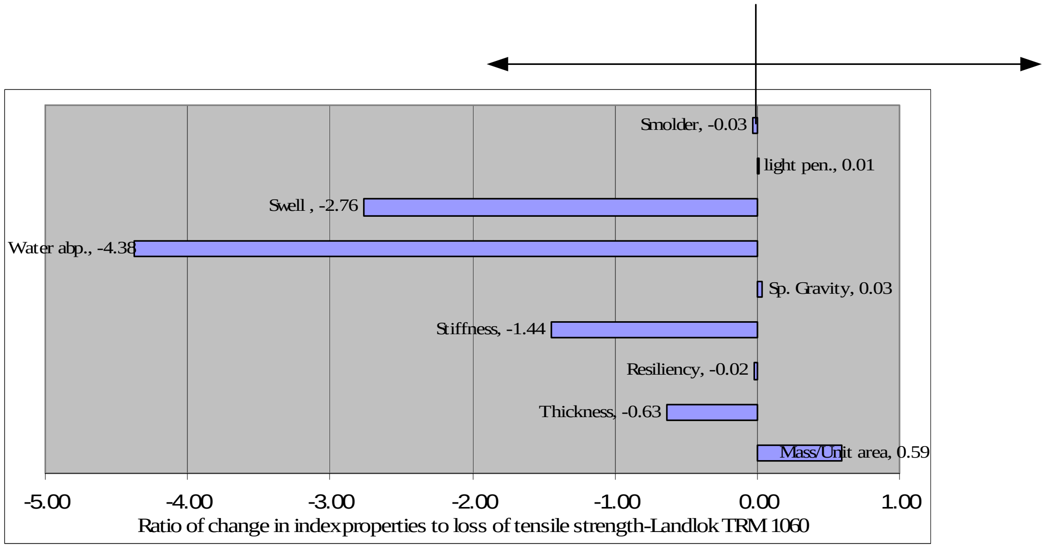

Fig.5.2. Property changes for Landlok TRM 1060

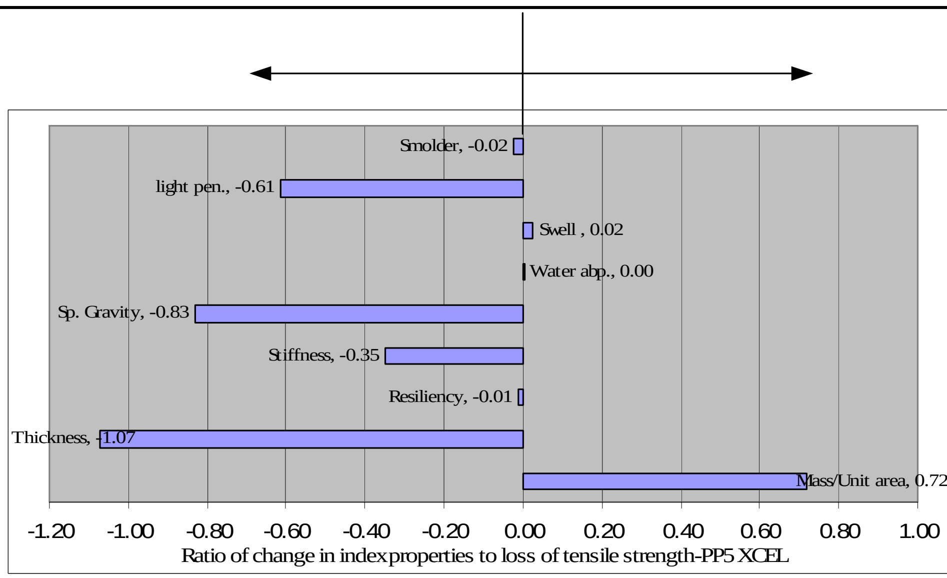

Fig.5.3. Property changes for PP5 XCEL

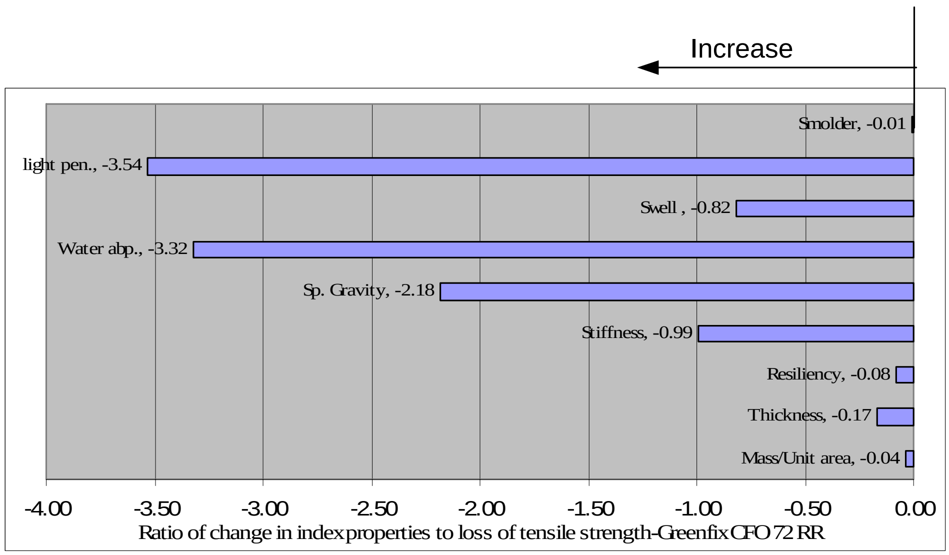

Fig.5.4. Property changes for Greenfix CFO 72 RR

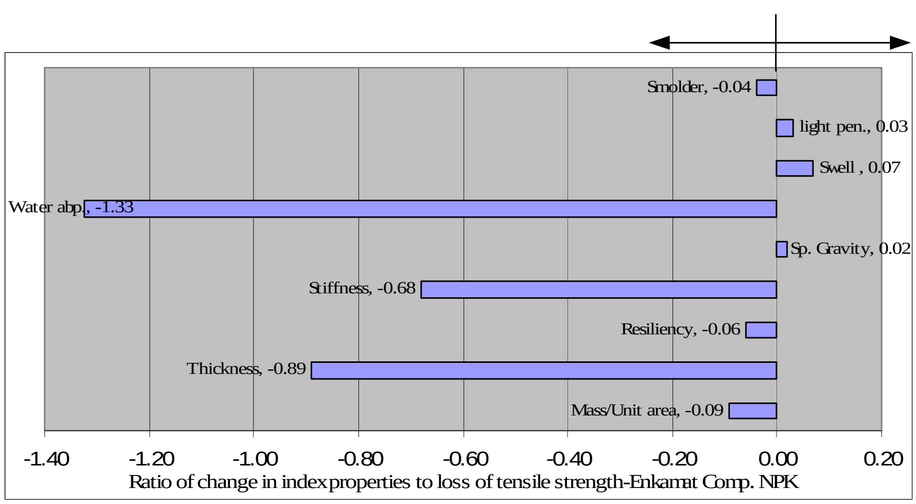

Fig.5.5. Property changes for Enkamat Comp NPK

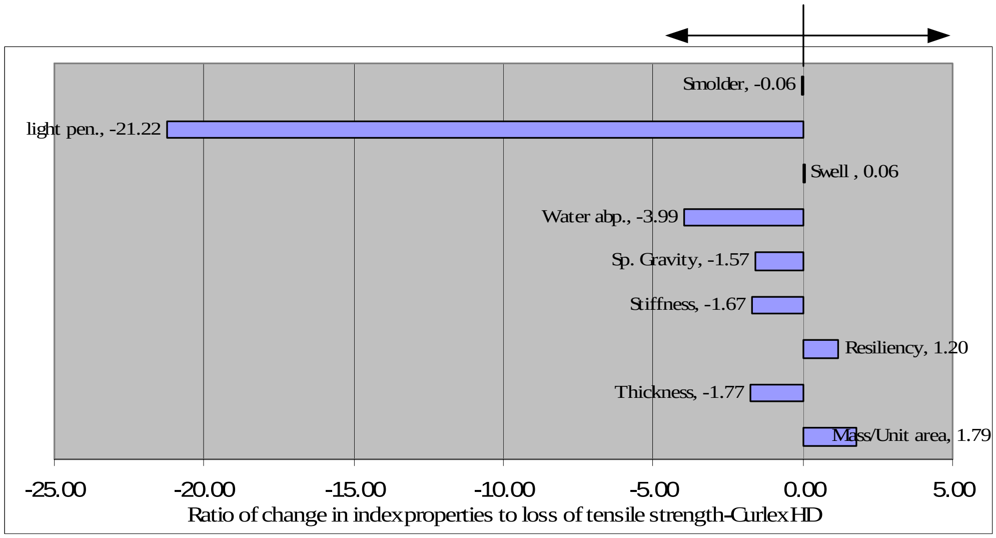

Fig.5.6. Property changes for Curlex HD

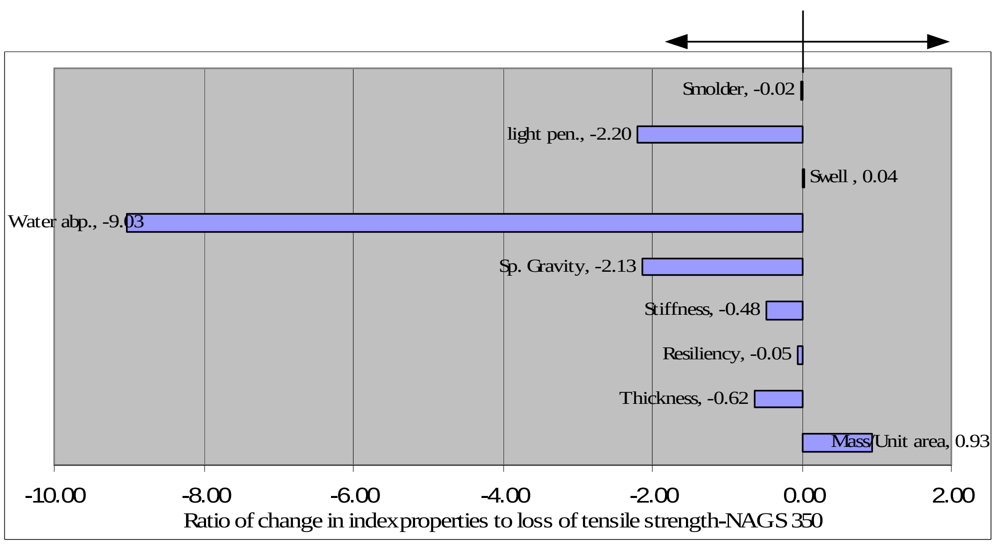

Fig.5.7. Property changes for NAG S 350

The graphs suggest that the following properties show major changes for most of the materials:

- *Light penetration:* The graphs show that the property which shows the maximum change (increase) is in the quantity of light penetration with a negative ratio of -21.22 for Curlex HD which is a type of composite material. Even for the other two composite materials, Enkamat Comp NPK and NAG S 350, with -3.64 and -2.20 as the values of light penetration respectively, light penetration shows the maximum increase when compared to other properties. Increase in light penetration may be because of the loss of the degradable material from the composite blanket. Also, it is due to growth of vegetation making its way through the blankets and thus expanding the open space in them leading to increased light penetration. Thus the composite materials can be said to serve their purpose.

- *Water Absorption:* The large increase in water absorption in NAG S 350, with a ratio of -9.03 may be because of inclusion of organic material in the blanket after its use for erosion control because the organic matter has a greater absorption capacity than the raw materials forming NAG S 350. The same can be said for Landlok TRM 1060 with a ratio of -4.38. It has a loosely bonded blanket, so that the fibers inside the net are lost giving a way to the organic matter. This property also shows the maximum change (increase) for Enkamat NPK which is a composite material and a second maximum change (increase) for Greenfix CFO72 RR which also happens to be a composite material.

- *Specific gravity:* For the natural material, Enviromat, specific gravity shows the maximum increase with a ratio of -2.75. If the used material specimen of Enviromat is observed, it can be seen that the blanket structure is hardly visible, there is a torn structure with a lot of soil and organic matter which increases its specific gravity to a large extent. This natural material can be speculated to have lesser erosion control capacity after its application for three years.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions can be made from the above results and analysis.

6.1.1 Conclusions Related to Index Properties

6.1.1.1 Tensile Strength

Tensile strength of the material is the most important property where erosion control is concerned. The results of the tests prove that tensile strength decreases the most for the natural materials which is 80%, while it reduces around 50% for the synthetic and composite materials. Thus the synthetic and composite materials can stay in place for a longer duration of time than the average period of 3 years which is termed to be sufficient for vegetation growth. Tensile strength is the property which can help the material stay in place when subjected to storm water and ultraviolet rays of sun. A strength loss of around 50% shows a reasonably good performance by the blankets of synthetic and composite nature. It can also be speculated that their longevity is sufficient enough to accommodate a growth of vegetation, if possible, for erosion control.

6.1.1.2 Stiffness

Stiffness is another important property related to the aging of erosion control materials. It is proved that all the materials show an increase in their stiffness. As the materials grow stiff due to their exposure to sun, their flexibility decreases. This may be termed to be a negative factor considering the fact that stiffer blankets may not provide enough flexibility for allowing the vegetation to grow through them, however, on the other hand more stiffness suggests that the blankets could be more likely to stay in place for erosion control.

6.1.1.3 Light Penetration

Light penetration is an important property when erosion control is considered because the amount of light penetration allowed through the material can be used to speculate if and how much vegetation growth could have taken place through the blanket. The composite materials show very high increments in light penetration after their use for erosion control. At the same time, their other properties do not undergo such a large amount of change. This can also be used to speculate the possibility of vegetation growth.

6.1.2 Final Conclusions

From the analyses of results in the previous chapter, the following conclusions can be made to evaluate if this study has succeeded to achieve its aforementioned goals in section 3.2.2, Chapter III:

- There is only one natural material tested, it can be observed though it is an environmentally-friendly method of erosion control, it does not stand the test of time which is relevant from its large strength loss. The fibers degrade relatively quickly and there is lot of soil in the remaining material, shown by the significant increase in the stiffness and thickness. Hence a growth of vegetation during erosion cannot be speculated because there is nothing to hold back the continuously flowing soil.

- The purely synthetic materials, it can be seen if the materials are observed, have a loosely bonded structure. The fibers in the nets are polymers which are not easily degradable. However, being loosely bonded, these fibers can get washed away and become a hazard to the environment. Except for this side effect, their behavior is pretty much like the composite materials or TRMs. However, this disadvantage cannot be overlooked because of the environmental threats posed by non-degradable waste generated by the use of these materials.

- The composite materials show about 50 % strength loss which is reasonable considering the fact that that they have served their stipulated use time of 3 years. The increase in light penetration is very large compared to the change in other properties which can be used to speculate the growth of vegetation which can be favorable for erosion control. The properties like stiffness and resiliency do not show much change confirming that the purpose of erosion control may be still being served to a fair extent.

6.2 Recommendations for Future Study

The following recommendations can be made for a future study regarding longevity of erosion control geosynthetics.

- The aging of materials considered in this study is by natural factors where the materials were actually applied in the field for a time of 3 years. Study of an accelerated aging by artificial methods will help to understand the change in properties under controlled conditions with better choice of effects on the materials, like different ultra-violet light intensities and different types of water exposure cycles.
- This study mostly consists on blankets with their synthetic part made of polypropylene. A study which could include more different blankets so that maximum number of polymers could be included will be more useful because this will help us decide that which polymer is best suited for longer-lasting erosion control blankets.
- Performance testing of these materials at different times after being put to use can be done to study the change in erosion control capacity. These tests may include rainfall simulator testing, bench-scale rainfall tests etc. This will help in studying that how the erosion control quality changes with aging.

- Vegetation growth is the ultimate solution for erosion control. A study can be made to link the RECPs to vegetation growth if it can be done in some way. To investigate if there is any actual growth of vegetation in the field by putting seeds at the same time when these materials are applied for erosion control may be an option for the same.

Thus it can be said that this analysis of index properties has helped us in finding that composite materials or TRMs achieve the balance of being less vulnerable to aging effects while not posing a great threat to the environment. Though there is loss of strength among the fibers, it is such that the existence of netting for a long time is confirmed. The promotion of vegetation growth is the best achievement of the composite materials because as explained earlier vegetation is the only thing which can be ultimately relied upon for long-lasting erosion control. Thus the promotion of use of the composite materials for erosion control in the upcoming future is justified.

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APPENDIX

Test Results

Mass per unit area in g/m^2

	Enkamat		Enviromat		Landlok TRM 1060		PP5 Xcel		NAG S350		Greenfix CFO		Curlex HD	
No.	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	787.6	867.6	655.8	761.3	551.2	570.6	324.5	122.0	156.3	34.6	693.4	576.5	657.8	25.2
2	865.1	775.0	694.6	777.5	507.6	462.1	231.7	252.8	219.5	102.3	882.7	629.0	1055.9	25.2
3	766.3	985.7	612.3	562.3	454.3	133.0	243.3	112.9	190.8	100.3	764.5	895.6	604.5	30.0
4	847.7	876.9	609.3	599.6	405.9	574.5	396.3	437.9	231.2	132.0	813.2	756.4	677.2	28.1
5	754.7	690.3	597.7	453.1	389.4	649.1	345.4	330.3	310.3	261.3	799.3	837.0	629.7	27.1
6	573.5	635.5	570.6	398.8	445.6	123.9	290.7	419.5	192.0	121.1	760.1	756.1	799.2	28.1
7	962.0	1098.9	497.9	523.6	504.7	712.0	213.6	188.5	178.9	83.2	699.3	910.4	482.4	35.8
8	1085.0	973.3	541.5	376.1	487.3	575.4	218.3	121.6	215.0	92.3	856.9	795.3	559.0	30.0
9	932.9	1021.1	595.8	446.8	476.6	628.7	267.1	121.0	283.4	121.6	760.5	802.4	598.7	32.9
10	938.7	845.4	583.2	671.3	526.0	600.6	233.4	380.7	173.1	53.4	875.9	705.6	570.6	27.1
11	916.4	1129.8	601.6	342.3	407.8	231.9	252.4	111.0	176.2	82.1	752.9	699.9	722.7	32.9
12	874.8	900.3	591.9	430.9	454.3	602.6	190.2	278.0	216.4	121.6	733.6	792.8	525.1	30.0
Avg	**858.7**	**900.0**	**596.0**	**528.6**	**467.6**	**325.0**	**267.2**	**239.7**	**211.9**	**108.8**	**782.7**	**789.5**	**656.9**	**29.4**
D	**129.1**	**151.9**	**49.7**	**147.5**	**50.6**	**206.4**	**61.1**	**127.4**	**45.8**	**56.1**	**63.9**	**99.3**	**152.5**	**3.3**

Thickness in mm

No.	Enkamat unused	Enkamat used	Enviromat unused	Enviromat used	Landlok TRM unused	Landlok TRM used	PP5 Xcel unused	PP5 Xcel used	NAG S350 unused	NAG S350 used	Greenfix CFO unused	Greenfix CFO used	Curlex HD 125 unused	Curlex HD 125 used
1	20.40	11.20	5.46	7.65	7.77	8.94	2.31	4.00	4.56	2.12	6.77	8.93	10.24	10.24
2	22.43	10.72	6.46	5.76	7.89	8.29	3.29	4.69	3.43	1.98	6.48	9.65	11.09	11.09
3	21.36	9.43	5.76	6.12	6.09	7.68	2.20	4.88	4.34	2.66	6.90	8.12	9.23	9.23
4	20.99	11.56	5.65	8.34	5.99	8.99	3.98	5.31	2.91	2.91	6.65	8.67	11.56	11.56
5	21.51	10.52	5.89	6.09	5.72	10.29	3.44	5.56	3.77	2.67	6.72	7.97	10.03	10.03
6	22.37	23.98	5.66	7.55	6.56	9.87	3.91	5.44	3.11	1.94	8.69	8.12	10.65	14.56
7	20.28	33.87	4.87	8.34	7.97	10.75	2.33	6.23	2.89	2.32	7.70	6.67	8.73	8.73
8	22.32	26.98	5.10	6.51	6.92	7.74	3.54	3.93	4.01	2.34	6.91	7.24	9.64	15.32
9	20.26	34.87	6.01	6.97	7.24	8.14	3.72	5.09	3.89	2.77	6.99	6.92	10.16	17.65
10	20.01	11.98	6.63	5.73	7.15	9.59	4.32	6.53	3.20	2.19	7.87	6.58	10.76	19.43
11	18.23	12.21	5.71	8.99	6.44	8.28	2.73	4.83	3.76	2.56	6.91	7.68	11.95	11.95
12	19.85	11.31	5.89	6.32	6.84	9.37	3.50	4.10	3.22	2.64	7.21	7.88	10.59	10.59
Avg	**20.83**	**28.67**	**5.76**	**7.03**	**6.88**	**8.99**	**3.27**	**5.05**	**3.59**	**4.87**	**7.15**	**7.87**	**10.39**	**12.53**
D	**1.25**	**9.69**	**0.49**	**1.12**	**0.75**	**1.00**	**0.71**	**0.83**	**0.55**	**0.32**	**0.64**	**0.93**	**0.92**	**3.43**

Percent recovery in % for Resiliency

	Enkamat		Enviromat		Landlok TRM 1060		PP5 Xcel		NAG S350		Greenfix CFO		Curlex HD 125	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	78.7	69.1	83.5	78.6	100.8	93.1	95.7	101.9	77.9	98.6	100.2	79.7	65.9	191.0
2	65.7	86.7	71.1	54.5	80.5	98.8	99.2	104.8	89.5	76.7	118.4	89.9	80.8	233.8
3	89.0	104.3	77.3	87.2	96.7	112.0	89.4	99.5	83.3	100.9	80.3	92.1	77.2	141.8
4	63.4	74.4	80.3	77.6	99.6	94.3	86.8	96.6	96.7	90.9	119.3	100.6	92.1	112.6
5	87.5	99.7	75.3	59.0	101.5	99.4	97.5	86.8	79.4	86.8	100.4	112.9	82.8	106.2
6	80.0	115.5	78.7	86.7	101.8	93.8	81.8	88.5	77.7	100.4	95.4	98.4	83.3	94.9
7	65.9	96.1	71.8	95.3	103.8	99.3	85.4	86.7	92.2	84.4	98.9	100.5	81.3	107.5
8	88.3	97.0	77.1	79.7	104.7	98.1	86.6	98.6	99.8	70.3	85.6	87.4	87.0	133.0
9	75.6	101.2	69.8	88.7	99.1	98.7	100.3	97.7	100.3	90.7	112.3	100.8	85.1	118.5
10	69.2	92.5	66.8	94.5	116.6	97.9	103.4	95.7	90.9	97.2	107.9	95.5	73.5	162.5
11	96.5	98.4	82.8	64.6	106.2	107.0	106.6	88.6	79.0	106.6	98.4	100.3	94.7	111.1
12	83.4	101.8	81.5	59.4	97.2	101.5	129.2	84.6	119.2	109.7	95.2	94.4	74.1	89.3
Average	**78.6**	**94.7**	**76.3**	**77.2**	**100.7**	**99.5**	**96.8**	**94.2**	**90.5**	**92.8**	**101.0**	**101.9**	**81.5**	**67.0**
D	**10.8**	**12.8**	**5.4**	**14.4**	**8.3**	**5.4**	**12.9**	**6.8**	**12.4**	**11.8**	**11.9**	**8.4**	**8.1**	**43.0**

Specific gravity and density

	Enkamat				Enviromat				Landlok TRM 1060				PP5 Xcel			
	Sp. gravity (23/23^{0}c)		Density (kg/m^3)		Sp. gravity (23/23^{0}c)		Density (kg/m^3)		Sp. gravity (23/23^{0}c)		Density (kg/m^3)		Sp. gravity (23/23^{0}c)		Density (kg/m^3)	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	0.4	0.9	361.0	871.2	0.2	0.3	192.4	237.5	0.5	1.8	514.2	1772.7	0.7	0.4	316.8	396.3
2	0.5	0.6	451.2	577.3	0.2	0.3	173.4	210.4	0.3	0.5	347.6	516.8	0.9	0.5	498.5	532.4
Avg	**0.4**	**0.7**	**406.1**	**724.3**	**0.2**	**0.3**	**182.9**	**223.9**	**0.4**	**0.7**	**430.9**	**1144.7**	**0.8**	**1.0**	**407.7**	**464.4**
D	**0.1**	**0.2**	**63.8**	**207.9**	**0.0**	**0.0**	**13.4**	**19.2**	**0.1**	**0.9**	**117.8**	**888.1**	**0.1**	**0.1**	**128.5**	**96.2**

Specific gravity and density

	NAG S350				Greenfix CFO 72 RR				Curlex HD			
	Sp. gravity (23/23^{0}c)		Density (kg/m^3)		Sp. gravity (23/23^{0}c)		Density (kg/m^3)		Sp. gravity (23/23^{0}c)		Density (kg/m^3)	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	0.1	0.0	76.8	21.7	0.4	0.9	298.5	493.7	0.3	0.1	303.3	58.5
2	0.2	0.1	85.4	17.4	0.3	0.7	394.5	582.4	0.4	0.1	372.3	52.3
Avg	**0.2**	**0.2**	**81.1**	**19.5**	**0.3**	**0.8**	**346.5**	**538.1**	**0.3**	**0.4**	**337.8**	**55.4**
D	**0.0**	**0.0**	**6.1**	**3.0**	**0.0**	**0.1**	**67.9**	**62.7**	**0.0**	**0.0**	**48.8**	**4.3**

Absorption capacity (ratio of water absorbed to original mass)

	Enkamat		Enviromat		Landlok TRM		PP5 Xcel		NAG S350		Greenfix CFO		Curlex HD II	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	4.55	6.82	14.98	28.34	0.36	1.05	0.27	0.75	0.35	1.72	2.29	6.92	2.86	8.91
2	2.32	4.81	18.95	23.51	0.27	1.11	0.97	1.04	0.71	3.61	3.71	8.36	2.44	7.83
3	3.54	5.97	15.25	26.59	0.40	1.06	1.02	2.11	0.39	2.97	2.48	9.91	2.12	6.47
Avg	**3.47**	**5.87**	**16.40**	**26.15**	**0.34**	**1.07**	**0.75**	**1.30**	**0.48**	**2.77**	**2.83**	**8.40**	**2.47**	**7.74**
D	**1.12**	**1.01**	**2.22**	**2.45**	**0.07**	**0.03**	**0.42**	**0.72**	**0.20**	**0.96**	**0.77**	**1.50**	**0.37**	**1.22**

Specimen Swell in %

	Enkamat		Enviromat		Landlok TRM		PP5 Xcel		NAG S350		Greenfix CFO		Curlex HD	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	-3.0	1.7	-0.2	9.6	9.8	-9.6	19.2	-30.2	19.8	5.4	6.8	-3.9	15.7	6.7
2	-3.2	-4.3	16.3	6.5	3.1	-1.5	-0.3	5.6	12.3	6.6	9.6	10.3	-8.7	-2.7
3	-21.7	-2.3	5.4	9.4	12.8	0.8	4.4	-48.5	15.8	9.2	10.3	5.7	-8.1	6.6
4	-16.5	-3.0	17.9	12.6	-1.7	0.7	8.6	13.4	8.7	-4.6	9.2	8.3	24.3	10.6
5	10.1	-0.2	15.2	-2.3	3.5	1.9	11.5	-2.9	-5.5	-0.7	10.3	-2.8	-5.1	-3.5
6	-4.8	-1.9	-27.4	5.5	0.6	2.6	-7.6	-18.8	9.6	10.3	-4.2	3.2	4.9	6.9
7	3.6	0.8	28.5	11.3	4.5	3.1	8.6	-7.5	-7.8	3.4	12.4	11.6	4.5	4.9
8	-2.7	3.2	5.0	16.5	6.4	-4.9	-5.5	-8.4	9.3	6.0	8.0	7.7	-6.5	-3.6
9	-5.2	-0.3	8.4	10.7	-0.1	-4.1	3.5	8.4	8.5	-0.7	10.0	-1.7	-5.6	10.3
10	-2.4	1.5	10.2	-0.8	3.0	-3.2	-6.7	33.8	-3.3	53.4	12.0	4.6	14.8	3.9
Avg	**-4.6**	**-0.5**	**7.9**	**7.9**	**4.2**	**4.7**	**3.6**	**-5.5**	**6.7**	**8.8**	**8.4**	**8.7**	**3.0**	**3.0**
D	**9.0**	**2.4**	**14.8**	**5.8**	**4.5**	**4.0**	**8.7**	**23.3**	**9.2**	**16.3**	**4.7**	**5.5**	**11.8**	**5.4**

Light penetration in %

	Enkamat		Enviromat		Landlok TRM		PP5 Xcel		NAG S350		Greenfix CFO		Curlex HD	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	6.0	8.4	0.1	1.3	28.4	8.0	16.7	20.0	34.4	78.7	1.2	4.5	5.3	67.9
2	5.0	13.2	2.2	2.4	20.1	45.7	18.9	22.8	46.3	86.4	1.0	4.0	6.7	75.6
3	2.5	17.5	1.1	1.4	18.0	60.0	15.2	23.7	39.8	94.3	2.3	5.4	4.4	59.2
Avg	**4.5**	**4.2**	**1.1**	**1.0**	**22.2**	**21.3**	**16.9**	**22.2**	**40.2**	**86.4**	**1.5**	**4.6**	**5.5**	**67.6**
D	**1.8**	**4.6**	**1.1**	**0.6**	**5.5**	**26.9**	**1.8**	**1.9**	**5.9**	**7.8**	**0.7**	**0.7**	**1.1**	**8.2**

Smolder Resistance

	Enkamat				Enviromat				Landlok TRM 1060				PP5 Xcel			
	Max. dist. inches		Area in2		Max. dist. inches		Area in2		Max. dist. inches		Area in2		Max. dist. inches		Area in2	
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	1.8	1.3	0.6	0.5	2.3	2.2	0.8	1.3	1.8	2.4	1.0	0.8	2.7	2.4	1.8	1.7
2	1.8	1.9	0.6	0.7	2.3	3.4	1.1	1.3	3.1	2.8	1.1	1.4	3.0	2.1	1.0	1.0
3	1.7	2.1	0.7	1.0	2.0	2.8	0.7	1.2	2.8	2.5	1.7	1.2	2.8	2.3	1.8	1.4
Avg	**1.8**	**1.8**	**0.6**	**0.8**	**2.2**	**2.8**	**0.9**	**1.3**	**2.5**	**2.6**	**1.2**	**1.2**	**2.8**	**2.3**	**1.5**	**1.3**
D	**0.1**	**0.4**	**0.1**	**0.3**	**0.2**	**0.6**	**0.2**	**0.1**	**0.7**	**0.2**	**0.4**	**0.3**	**0.2**	**0.2**	**0.4**	**0.4**

Smolder Resistance

	NAG S350				Greenfix CFO 72 RR				Curlex HD			
	Max. dist.		Area		Max. dist.		Area		Max. dist.		Area	
	inches		in2		inches		in2					
	unused	used	unused	used	unused	used	unused	used	unused	used	unused	used
1	2.9	2.6	1.0	0.9	2.3	2.0	1.2	0.9	2.3	2.8	1.2	0.5
2	3.0	3.2	1.7	1.0	3.1	2.7	1.6	0.7	1.5	1.6	0.4	0.2
3	2.5	2.0	1.3	0.9	2.8	2.3	0.8	0.6	2.2	2.0	0.6	0.4
Avg	**2.8**	**2.6**	**1.3**	**0.9**	**2.7**	**2.3**	**1.2**	**0.7**	**2.0**	**2.1**	**0.7**	**0.3**
D	**0.3**	**0.6**	**0.4**	**0.1**	**0.4**	**0.4**	**0.4**	**0.2**	**0.4**	**0.6**	**0.4**	**0.1**

Stiffness

		Enkamat Machine				Enkamat Cross			
		Bending length		Flexural rigidity		Bending length		Flexural rigidity	
		cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
		unused	used	unused	used	unused	used	unused	used
1A		11.02	8.05	21827.20	23122.99	14.31	10.30	27382.19	29287.42
1B		10.72	8.50	23736.14	27221.57	11.72	10.05	22563.32	27206.18
1C		9.25	8.20	21639.36	24439.82	10.95	10.05	24716.29	27206.18
1D		9.83	7.75	19625.38	20632.96	11.09	10.70	26731.32	32833.77
2A		10.17	8.55	18297.27	26843.63	11.26	10.75	52983.41	71433.08
2B		11.62	8.30	20498.16	24557.11	12.87	12.30	84726.09	107001.36
2C		9.36	7.75	15267.12	19991.62	13.17	11.95	73643.33	98124.55
2D		10.26	6.75	12873.04	13208.52	11.46	10.25	48274.41	61922.08
3A		9.04	7.35	11728.61	16865.11	11.73	10.55	47838.92	89133.25
3B		10.31	9.80	27365.74	39976.56	11.03	9.95	67342.88	74774.17
3C		9.84	8.65	24536.11	27490.05	14.21	12.75	93762.17	157330.50
3D		10.77	9.65	31726.99	38168.85	11.94	10.65	72563.39	91691.95
4A		9.95	8.75	36728.16	38743.57	12.45	11.80	74327.17	91752.11
4B		8.18	6.92	29811.17	32784.28	12.37	11.05	53362.12	75345.42
4C		10.72	9.34	36721.87	39826.17	13.82	11.60	62518.02	87165.38
4D		9.25	7.77	23114.75	26358.28	12.45	11.40	56271.81	82734.11
Avg		**10.02**	**8.26**	**23468.57**	**27514.44**	**12.30**	**11.01**	**55562.93**	**75308.84**
D		**0.87**	**0.88**	**7528.40**	**8309.18**	**1.11**	**0.87**	**21993.20**	**34566.35**

Stiffness

	Enviromat Machine				Enviromat Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	8.25	5.48	27355.61	32781.72	10.95	8.43	42764.30	56733.98
1B	8.25	7.25	27355.61	29836.14	10.35	7.74	36112.71	65734.55
1C	9.50	6.95	41769.13	52763.05	10.70	9.52	39901.60	63829.25
1D	9.90	7.12	47270.50	51234.57	10.00	6.89	32571.59	56316.21
2A	11.00	10.72	59570.69	62738.09	11.90	9.85	72591.88	93827.96
2B	10.55	9.26	52554.75	67382.47	11.15	10.32	59713.39	75883.13
2C	9.30	7.93	36000.07	54637.57	9.80	7.59	40543.89	67228.28
2D	9.85	9.38	42772.36	76387.24	10.30	8.85	47071.59	63281.11
3A	9.80	8.25	41759.60	64731.93	9.30	7.58	28311.75	48329.62
3B	10.15	9.67	46395.54	64738.21	9.75	6.35	32623.58	64729.46
3C	9.75	8.33	41123.67	73483.22	11.65	10.72	55653.90	74822.55
3D	11.50	10.72	67479.46	83723.32	9.40	7.26	29234.88	45271.58
4A	10.05	8.36	49320.77	56347.19	9.80	8.15	44028.92	63298.46
4B	10.80	9.28	61207.25	83621.11	9.05	8.02	34674.13	56298.86
4C	9.70	8.93	44345.22	64738.57	9.35	9.14	38237.95	45289.11
4D	9.75	8.27	45034.51	73272.46	9.15	8.57	35836.29	56289.24
Avg	**9.88**	**8.49**	**45707.17**	**62026.05**	**10.16**	**8.44**	**41867.02**	**62322.71**
D	**0.86**	**1.39**	**10954.92**	**15562.48**	**0.89**	**1.24**	**11945.21**	**12369.43**

Stiffness

	Landlok TRM 1060 Machine				Landlok TRM 1060 Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	11.65	8.20	61236.31	22493.18	10.45	10.80	33337.17	65953.05
1B	10.05	12.30	39312.39	75914.48	11.55	8.95	45011.75	37534.68
1C	11.30	11.75	55881.31	66179.41	11.10	10.95	39952.95	68739.44
1D	11.40	9.55	57378.05	35531.98	11.50	10.65	44429.71	63243.00
2A	11.90	9.80	73281.16	37119.64	11.10	10.25	5152.37	49148.19
2B	12.25	10.70	79939.18	48314.43	9.70	8.55	3438.38	28525.57
2C	11.65	11.05	68758.95	53212.34	8.80	9.55	2567.36	39750.82
2D	12.05	10.65	76087.37	47640.29	10.75	11.20	4680.19	64119.48
3A	12.65	12.10	49635.84	73758.60	10.30	11.70	38508.84	77405.89
3B	10.90	9.15	31754.35	31894.80	11.40	10.40	52211.16	54364.63
3C	10.75	11.85	30461.35	69280.59	11.10	12.05	48196.74	84562.45
3D	11.05	9.40	33083.44	34581.20	14.05	12.20	97741.21	87759.86
4A	10.75	9.75	40142.66	35696.39	12.30	11.60	49714.97	71640.93
4B	11.25	9.30	46008.53	30978.42	11.55	12.20	41164.02	83342.55
4C	10.90	9.40	41846.61	31988.51	12.25	11.55	49111.15	70718.53
4D	11.25	11.20	46008.53	54108.37	10.90	10.70	34598.03	56226.18
Avg	**11.36**	**10.38**	**51926.00**	**46793.29**	**11.18**	**10.83**	**36863.50**	**62689.70**
D	**0.65**	**1.23**	**16201.73**	**16987.92**	**1.17**	**1.10**	**24347.53**	**17444.83**

Stiffness

	PP5 XCEL Machine				PP5 XCEL Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	7.64	8.05	14627.81	12712.59	8.43	9.50	32761.43	29661.07
1B	7.25	8.20	16257.27	13436.56	6.94	7.95	27368.74	17382.70
1C	7.11	7.80	17628.18	11564.59	7.68	8.15	22435.35	18727.89
1D	7.75	8.15	16271.25	13192.26	6.47	9.55	36482.32	30131.87
2A	7.15	7.65	16282.27	13425.66	7.93	8.35	41928.23	39792.68
2B	6.94	7.55	15261.93	12906.01	5.68	6.80	28371.12	21491.69
2C	7.46	7.95	18215.27	15067.89	7.38	7.40	34217.57	27697.40
2D	8.19	8.25	19261.32	16838.87	7.65	8.70	48372.28	45009.23
3A	8.04	8.35	16251.63	12570.73	6.84	8.05	18263.35	13262.87
3B	7.64	7.85	14257.27	10445.04	5.23	6.95	10253.13	8535.02
3C	8.23	8.85	16235.32	14966.86	8.16	8.65	21426.33	16455.02
3D	8.77	9.35	21527.16	17649.64	7.43	8.45	19336.59	15339.81
4A	9.32	9.85	23527.91	19853.45	7.82	8.35	16354.27	11455.28
4B	9.74	9.75	20375.35	19254.90	7.56	8.05	13251.24	10264.41
4C	8.46	8.75	16251.46	13917.19	8.23	9.10	16352.47	14827.59
4D	7.94	9.85	22651.46	19853.45	8.17	8.80	18256.35	13408.93
Avg	**7.98**	**8.51**	**17805.18**	**14853.48**	**7.35**	**8.30**	**25339.42**	**27786.78**
D	**0.79**	**0.79**	**2858.05**	**2974.47**	**0.92**	**0.79**	**10869.90**	**10711.24**

Stiffness

	NAG S-350 Machine				NAG S-350 Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	8.67	9.57	15247.47	9585.35	11.25	13.64	17827.38	12636.74
1B	7.68	9.65	17356.57	11736.39	9.36	10.38	18363.62	14736.28
1C	11.21	13.27	15736.14	10388.47	8.47	12.31	15272.36	11626.84
1D	9.54	10.21	16584.58	11837.46	8.73	11.25	14363.73	10383.28
2A	8.93	10.22	18373.47	10383.47	9.18	11.75	16353.83	11736.38
2B	9.43	11.38	11492.70	8814.94	8.10	9.36	17363.62	12352.92
2C	8.47	9.78	15363.81	11527.83	7.77	9.37	10272.48	9484.36
2D	7.54	8.83	18575.36	13252.84	8.48	10.83	15726.37	9353.82
3A	9.32	10.48	19832.34	16373.38	7.38	9.84	14262.83	9272.36
3B	8.57	10.82	15262.38	12625.92	8.65	12.81	17268.93	14362.29
3C	7.56	9.57	17363.37	13647.85	8.56	9.52	20383.81	12636.91
3D	8.24	9.73	18272.37	11827.32	10.36	13.89	16378.37	13727.92
4A	8.34	9.56	20393.48	19838.36	11.56	19.31	17326.37	12526.81
4B	7.66	10.36	17363.47	14353.84	9.91	12.69	15326.19	12627.64
4C	8.43	11.46	19282.34	17262.37	11.85	14.81	17265.54	13257.93
4D	7.78	9.73	18726.32	13746.38	12.83	13.64	18272.17	15275.48
Avg	**8.59**	**10.29**	**17201.64**	**12950.14**	**9.53**	**12.21**	**16376.73**	**18787.00**
D	**0.96**	**1.06**	**2225.95**	**2928.21**	**1.61**	**2.58**	**2275.85**	**1872.00**

Stiffness

	Greenfix CFO 72RR Machine				Greenfix CFO 72RR Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	9.74	7.47	64738.35	74638.36	12.63	11.71	35627.74	64388.36
1B	10.27	8.49	54763.83	75846.39	14.28	11.82	35737.37	54783.37
1C	11.82	9.84	63831.32	85464.35	9.46	7.95	47846.38	65834.15
1D	9.63	7.41	55637.26	75656.12	13.84	10.57	56789.20	84676.42
2A	9.72	8.45	65742.18	81252.95	9.46	8.49	28973.21	48767.21
2B	10.28	8.96	77583.35	93631.83	13.82	9.95	36356.14	64753.32
2C	7.64	7.12	85752.43	89347.43	10.82	8.45	45631.92	54653.29
2D	10.82	9.35	47914.32	74646.13	11.92	9.47	36261.95	54821.90
3A	13.84	11.82	84632.84	93837.32	12.73	10.28	34529.47	56843.22
3B	14.38	11.76	75465.32	83635.12	13.92	11.37	48267.12	78674.29
3C	16.23	13.84	103836.32	117253.21	12.83	10.84	28773.30	46726.10
3D	14.19	11.57	73534.21	84462.65	13.53	11.82	38628.92	74873.29
4A	12.46	9.72	95756.23	102826.31	12.47	10.73	28637.93	54730.93
4B	10.38	8.95	94736.32	99474.32	13.82	9.33	35654.47	47857.49
4C	11.72	9.75	36252.32	54637.38	14.28	8.31	34526.38	56849.94
4D	12.84	11.26	65357.21	73645.23	11.27	10.36	29336.41	46736.39
Avg	**11.62**	**9.74**	**71595.86**	**85015.94**	**12.57**	**10.09**	**37598.62**	**59748.10**
D	**2.24**	**1.88**	**18460.91**	**14587.54**	**1.59**	**1.31**	**8111.17**	**11575.10**

Stiffness

	Curlex HD Machine				Curlex HD Cross			
	Bending length		Flexural rigidity		Bending length		Flexural rigidity	
	cm	cm	mg.cm	mg.cm	cm	cm	mg.cm	mg.cm
	unused	used	unused	used	unused	used	unused	used
1A	10.15	12.31	61140.36	45378.22	10.30	11.21	29287.42	23567.47
1B	10.90	11.82	75719.78	45371.27	10.05	12.74	27206.18	24373.46
1C	9.50	11.21	50130.34	34748.82	10.05	12.74	27206.18	22735.43
1D	10.75	12.32	72636.55	64738.11	10.70	11.46	32833.77	30484.23
2A	10.65	11.21	92498.09	74653.96	10.75	10.96	71433.08	65474.11
2B	11.30	11.84	110489.06	93746.43	12.30	14.27	107001.36	94478.35
2C	10.05	12.42	77728.83	65734.35	11.95	12.38	98124.55	84646.56
2D	9.60	11.96	67748.18	54638.24	10.25	11.47	61922.08	53738.27
3A	11.00	14.25	128367.81	95757.85	10.55	13.74	89133.25	74649.54
3B	11.85	15.21	160484.52	116262.21	9.95	10.47	74774.17	65859.18
3C	8.05	10.36	50311.32	45378.87	12.75	13.47	157330.50	125426.32
3D	8.95	11.86	69142.84	66548.30	10.65	11.36	91691.95	85457.36
4A	10.15	12.41	86848.12	75856.46	11.80	12.47	91752.11	74648.35
4B	10.80	11.23	104624.54	95746.68	11.05	13.48	75345.42	64849.32
4C	9.20	10.38	64673.41	54748.54	11.60	12.35	87165.38	75653.43
4D	9.75	11.68	76979.69	71423.30	11.40	13.27	82734.11	69457.30
Avg	**10.17**	**12.03**	**84345.21**	**68795.73**	**11.01**	**12.36**	**75308.84**	**83429.80**
D	**0.97**	**1.24**	**29408.81**	**22587.99**	**0.87**	**1.11**	**34566.35**	**28420.32**

Tensile

	Enkamat Machine				Enkamat Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	unused	used	unused	used	unused	used
1	41.5	44.9	88.7	22.2	43.7	21.3	132.5	34.8
2	55.3	39.8	135.9	36.6	10.3	6.5	147.6	41.3
3	57.1	38.0	63.6	37.0	37.3	19.7	57.4	19.1
4	19.8	23.5	17.1	52.6	16.9	9.5	100.7	64.6
5	44.3	28.3	57.9	42.5	22.4	8.3	137.8	83.4
6					30.6	14.8	84.6	54.6
7					49.7	22.6	46.6	16.4
8					15.3	5.4	76.1	30.4
Avg	**43.6**	**34.9**	**72.7**	**38.2**	**28.3**	**13.5**	**97.9**	**43.1**
D	**14.9**	**8.8**	**43.7**	**11.0**	**14.4**	**7.0**	**38.2**	**23.1**

Tensile

	Enviromat Machine				Enviromat Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	unused	used	unused	used	unused	used
1	10.7	6.5	23.1	16.7	12.3	2.52	23.5	12.5
2	9.0	4.8	21.0	11.3	9.5	3.21	30.4	14.9
3	6.8	3.8	17.3	10.9	10.6	1.54	21.2	8.6
4	7.3	4.3	25.2	14.3	11.4	2.01	13.5	6.6
5	8.5	3.9	33.5	18.7	10.1	1.93	16.3	7.9
6					11.3	2.03	14.3	8.5
7					8.5	2.56	21.0	10.8
8					13.5	1.93	17.5	5.7
Avg	**8.5**	**4.6**	**24.0**	**14.4**	**10.9**	**2.15**	**19.7**	**9.5**
D	**1.5**	**1.1**	**6.0**	**3.4**	**1.6**	**1.6**	**5.6**	**3.1**

Tensile

	Landlok TRM 1060 Machine				Landlok TRM 1060 Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	unused	used	unused	used	unused	used
1	55.0	56.4	15.4	42.4	90.3	51.1	21.0	25.3
2	58.0	61.0	21.7	20.4	57.0	58.3	32.6	22.1
3	62.0	56.8	22.6	12.5	96.8	24.4	23.2	56.5
4	94.8	86.9	21.5	23.0	103.3	49.5	21.8	23.4
5	89.5	32.4	19.5	16.8	83.6	26.7	22.0	20.5
6					98.5	39.7	19.4	28.0
7					81.5	42.6	25.2	26.9
8					53.0	49.7	27.0	33.3
Avg	**71.9**	**58.7**	**20.1**	**23.0**	**83.0**	**42.8**	**24.0**	**29.5**
D	**18.8**	**19.4**	**2.9**	**11.5**	**18.8**	**12.0**	**4.2**	**11.6**

Tensile

	PP5 XCEL Machine				PP5 XCEL Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	unused	used	unused	used	unused	used
1	102.7	80.8	45.9	18.1	127.7	55.7	63.9	17.4
2	89.6	39.6	33.6	18.1	100.8	42.8	58.2	19.0
3	90.3	58.7	41.8	22.0	87.5	62.3	52.4	22.3
4	96.4	56.3	37.0	19.7	69.7	27.7	84.8	59.2
5	87.6	64.0	40.7	25.2	75.3	31.5	66.5	28.0
6					100.6	55.1	53.6	25.3
7					97.3	41.7	48.2	30.3
8					96.8	56.8	59.2	18.4
Avg	**93.3**	**59.9**	**39.8**	**20.6**	**94.5**	**46.7**	**60.8**	**27.5**
D	**6.2**	**14.8**	**4.7**	**3.0**	**17.8**	**12.7**	**11.4**	**13.6**

Tensile

		NAG S-350 Machine				NAG S-350 Cross			
		Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
		lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
		unused	used	unused	used	unused	used	unused	used
1		67.6	32.8	73.3	38.6	45.6	19.4	100.6	37.4
2		110.8	69.2	58.4	28.4	48.9	23.8	78.7	30.1
3		58.4	28.0	100.8	77.2	52.5	24.9	69.7	22.6
4		74.7	47.8	85.3	64.4	87.0	21.3	90.1	28.9
5		66.3	29.6	62.7	29.4	74.4	64.4	84.4	38.6
6						100.4	67.3	74.8	18.9
7						83.4	28.9	81.3	34.5
8						82.3	23.8	75.2	36.7
Avg		**75.6**	**41.5**	**76.1**	**47.6**	**71.8**	**34.2**	**81.8**	**31.0**
D		**20.5**	**17.4**	**17.3**	**22.0**	**20.3**	**19.7**	**9.8**	**7.2**

Tensile

	Greenfix CFO 72RR Machine				Greenfix CFO 72RR Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	unused	used	unused	used	unused	used
1	45.6	14.8	37.7	12.8	75.6	29.7	110.8	37.8
2	65.4	18.5	76.6	24.8	86.4	30.5	86.9	43.1
3	58.6	28.4	61.3	20.4	97.4	33.8	95.4	29.8
4	63.2	23.9	58.5	17.4	38.3	13.5	77.9	33.8
5	39.2	11.2	66.9	25.5	64.1	28.4	84.6	21.8
6					85.5	37.8	75.4	30.1
7					77.5	48.9	84.4	53.3
8					92.3	28.3	62.8	13.8
Avg	**54.4**	**19.4**	**60.2**	**20.2**	**77.1**	**31.4**	**84.8**	**33.0**
D	**11.4**	**6.9**	**14.3**	**5.3**	**18.8**	**10.0**	**14.2**	**12.2**

Tensile

	Curlex HD Machine				Curlex HD Cross			
	Tensile peak force		Relative elongation		Tensile peak force		Relative elongation	
	lbs/in^2	lbs/in^2	%	%	lbs/in^2	lbs/in^2	%	%
	unused	used	Unused	used	unused	used	unused	used
1	40.8	28.7	76.6	35.8	14.8	6.8	38.9	14.8
2	26.4	12.4	30.1	19.0	41.5	13.8	51.0	32.4
3	17.7	9.7	47.3	20.7	9.6	3.6	32.9	17.3
4	7.1	3.9	12.2	4.9	23.6	11.5	81.4	33.9
5	8.1	3.7	55.2	31.6	29.7	18.6	78.0	41.9
6					1.8	0.9	63.3	28.4
7					26.5	11.9	92.7	31.5
8					9.8	6.2	25.7	15.6
Avg	**20.0**	**11.7**	**44.3**	**22.4**	**19.7**	**9.2**	**58.0**	**27.0**
D	**14.0**	**10.2**	**24.5**	**12.1**	**13.0**	**5.8**	**24.7**	**9.9**

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