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ABSTRACT

In recent years, there has been a great deal of interest in the development and use of natural-fiber rolled erosion control products (RECPs) to sustainably manage soil erosion. Natural fibers offer many advantages over synthetic fibers in that they are biodegradable, can absorb water, and can easily conform to underlying soil surfaces. In the US, coir, jute, straw, and wood excelsior fibers are commonly used to manufacture RECPs; however, efforts are being made around the world (e.g. United Kingdom, Canada, and the US) to explore potential uses of other natural fibers, such as hemp, flax, sugarcane, peanut shells, palm leaves, and cotton. Many researchers have characterized the properties of natural-fiber RECPs and documented their successful use in erosion control applications. For example, work has been done in India to evaluate the physical and engineering characteristics of coir and jute fibers for use in erosion control. Research efforts in the US and Europe have focused on the development of standardized test methods for characterizing RECPs and the performance of large- and small-scale tests. Many case histories have been published that document the successful use of natural-fiber RECPs. This paper presents an overview of natural-fiber RECP practices that are being used around the world and emergent fibers that are being evaluated for use as RECPs. International practices and guidance for the selection of natural-fiber RECPs for erosion control are given.

INTRODUCTION

Soil erosion is a significant issue in the sustainable management of land resources. Although agricultural lands are the primary source of soil erosion, with more than 80% being severely to moderately eroded (Pimentel et al. 1995), accelerated erosion rates from unprotected hillslopes and construction sites are of particular concern because of the relatively high rates at which they erode (Ziegler et al. 1997, Viadero 2006). Soil erosion decreases the stability of slopes; reduces soil productivity through the loss of water, nutrients, soil organic matter, and soil biota; and can adversely impact the quality of surface waters entering down-gradient streams.

Rolled erosion control products (RECPs) provide engineers with a low-cost and effective means to meet these challenges. RECPs are temporary degradable or long-term non-degradable products manufactured or fabricated into rolls designed to reduce soil erosion and assist in the growth, establishment, and protection of vegetation (ECTC 2001). Because they are manufactured into rolls, they can be easily installed and anchored along a slope or drainage channel. RECPs provide immediate ground cover to protect against raindrop impact, stabilize seed and soil within their structures, allowing seeds to germinate quickly and vegetation to grow, and reinforce vegetation once it is established.

NATURAL-FIBER RECPs

Many different types of RECPs have emerged since natural-fiber jute mats were first used for erosion control in the 1950s in the US (Lancaster and Myrowich 2005) and in India (C-DOCT 2002). In the US, RECPs made of synthetic fibers, such as polypropylene, polyvinyl chloride, polyester, and nylon initially dominated the market. This could be due in part to their perceived superior performance to natural-fiber RECPs. However, RECPs made of natural fibers, such as coir, jute, straw, and wood excelsior, reemerged in the 1990s. Although it has been shown that natural fibers offer many advantages over synthetic fibers due to their biodegradability, water absorption, and flexibility, it is only in the last 10 years that natural fibers have received attention. This most recent thrust in the development of new natural-fiber products in the US and around the world has stemmed from a renewed focus on sustainability and the use of renewable, locally available, low-cost, and abundant materials.

Shepley et al. (2002) reported that RECPs made of natural fibers were more popular than those made of synthetic fibers in the US, based on a survey of manufacturers of both synthetic and natural fiber RECPs. The most popular erosion control RECPs in the US are currently made of straw and wood excelsior (Shepley et al. 2002), which are native to the US. A review of the 2009 Specifier's Guide (IFAI 2009), which compiles product listings from participating manufacturers, indicates that 53 different natural-fiber RECPs (19 wood, 16 straw, 9 coir, 6 straw/coir blends, and 3 jute) and 28 different non-degradable RECPs (3 with a natural-fiber matrix) are currently available in the US. For these products, coir and jute are predominately exported from Sri Lanka and India.

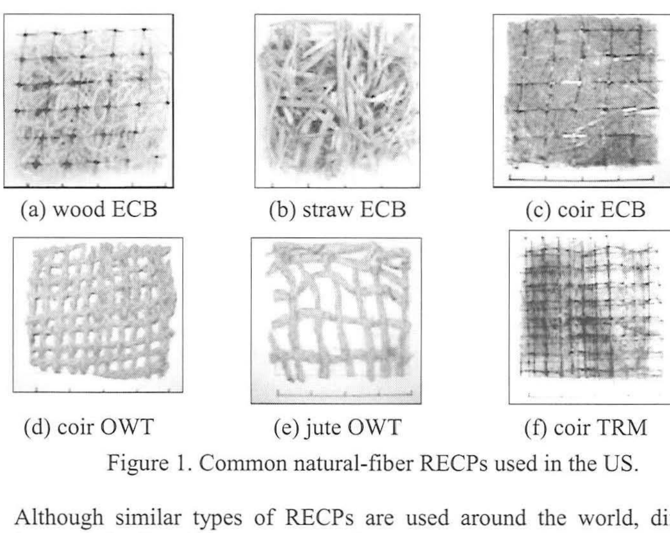
Work is also being conducted in the US to evaluate other types of natural fibers for use as RECPs. For example, work has been done to evaluate the use of fiber from sugarcane stalks (Thames 1997) and sugarcane bagasse (Dinu and Saska 2006) in RECPs. Sugarcane bagasse erosion control mats were found to be comparable in specific mass, thickness, and swelling, lower in tensile strength, and higher in water absorption to four commercially available straw, coconut, and wood excelsior mats (Dinu and Saska 2006). Fibers from peanut shells have also been evaluated for use in RECPs (Bieak and George 2003.) They found that mats could be made to produce comparable flexibility, strength, and light and moisture transmission requirements to commercially available RECPs. Cotton fiber is also being used in commercially available, hydraulically applied erosion control products (HECPs) (Cotton Inc. 2008). The cotton being used is a byproduct of the cotton-gin process, is non-toxic, adds nutrients to the soil, and requires less water during applications than commonly used HECPs.

In India, RECPs have traditionally been manufactured from coir or jute fibers, which are native to India. India is the largest country that produces coir fiber (Venkatappa Rao and Balan 2000a). Coir has high durability, slow biodegradation, is less sensitive to ultraviolet radiation than other natural fibers, and is reputed to be the strongest of all known natural fibers (C-DOCT 2002). Coir fiber RECPs are also being manufactured in countries such as Canada and South Africa. Jute is also widely available in India; however, degrades quickly in humid conditions and is susceptible to microbial attack (Banerjee and Unni 2000).

Work is also being conducted around the world on other types of natural fibers. For example, extensive work on the use of palm leaves from *Borassus aethiopum*, grown in West Africa, and *Mauritia flexuosa*, grown in Latin America, is being conducted in the United Kingdom (Smets et al. 2007, Bhattacharyya et al. 2009). The palm-leave mats have been found to significantly reduce soil erosion from bare soil slopes. Recently, products made from wheat and barley straw, hemp, and flax have emerged in Canada. Hemp fiber mats are also being manufactured and used in the United Kingdom to protect soil surfaces from wind and rain erosion.

CHARACTERIZATION OF NATURAL FIBERS

Structure type is typically used to broadly define and classify different types of RECPs. In the US, the Erosion Control Technology Council (ECTC) developed classifications for structure type and published standard definitions (ECTC 2001): (1) Erosion control nets (ECNs) are temporary, degradable planar woven natural fiber or extruded geosynthetic meshes used to anchor loose fiber mulches; (2) Open weave textiles (OWTs) are temporary, degradable RECPs composed of processed natural or polymer yarns woven into a matrix, used to provide erosion control and facilitate vegetation establishment; (3) Erosion control blankets (ECBs) are temporary, degradable RECPs composed of natural or polymer fibers that are mechanically, structurally, or chemically bound together to form continuous matrices; and (4) Turf reinforcement mats (TRMs) are long-term, non-degradable RECPs composed of UV-stabilized, non-degradable, synthetic fibers, nettings and/or filaments processed into three-dimensional (3-D) reinforcement matrices. Figure 1 shows several natural-fiber RECPs, characterized as ECBs, OWTs, and TRMs, that are commonly used in the US.



(a) wood ECB (b) straw ECB (c) coir ECB

(d) coir OWT (e) jute OWT (f) coir TRM

Figure 1. Common natural-fiber RECPs used in the US.

Although similar types of RECPs are used around the world, different terminology can be found in some areas. For example, the term "erosion control meshes" (ECMs) is commonly used to refer to OWTs in India (Venkatappa Rao 2000). In the United Kingdom, the term "geotextile" is commonly used to refer to a RECP, and "mats" is broadly used to include OWTs (Bhattacharyya et al. 2009).

Fiber type

Although structure type is important in defining and classifying different RECPs, it is the matrix fiber type that defines the ultimate performance and functional longevity of RECPs. Natural fibers can vary widely in their chemical composition, physical, morphological, and mechanical properties, and longevity. For example, straw RECPs have typical functional longevities in the range of three to twelve months; whereas, coir RECPs have typical functional longevities in the range of three years. The functional longevity and strength of coir fiber is due to its lignin content (C-DOCT 2002). A comparison of lignin and cellulose composition for natural fibers used in RECPs is given in Table 1.

Table 1. Chemical composition of some natural fibers used in RECPs (after Rowell 2001)

Fiber	% Lignin	% Cellulose
Coir	30-45	35-62
Jute	21-26	45-63
Wheat straw	16-23	33-39
Deciduous wood	23-30	38-49
Sugarcane bagasse	18-26	32-37
Cotton	0.7-1.6	85-90
Hemp	9-13	57-77
Flax	21-23	43-47

Natural fibers used in RECPs typically come from vegetable sources due to their enhanced strength, elongation, and durability in comparison to animal and mineral fibers (Rankilor 2000). They can further be categorized based on the part of the plant they come from: (1) bast/stem (i.e. jute); (2) seed/fruit (i.e. coir); (3) stalk (i.e. straw); or (4) hardwood (i.e. wood excelsior). This difference in origin provides the basis for differences in their basic properties. For example, bast/stem fibers generally have higher tensile strengths than other vegetable fibers. Seed/fruit fibers protect the seeds and fruits of plants.

LABORATORY TESTING

Many researchers have characterized the properties of RECPs and documented their successful use in erosion control applications. In India, a significant amount of work has been done to evaluate the physical and engineering characteristics of coir and jute RECPs (i.e. Venkatappa Rao and Balan 2000b, Venkatappa Rao et al. 2000). In other parts of the world, such as in the US and Europe, efforts have focused on the development of standardized test methods for characterizing RECPs (Sprague et al. 2002) and the performance of large-scale and small-scale bench-scale tests (i.e. Rickson 2002 and Smith et al. 2007).

In the US, the Erosion Control Technology Council (ECTC) in conjunction with TRI/Environmental, Inc. (TRI) recently developed index and bench-scale tests for the characterization of RECPs, several of which have become American Society for Testing and Materials (ASTM) standardized test methods. Index tests provide characteristic physical properties of RECPs and allow for the comparison of different RECPs. Performance tests provide information about the erosion control performance of RECPs under conditions similar to the intended application. Although many manufacturers and researchers believe these tests are important, they are not being widely used by manufacturers in the US. In addition, the tests are currently only being performed by one testing laboratory (TRI) and manufacturers' in-house testing laboratories. There have also been few studies that relate basic index properties to laboratory (e.g. Ziegler and Sutherland 1998, Rickson 2002) or field performance (e.g. Fifield 1992, Smith et al. 2005). Selected standardized index and bench-scale tests are summarized below.

Light penetration

Light penetration is measured in accordance with ECTC (2001) and ASTM D6567. In the test, light is projected through frosted glass to dissipate the light, then through a RECP specimen in a closed container. The amount of light that passes through the RECP is measured using a light meter. The percentage light penetration is calculated as the ratio of the amount of light that passes through a RECP specimen to the amount of light that passes without a specimen.

Water absorption

Water absorption testing is performed in accordance with ECTC (2001) and ASTM D1117. In the test, RECP specimens are placed on a screen and submerged in water for 24 hours. The RECP specimens are removed, allowed to drain for 10 minutes, and weighed. The water absorptive capacity is calculated as the ratio of the water held by the RECP to the original dry weight of the specimen.

Rainsplash erosion

Rainsplash erosion testing is performed in accordance with ASTM D7101. In the test, rainfall is produced by a laboratory rainsplash simulator that is capable of creating uniform drops with a median diameter of 3.0 to 3.5mm from a drop height of 2000 mm. An adjustable slope table containing three channels is located beneath the simulator. The base of each channel contains a recessed hole where prepared soil cores are placed and tested.

Tests are performed for durations of 30 minutes. Soil is collected and runoff is measured at 5-minute increments during the test. Tests are conducted for rainfall intensities of 2±0.2 in/hr, 4±0.2 in/hr, and 6±0.2 in/hr. A minimum of five tests is performed for each condition tested. Photographs of the rainfall simulator constructed at Syracuse University are shown on Figure 2.

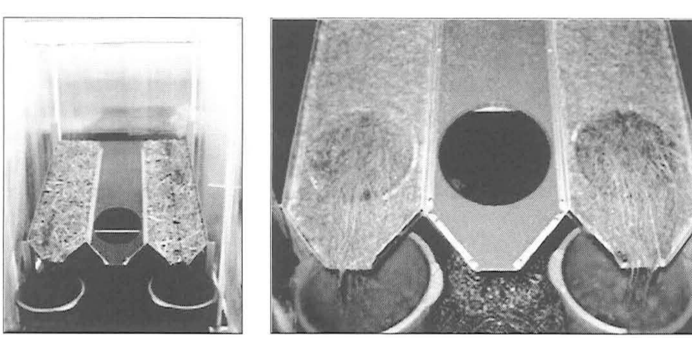


Figure 2. Photographs of the rainsplash simulator at Syracuse University.

Vegetation enhancement

Vegetation enhancement tests are performed in accordance with ASTM D7322. In the test, containers of soil are sown with seeds and watered. RECPs are then placed on the containers, with several containers remaining uncovered to serve as bare soil controls. The containers are then placed in an environmentally controlled chamber. The containers are periodically watered and monitored for vegetative growth. The percentage vegetation improvement is calculated as the ratio of the weight of vegetation in the RECP-covered containers to the non-RECP covered bare soil control containers, measured at 21 days germination. Photographs of the container and environmentally controlled chamber at Syracuse University are shown in Figure 3.

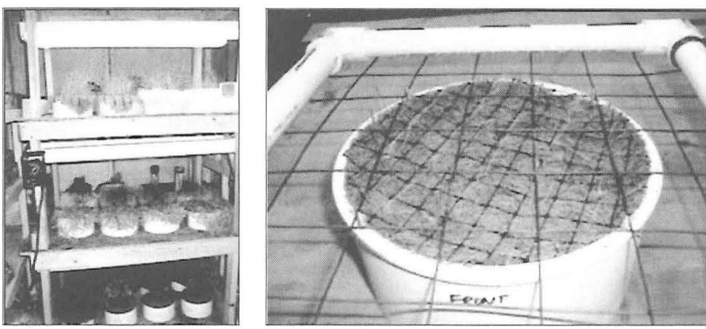


Figure 3. Photographs of the (a) environmentally controlled chamber and (b) container for the vegetation enhancement tests at Syracuse University

Although significant progress has been made in characterizing RECPs and developing test methods, there is a need for universally-accepted RECP test methods and procedures. It is believed that standardization is necessary in countries such as India to be able to compete in international RECP markets. The test methods also need to be thoroughly evaluated to determine their usefulness, repeatability, and reproducibility. There is also a need to establish correlations between measured index properties and bench-scale performance of RECPs and field parameters to aid in the proper design of RECPs. Without this, design will continue to be based on maximum allowable slopes and shear stresses, without consideration for the unique and beneficial properties of natural fibers.

FIELD STUDIES

RECPs are used around the world in a variety of applications and many case studies have been published documenting their successful use. For example, coir erosion control mats are being used to revegetate steep bare slopes in India (Venkatappa Rao and Balan 2000c) and natural jute products are being used for slope protection and quarry restoration in Hong Kong (Lam and Braim 2002). In the US, the largest RECP market is in the highway construction industry, where engineers are faced with erosion from highway drainage ditches and cut and fill slopes (Shepley 2002.) RECPs are also commonly used in landfill, urban and suburban drainage areas, building construction, and landscaping markets (Shepley 2002). In addition to the large number of case studies that have been published, the suitability and performance of RECPs for erosion control applications have been evaluated by many researchers. Some of these are described below.

McCullah and Howard (2000) compared the field performance of 13 different RECPs installed on a 4H:1V slope over a 9-month period. The RECPs were made from straw, rice straw, straw/coconut, coconut, and aspen fibers. Sediment collection troughs were installed at the base of each test section. On average, the RECPs provided an 81% reduction in soil loss than the unprotected bare soil control slope.

Casas et al. (2002) compared the performance of 5 different RECPs for the revegetation of burned slope areas in Spain. The RECPs included a coir grid, a jute grid, a high density polyethylene (HDPE) geogrid, straw mulching, and a straw/coir organic mat. For the study, the RECPs were seeded with 7 different grass species and evaluated for growth every 15 days over a 3-month period. It was found that the straw/coir organic mat, followed by the coir grid, was the most effective RECP for the establishment of vegetation at the site, based on vegetation survival rates.

Bhatia et al. (2002) compared the performance of 7 different RECPs installed in a drainage channel in central New York. The RECPs included wood excelsior and straw/coir ECBs and TRMs made of nylon, PP net with polyolefin matrices, and PP net with coir matrices. The performance of the RECPs was evaluated based on visual observations of vegetative growth and measured deformations of channel cross-sections. With the exception of one TRM, the RECPs were successful in establishing vegetation over the 22-month evaluation period, although to varying degrees. It was also found that the cross-sections, with the exception of two, exhibited soil/sediment deposition. The erosion that did occur was minimal and did not impact the overall performance of the channel.

Smith et al. (2005) considered these RECP properties and related them to the performance of six different RECPs (PP matrix and triple PP net, coir fiber matrix and triple PP net, PP strands reinforced with coir twine, and triple PP mat of bioriented geogrids) installed in a drainage channel in central New York, in terms of both soil erosion and vegetative growth. It was found that percentage area cover and water holding capacity/percentage wet weight play a direct role in initial soil erosion protection and long-term vegetation establishment. It was difficult to assess the importance of RECP induced roughness and depth of water ponded at the site because of the relatively good performance of the RECPs and the limited flow in the channels. However, it is believed that these properties can play an important role in critical applications, such as in highly erosive soils.

Vishnudas et al. (2006) conducted field tests in the Amachal Watershed in Trivandrum, Kerala, India to evaluate the effectiveness of coir RECPs for embankment protection. The fresh coir matting RECP used for the study had a smallest mesh opening of 6 x 6 mm^2, a density of 0.74 kg/m^3, and a tensile strength of 13.8 kN/m^3. The experiment was conducted in three stages, coir RECP with grass *(Axonopus compressus)*, coir RECP alone, and a bare soil control plot. The tensile strength of the RECPs was found to have reduced by about 70% seven months after installation and further reduced by about 81% at the end of nine months. The establishment of vegetation during this period was found to be effective in erosion control.

In summary, a significant amount of work has been done that documents the successful performance of RECPs in erosion control applications. RECPs effectively reduced soil erosion in the majority of the field studies reviewed.

Differences in RECP performance were observed in terms of the growth of vegetation. Several researchers also noted index properties of RECPs that they believe are important to their performance. For example, Smith et al. (2005) found that percentage area cover and water holding capacity/percentage wet weight play a direct role in initial soil erosion protection and long-term vegetation establishment. Although these studies provide important information about the performance of RECPs, the majority of studies are qualitative in nature and only provide information on particular site conditions, such as climate, soil types, vegetation types, and topography.

CONCLUSION

Although significant progress has been made in characterizing RECPs and developing test methods, there is a need for universally-accepted RECP test methods and procedures. RECP test methods need to be thoroughly evaluated to determine their usefulness, repeatability, and reproducibility. There is also a need to establish correlations between measured index properties and bench-scale performance of RECPs and field parameters to aid in the proper design of RECPs.

A significant amount of work has been done that documents the successful performance of RECPs in erosion control applications. RECPs effectively reduced soil erosion in the majority of the field studies reviewed. In general, there was little distinction in the overall performance of the various types of RECPs in terms of minimizing soil erosion, whether they were made of synthetic or natural fibers. Differences in RECP performance were observed in terms of the growth of vegetation. In general, natural fiber RECPs were found to be more effective in establishing vegetation than synthetic fiber RECPs.

Both natural and synthetic RECPs were effective in reducing rainsplash erosion in the laboratory, although to varying degrees, with the exception of buried TRMs. In general, the natural fiber OWTs and ECBs (jute, coir, wood) were more effective in reducing rainsplash erosion than the synthetic fiber TRMs. High surface coverage, thickness, and water absorption capacity were noted as being important RECP properties. In terms of overland flow, there were varying results. RECP properties such as good drapability and thick fibers were noted as being important.

There is a need for: universally-accepted RECP testing methods and procedures; global education on the different types of RECPs available and their effectiveness; and proper design guidelines. These goals will only be realized through international collaboration between manufacturers, designers, engineers, and researchers.

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