Evaluation of Effectiveness and Cost-Benefits of Woolen Roadside Reclamation Products: Lab Tests

Task 3 Report

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November 2016

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Acknowledgements

The authors would like to thank the technical advisory committee for providing their expertise and sharing information for this project:
Kris Christensen
Jennifer Davis
Scott Helm
Phil Johnson
Alan Woodmansey

We acknowledge Phil Johnson for his excellent idea to explore wool as a potential fiber for improving roadside reclamation materials. We thank Michael Ramy Jr. and Brian Dingels of Ramy Turf Products and Ero-Guard, Inc. for their interest in participating in this research. Their knowledge and skills of ECB development was responsible for the development of the woolen ECB product and directly contributed to the success of this research.

We are indebted to the Montana wool experts and producers who taught us about wool production, its manufacture into products and the wool industry. Contributors were Sue and Ed James of Sugar Loaf Wool Carding Mill, LLC, Becky Weed and Dave Tyler of Thirteen Mile Lamb and Wool Company, and Thayne Mackey of Brookside Woolen Mill.

Finally, the authors would like to thank Eli Cuelho of WTI for organizing and interpreting the standard tests conducted on the woolen erosion control products, and Stuart Jennings of KCH for

organizing and interpreting analytical tests.

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Glossary

Batt	a piece of felted or carded wool material in rolls or sheets, such as wool
Carding	a mechanical process to disentangle unorganized clumps of wool fiber and align them to be parallel with one another
Felt	a textile that is produced by matting, condensing and pressing fibers, such as wool, together
Needle felt	“barbed” needles in machines enter wool and grab top layers and intertwine them with interior layers of fibers in a continuous repeated process to make wool fabric
Noil	short fiber removed by the combing of wool
Roving	a slightly twisted roll or strand of unspun wool fiber
Scour	the removal of wool wax (lanolin), suint (perspiration), dirt, excrement, dust and other matter from the fleece in water.
Wet felt	warm soapy water is applied to layers of wool and it is repeatedly agitated and compressed to make a single piece of fabric
Worsted	wool or yarns that have a long staple length (4 inch fibers and longer only), are carded *and* combed, are stronger, finer, smoother and harder than woolen yarns/wool

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC	ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

1 INTRODUCTION

This document is the Task 3 Report for evaluating the effectiveness of woolen roadside reclamation products. The overall objective of the project is to evaluate wool products that can be used for roadside reclamation projects by the Montana Department of Transportation (MDT) and other agencies. The project seeks to develop and test potential wool products that can be easily produced as complementary or replacement products for existing roadside reclamation and best management practices. The project team selected laboratory tests for the most promising wool products (see Task 2 Report) to assure they meet specifications for MDT and Federal Highway Administration (FHWA) deployment.

The primary objective of Task 3 and this report is to evaluate key geotextile material characteristics and the nutrient content of the woolen products developed by this project, as well as those of the standard reclamation erosion control products. This task seeks to compare existing specifications of roadside reclamation products to their woolen equivalents. The results will assure transportation agencies that woolen materials developed by the project meet or exceed the specifications of comparable existing reclamation products.

First, the research team collected required specifications of products from MDT. Then, the research team, working with the Technical Panel and Western Transportation Institute's (WTI) geotextile specialist, sent samples to a commercial lab to evaluate whether the woolen erosion control products met minimum required material properties outlined in *Montana's Standard Specifications for Road and Bridge Construction*. Specifically, the commercial lab evaluated tensile strength (ASTM D4595), performance in protecting hillslopes from rainfall-induced erosion (ASTM D6459), and performance in protecting earthen channels from stormwater-induced erosion (ASTM D6460).

Lab tests of woolen and standard reclamation product chemical and physical characteristics were also deemed important to measure as a comparison of products. These tests determined whether wool was providing additional macro- or micro-nutrients or increased water holding capacity compared to standard products.

The wool silt fence products developed for this project were not developed to the stage of commercialization. It was decided that the use of limited project funds to test the wool silt fence was not an efficient or effective use of funding.

2 BACKGROUND

Highway rights-of-way management following road construction on MDT lands requires creating conditions conducive to the establishment and survival of reclamation species while controlling soil erosion, surface runoff, and water sedimentation. Woolen erosion control products have many attributes that may make them superior to existing standard materials. This project seeks to develop and test the effectiveness of woolen erosion control, soil retention and vegetation establishment products for roadside reclamation purposes. Wool products will be compared to existing materials that often use imported coconut fiber (coir) in erosion control fabrics or synthetic non-biodegradable geotextile materials. Another standard practice is to use blankets of wood-based compost along roadsides, particularly in harsh environments or on slopes, to increase protection of seedlings, add nutrients, retain moisture, and reduce erosion to increase the success rate of re-vegetation. The project includes lab tests of the wool that is added to wood-based compost to potentially increase its effectiveness.

Erosion control fabrics generally meet the requirements established by the Erosion Control Technology Council and the U.S. Department of Transportation, Federal Highway Administration's standard specifications for construction of roads and bridges on federal highway projects [FP-03 2003 Section 713.17, Type 3.B]. There are several types of erosion control blankets (ECB) including temporary (short-term) and extended (long-term). The short-term products are all double-netted, 100% straw products that are light-duty and used primarily for enhancing plant establishment, or as a covering over compost/mulch for retention purposes. The short-term performance period is one growing season. The long-term products are all double-netted, 70% straw /30% coconut blankets used primarily for enhancing plant establishment on slopes steeper than 3:1 and to line ditches. The performance of the long-term blanket should extend beyond one growing season.

One of the most commonly used rolled ECBs produced is comprised of straw with coconut fibers (coir). According to the manufacturer's information sheet, this type of rolled ECB has a functional longevity of up to eighteen months. Rolled ECB products are intended to reduce soil erosion, water run-off and improve the environment for revegetation.

2.1 Standardized Laboratory Tests

The project developed new wool ECB products that have not been described according to MDT Manual's categories (short- or long-term blanket) or performance standards. The wool products use needs to be specified in standard provisions such as coir netting products and hybrid blankets. These categories include product types that can be applied to over 95% of the sites and conditions that MDT would use an ECB or matting. (per. comm., Phil Johnson, MDT Reclamation Specialist). Lab tests were selected based on specifications and performance attributes that influence overall function of the ECB. Test methods and specifications evaluated during this project were provided by MDT for rolled ECVBs and are generally the same as those contained in the MDT Manual, with exception of mass per unit area.

Laboratory tests for the wool/straw ECB develop by this project were selected based on requirements in MDT's manual, *Standard Specifications for Road and Bridge Construction*

(MDT Manual including the *Supplemental Specifications*) and the number of replications were limited by the costs for the tests. The MDT Manual has three performance attributes for temporary rolled erosion control products-type III; they are minimum tensile strength, maximum "C" factor (soil loss), and minimum shear stress tests (MDT 2014). Cost estimates were obtained from two laboratories: Testing, Research, Consulting and Field Services (TRI Environmental, Inc.) and Geo Testing Express.

The selected standardized laboratory tests for the wool/straw ECB are defined as follows:

1) Mass per unit area of the combined fiber matrix and netting (g/m^2): A measure of the bulk of the matrix and netting/stitching.
2) Tensile strength – machine direction (kg/m^2): A measure of the strength of the materials used in the blanket's netting and stitching. The purpose of the netting/stitching is to hold the matrix in place. The stronger the netting/stitching, the longer the matrix remains in uniform distribution.
3) C Factor (measured shear strength @ loss of 0.5 inch (1.27 cm) of soil (kg/m^2): A measure of the ability of the blanket to protect the soil resource beneath the blanket.
4) Minimum shear strength – un-vegetated condition (kg/m^2): A measure of the strength of the blanket to withstand surface flow forces.

The results of the laboratory tests were used to compare wool ECB products to the standard ECB products, MDT performance standards, and MDT terms.

2.2 Analytical Laboratory Tests

Roadside reclamation products containing wool may perform similarly or better than traditional straw/coconut ECBs. Some ECBs may provide soil moisture retention to aid in plant growth. Scoured weed-seed free wool can store up to 400% of its weight in water (Upton 2003). Wool becomes saturated at 33% of its weight of moisture-free fibers (D'Arcy 1990). That is, when scoured wool absorbs water greater than 33% of its weight, the moisture is more readily available for plant growth and adsorption. This characteristic could make woolen erosion control blanket more advantageous in drier climates. In addition, sheep wool contains up to 17% nitrogen and can act as a slow release fertilizer for plant growth and development (Herfort 2010). Research from Europe testing the use of woolen fabrics for establishing vegetation on green roofs resulted in over three times more plant canopy cover when wool was used in mats compared to traditional coconut fibers mats (Herfort 2010). Thus, in addition to ECB performance tests, analytical tests were selected to characterize their nutrient content and water holding capacity for felted wool matts, 100% rolled wool ECB, straw/coconut rolled ECB and compost. The former two products were developed by the project; the latter two products are the controls for future (Task 4) field experiments.

3 MATERIALS AND METHODS

While various performance values of wool have been described in published literature that document the benefits of wool products, such as their strength and durability, water holding capacity and nutrient value; the capabilities of the new woolen roadside revegetation products developed by this project were unknown. Therefore, laboratory tests were used to quantify particular attributes of the woolen products and to use these values to compare to standard reclamation products used by MDT and other transportation agencies.

3.1 Standardized Laboratory Tests

Physical property testing was performed including measurement of mass per unit area of the newly developed wool reclamation products used in this study. The manufacturers of pure wool ECBs and wool/straw ECBs estimated the weight and proportion of wool and other components in each product and labeled them accordingly. We quantified the total mass of each product as well as the amount of wool in each product similar methods employed by the American Society for Testing and Materials (ASTM) D6475 standard (Standard Test Method for Measuring Mass Per Unit Area of Erosion Control Blankets). Mass per unit area was measured by subsampling five 10 cm by 10 cm (3.9 inch by 3.9 inch) pieces of each product and weighing each sample.

Material lab testing methods for geotextile fabrics for use in slope stabilization and erosion control followed standard ASTM testing methods. The number of wool/straw products and replications tested was dependent on available project funds. Testing requirements followed MDT's *Standard Specifications for Road and Bridge Construction*, 2014 edition. Page 503 of this MDT publication includes Table 713-5, which lists the following standards for "Temporary Rolled Erosion Control Property Requirements": ASTM D4595, minimum tensile strength, ASTM D6459, maximum C Factor (soil loss) and ASTM 6460, minimum shear stress.

Due to the high cost of lab tests and the limited funds, only one product and one replication of tensile strength, C factor, and shear stress was ordered from the lab (**Error! Reference source not found.**). The wool product tested was the 50% wool / 50% straw ECB because it is similar to the standard 70% straw / 30% coconut ECB currently used on most MDT roadside revegetation projects and was the product used as a control for the field experiments. Also, there were adequate quantities of these two products needed for laboratory testing. The 50% wool / 50% straw ECB was tested at TRI Environmental, Inc.'s (TRI) laboratory during summer 2016 for minimum tensile strength (ASTM D 4595), maximum C factor (ASTM D 6459) and minimum shear stress (ASTM D 6460). The 70% straw / 30% coconut ECB control product (Ero-Guard) was tested at TRI Environmental Laboratory in 2007 for tensile properties (ASTM D 6818).

Table 1. The products and lab tests evaluated.

Wool Product	Test	Purpose	Replication	Lab
50% Straw / 50% Wool ECB	ASTM D4595	Minimum tensile strength	1	TRI
50% Straw / 50% Wool ECB	ASTM D6459	Maximum "C" Factor (soil loss)	1	TRI
50% Straw / 50% Wool ECB	ASTM D6460	Minimum shear stress	1	TRI

3.2 Analytical Laboratory Tests

To aid in understanding the nutrient and water holding capacity benefits of the wool in each product, the woolen products were sent for laboratory tests for a suite of nutrients and water holding capacity measurements using standard lab methods at Energy Laboratory in Helena, MT (**Error! Reference source not found.**). Also, the standard straw/coconut ECB was sent for the same tests, for comparison purposes. The nutrient and water capacity tests (Table 2) were selected for their ability to influence seedling establishment and plant growth. These are common tests used by transportation departments to evaluate roadside soils before developing reclamation plans.

The following four products were tested:
1. Wool batt, which is a pure wool ECB derived from scoured wool that is subsequently carded and then felted by agitating in water.
2. Scoured wool, this product was used both at different ratios in the various rolled straw/wool ECBs and was added to the wood-based compost.
3. The standard rolled straw/coconut ECB, which is used as a control in field experiments.
4. A typical wood-based compost, which is used as a control in field experiments.

Table 2. Analytical methods for products and soil samples.

Measure of Interest	Analysis
pH (acidity level)	Saturated Paste
Electric Conductivity (EC)	Saturated Paste
Sodium Adsorption Ratio (SAR)	Calculation
Calcium (Ca)	Saturated Paste
Magnesium (Mg)	Saturated Paste
Sodium (Na)	Saturated Paste
Organic Matter (OM) Organic Carbon (OC)	Walkley-Black
Potassium (K)	NH_4OAC Extractable
Phosphorus (P)	Olsen
Nitrate (NO_3)	KCL Extract
Total Kjeldahl Nitrogen (TKN)	TKN Prep
Nitrogen (N), Total	Calculation
Carbon:Nitrogen (C:N) Ratio	Calculation
Percent Saturation	Pressure Plant
Water Holding Capacity (WHC)	Pressure Plant

4 RESULTS

The Task 3 laboratory bench test results identified attributes of the woolen products that are important for determining their success as viable commercial products. Lab results also compared and contrasted wool product attributes with standard industry products that are currently standard products being used by MDT and other agencies.

4.1 Standardized Laboratory Tests

Mass per Unit Area

Product mass (g/m^2), also referred to as area density, was measured for the newly developed wool reclamation products used in this study. Mass per unit area was determined for the wool reclamation products field tested on the US Highway 287 test site near Three Forks, MT, the wool silt fence that was field tested along U.S. Highway 14 near Martinsdale, MT, and the wool/straw ECBs field tested at the WTI's Transcend 2:1 (V:H) test slope near Lewistown, MT (Table 3).

Three different wool silt fence products, two carded pure wool blankets, and the four-pass needle punched pure wool blanket were tested for mass per unit area (Table 3). Table 3 provides the average weight of each product, and Table 4 provides a new naming convention for each product that will be carried through the remainder of this report. The light weight felted wool and wool/burlap silt fence had relatively even distribution of woolen material throughout each product. The heavier weight felted wool silt fence was highly variable in the mass per unit area of wool with some areas having twice the area density as other areas within the same product (Table 3). This most likely is a result of its manufacturing process, since this product was felted by agitating in a water tank (wet-felted) which has little quality control. Similarly, the heavier weight carded wool blanket had high variability area density compared to the lighter weight carded wool blanket. Carding is the first process in the felting process of wool where the fibers are aligned, and thus is not usually considered a "finished product". All developmental products had a lower mass per unit area than originally described during the manufacturing phase of the project (Tables 3 and 4).

The wool/straw ECBs made by Ero-Guard, Inc. (Ramy Turf Products, LLC) were manufactured and named according to the estimated ratio of wool to straw used for each ECB. The mass per unit area tested the accuracy of the naming convention and identified the true proportions of wool to straw in each product (Table 3). The mass of each component varied by as much as two times the weight in replications of the same product indicating that the wool and straw were not evenly distributed. This is understandable, given this was the first time Ero-Guard used its machinery to produce the variety of wool-straw rolled ECB products. The company and its technicians had to experiment with its machinery since it had never used wool (nor was designed to use wool) before this project. Control of the flow of wool and straw from the hoppers was particularly difficult to meet the desired wool:straw ratios in a consistent manner. This wool-straw mixture flows from the hoppers and is then placed between the two layers of netting and then the unit is stitched together to create the ECB.

Table 3. Mass per unit area of the wool reclamation products[1].

Products	Mass per Unit Area (grams (g)/meter^2 (m^2))					Average Mass (g/m^2)	Percent Composition
	1	2	3	4	5		
Wool Silt Fence (400 g/m^2)	173	354	169	244	232	234	-
Wool Silt Fence (200 g/m^2)	141	145	116	120	180	140	-
Wool / Burlap Silt fence							
Wool Component	188	189	169	234	191	194	-
Burlap Component	348	358	354	361	325	349	-
Carded Blanket (136 g/m^2)	62	47	105	54	99	73	-
Carded Blanket (68 g/m^2)	54	32	51	35	49	44	-
Needle Punch Wool Blanket	57	62	89	57	92	71	-
100% Wool ECB							
Wool Component	249	346	371	237	306	302	97%
Straw Component	15	11	14	5	1	9	3%
70% Wool / 30% Straw ECB							
Wool Component	146	168	180	207	178	176	54%
Straw Component	171	169	132	156	135	152	46%
60 Wool / 40% Straw ECB							
Wool Component	153	207	126	159	118	153	47%
Straw Component	176	219	179	180	118	174	53%
50% Wool / 50% Straw ECB							
Wool Component	103	93	105	122	76	100	38%
Straw Component	155	99	176	239	158	165	62%
30% Wool / 70% Straw ECB							
Wool Component	55	60	65	57	60	59	24%
Straw Component	205	327	219	146	195	219	76%
70% straw / 30% coconut (control) ECB[2]							
Straw / coconut combined	306	448	324	333	250	332	-

[1]See the metric conversion table at the beginning of this report.
[2]Data provided by Ero-Guard, Inc. for AASHTO NTPEP Rolled Erosion Control Product (RECP) Test Report, ASTM 6475.

The standard straw/coconut ECB was also variable in the distribution of the two components indicating that even distribution may not be common. The 100% wool ECB was the most accurate description of all the ECB, with 97% wool component. In general, the wool/straw ECBs tended to underestimate the wool component and overestimate the straw component (Table 4). The jute netting component of each blanket was relatively constant as it is the same product used for all the ECBs used in this study.

The results in Table 3 indicate the quantity of wool that is needed per square meter to manufacture the product that was tested by the project. For example, the most wool used by a product developed for the project is by the 100% wool ECB which requires approximately 300 g/m^2 of wool (8.8 ounces (oz) per square yard (yd^2) or the heavier pure wool silt fence which used 244 g/m^2 of wool (7.2 oz/yd^2). For future tasks of this project, this information will be helpful in evaluating relative costs, since wool is the most expensive raw material, relative to straw and jute, in the erosion control blankets and is an additive to compost.

Table 4. New product naming convention based on the product's actual weight and proportions.

Original Product Name / Description	New Product Name / Measured Description
Wool Silt Fence (400 g/m^2; 12 oz/yd^2)	Wool Silt Fence (244 g/m^2; 7 oz/yd^2)
Wool Silt Fence (200 g/m^2; 6 oz/yd^2)	Wool Silt Fence (140 g/m^2; 4 oz/yd^2)
Wool / Burlap Silt fence	Wool / Burlap Silt fence (194:349 g/m^2; 6:10 oz/yd^2)
Carded Wool Blanket (136 g/m^2; 4 oz/yd^2)	Carded Wool Blanket (73 g/m^2; 2 oz/yd^2)
Carded Wool Blanket (68 g/m^2; 2 oz/yd^2)	Carded Wool Blanket (44 g/m^2; 1 oz/yd^2)
Needle Punch Wool Blanket	Needle Punch Wool Blanket (71 g/m^2; 2 oz/yd^2)
100% Wool ECB	100% Wool ECB
70% Wool / 30% Straw ECB	55% Wool / 45% Straw ECB
60 Wool / 40% Straw ECB	50% Wool / 50% Straw ECB
50% Wool / 50% Straw ECB	40% Wool / 60% Straw ECB
30% Wool / 70% Straw ECB	25% Wool / 75% Straw ECB

Tensile Properties

Six replicates were tested to determine the tensile properties of the wool/straw ECB (using ASTM D 4595), and five replicates were tested to determine the tensile properties of the straw/coconut ECB (using ASTM D 6818). The results of these tests are summarized in Table 5. The two products had comparable ultimate strength values in the machine direction (MD); however, the wool/straw ECB had a greater ultimate strength in the cross-machine direction (XMD). The percent elongation was two and five times lower for the wool/straw ECB than the standard ECB indicating that the wool product is stiffer than the coconut/straw product.

Table 5. Results of the tensile property tests for the wool/straw and straw/coconut ECBs.

Product and Laboratory Test	Replicate[1]						Mean
	1	2	3	4	5	6	
40% Wool / 60% Straw ECB (previously called) 50% Wool / 50% Straw ECB (ASTM D 4595)							
MD- Ultimate Strength (kilogram/meter ((kg/m))	350	348	407	375	257	371	**351 kg/m**
XMD – Ultimate Strength (kg/m)	182	302	177	302	196	220	**230 kg/m**
MD – Elongation @ Ult. Load (%)	11.8	7.34	5.85	8.37	13.3	7.34	**9.0 %**
XMD – Elongation @ Ult. Load (%)	8.74	7.10	5.33	5.77	3.03	7.71	**6.3 %**
70% Straw / 30% Coconut ECB (ASTM D 6818)[3]							
MD- Ultimate Strength (kg/m)	350	451	430	336	395	-	**392 kg/m**
XMD – Ultimate Strength (kg/m)	173	173	170	175	184	-	**175 kg/m**
MD – Elongation @ Ult. Load (%)	17.3	26.0	18.7	22.7	22.0	-	**21.3 %**
XMD – Elongation @ Ult. Load (%)	25.3	35.3	32.7	32.0	29.3	-	**30.9 %**

[1]See the metric conversion table at the beginning of this report.
[2]MD = machine direction; XMD = cross-machine direction.
[3]Data provided by Ero-Guard, Inc. for AASHTO NTPEP Rolled Erosion Control Product (RECP) Test Report.

To determine how the wool ECB met MDT standards, we compared our results to the MDT Temporary Rolled Erosion Control properties for short- and long-term blankets (Tables 6 and 7). In Table 6, Type II is a short-term (12 month) ECB, and Type III is a long-term ECB (24 months). The wool ECB had an average tensile strength machine direction of 351 kg/m which met MDT standards for a short term (Type II B, C) or long term (Type III A) ECB. The wool ECB also met MDTs updated supplemental specifications of a minimum tensile strength of 190 lbs/ft (Table 7).

Table 6. MDT material specifications for temporary rolled erosion control, 2014.

TEMPORARY ROLLED EROSION CONTROL

Property	Type II				Type III		Type IV	Test Method
	A[1]	B	C	D	A[1]	B		
Typical functional longevity[2] (months)	12				24		36	N/A
Minimum tensile strength[3] lbs/ft^2 (kg/m^2)	5 (24.4)	50 (244.1)		75 (366.2)	25 (122.1)	100 (488.2)	125 (610.3)	ASTM D4595
Maximum "C" factor[4]	0.10 at 1V:5H	0.10 at 1V:4H	0.10 at 1V:3H	0.10 at 1V:2H	0.10 at 1V:5H	0.25 at 1V:1.5H	0.25 at 1V:1H	ASTM D6459
Minimum permissible shear stress[5,6] psf (Pa)	.25 (12)	.50 (23.9)	1.50 (71.8)	1.75 (83.8)	.25 (12)	2.00 (95.8)	2.25 (107.7)	ASTM D6460

Notes:

1. Obtain max "C" factor and allowable shear stress for mulch control nettings with the netting used in conjunction with pre-applied mulch material.
2. Functional longevities are for guidance only. Actual functional longevities may vary based on site and climatic conditions.
3. Minimum average roll values, machine direction.
4. "C" factor calculated as ratio of soil loss from rolled erosion control product protected slope (tested at specified or greater gradient, v:h) to ratio of soil loss from unprotected (control) plot in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #2.
5. Minimum shear stress the rolled erosion control product (un-vegetated) can sustain without physical damage or excess erosion (>½-inch (13 mm) soil loss) during a 30-minute flow event in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using ECTC test method #3.
6. The permissible shear stress levels established for each performance category are based on historical experience with products characterized by Manning's roughness coefficients in the range of 0.01 to 0.05.

[1]Source: Excerpted table from MDT Materials Specifications Manual, Table 713-5.

Table 7. MDT material updated specifications for temporary rolled erosion control, 2014 supplement.

ROLLED EROSION CONTROL

Type	Mass[1] (lbs/Yd)	Tensile Strength – MD[2] (lbs/ft)	Min. Shear Strength (lbs/ft^2)
Short term	0.5	190	1.70 [3]
Long term	0.5	190	2.0 [3]
High performance	0.6	190	2.25 [3]
TRM – natural fiber matrix	0.8	500	10.0 [4]
TRM – synthetic fiber matrix	0.5	300	12.0 [4]

Notes:
1. Combined fiber matrix and netting
2. Machine direct
3. Minimum shear stress the rolled erosion control product (un-vegetated) can sustain without physical damage or excess erosion (>1⁄2-inch soil loss) during a 30-minute flow event per ASTM D6460.
4. Minimum shear stress the TRM (fully vegetated) can sustain without physical damage or excess erosion (>1⁄2-inch soil loss) during a 30-minute flow event per ASTM D6460.

[1]Source: MDT Materials Specifications Manual, Supplemental Specifications, Table 713-4.

C Factor (soil loss)

A single replicate of the C-factor test (ASTM D6459) was conducted using the wool/straw ECB at 5, 10, and 15 centimeters (cm) (2, 3.9, and 5.9 in) rainfall rates. The results from this test are summarized in Table 8. The lab test bed size was 2.4 m-wide and 12-m long (~8 feet x 40 feet) and the slope had a ratio of 3 horizontal units to 1 vertical unit (3H:1V). Each event was twenty minutes in duration. Soil loss was negligible for the 5 and 10 cm rainfall rates but reached 23.7 kilograms (kg) of soil when rainfall was increased to 15 cm (5.9 in) for 20 minutes (Table 8, Figure 1). The single replicate C-factor was 0.060 indicating that it met the requirements of the MDT standard specifications for this material (Tables 6 and 7). The C-factor of 0.06 is less than the maximum allowed 0.10 for a short term ECB (Type II C; Table 6). Images of the C-factor test illustrate the wool product was able to control soil loss for the majority of the test slope, with some rills starting after the 15 cm rain event (Figure 1).

Table 8. Results of the maximum C factor (ASTM D 6459) test for 40% Wool / 60% Straw ECB.

Product	Intensity (centimeters/hour)	Runoff (liters)	Cumulative R Factor	Soil Loss (kilograms/plot/event)	Cumulative Soil Loss (tons/acre)	Single Replicate C-Factor
40% Wool /60% Straw ECB	5.2	4.5	6.74	0.0	0.00	0.060
	10.1	340.9	50.42	0.17	0.03	
	15.3	1041.7	163.55	23.65	3.58	

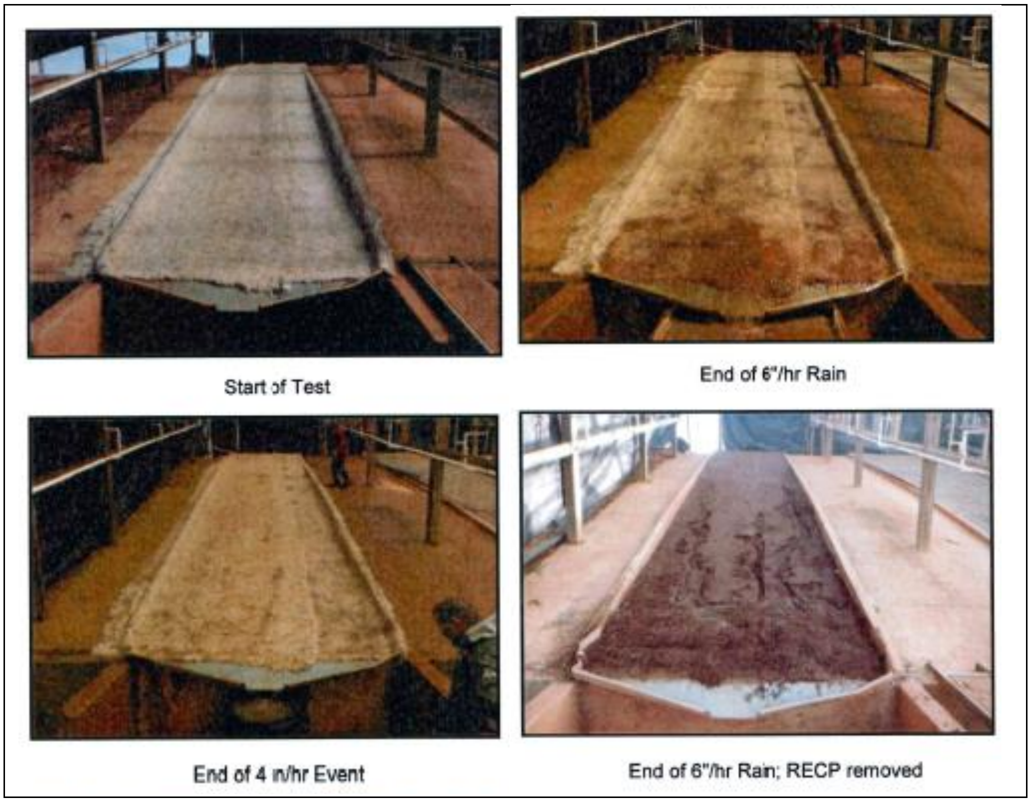

Figure 1. Images of intensities for C factor (ASTM D 6459) test for wool/straw ECB (photo by TRI).

Shear Stress Test

The minimum shear stress test (ASTM D 6460), modified for a single replication, was conducted in June 2016. The flume size was 0.6 m wide by 12 m long (2 x 40 ft), had a 10% slope, and each event was thirty minutes in duration. The unvegetated test was conducted at a shear range of 2.4 – 9.8 kg/m^2 (0.5 - 2.0 lbs per square ft (psf)). Shear levels 1 and 2 were tested but levels 3 and 4 could not be run since the erosion threshold of 1.3 cm (0.5 in) had been exceeded (Table 9). The resulting shear stress range for the wool product was 4.3 – 6.5 kgsm (0.9 – 1.3 psf). The 40% wool/ 60% straw ECB exceeded the minimum bed shear stress specified in the MDT standard specifications for short term ECB (Type II B; Table 6) for low level events, but not for high level events. The shear test results were lower than the updated minimum shear stress (1.7 psf) required by MDT for short term ECBs (Table 7). Images of the shear stress test illustrate rills forming the length of the test slope after the low-medium flow event (Figure 2).

Table 9. Results of the minimum shear stress test (ASTM D 6460) for wool/straw ECB.

Shear Level	Depth (cm)	Velocity (mps)[1]	Flow (cms)	Manning's Roughness	Maximum Bed Shear Stress (kgsm; Pa)	CSLI (cm)	Cumulative CSLI (cm)
1	4.3	1.0	0.03 cms	0.039	4.3 kgsm 42.2 Pa	0.4 cm	0.4
2	6.4	1.6	0.06 cms	0.032	6.5 kgsm 63.7 Pa	1.4 cm	1.8
3	Higher flow not run since erosion threshold of 1.3 cm (0.5 in) was exceeded.						
4	Higher flow not run since erosion threshold of 1.3 cm (0.5 in) was exceeded.						

[1] Units are as follows: mps = meters per second; cms = cubic meters per second; kgsm = kilograms per square meter; Pa = pascal (for comparison to MDT standards); CSLI: Clopper soil loss index.

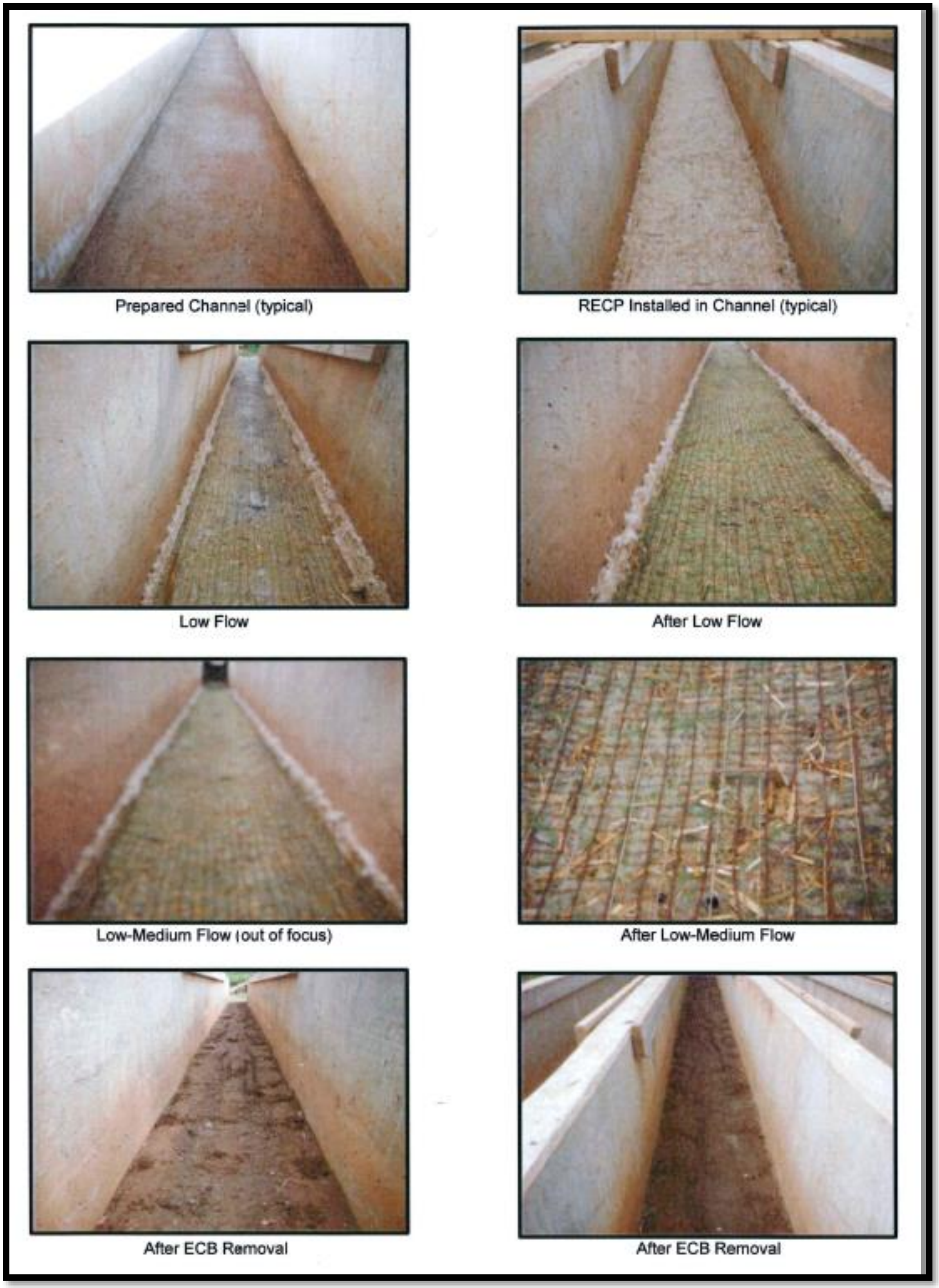

Figure 2. Images of flow levels for minimum shear stress (ASTM D 6460) test for wool/straw ECB (photo by TRI).

4.2 Analytical Laboratory Tests

Laboratory tests of the nutritional, water holding capacity and related chemical characteristics of wool and standard reclamation products provided varying results (**Error! Reference source not found.**). Note that the chemical analytical tests applied to the products used in this research study are designed for soil and not specifically for ECBs, so some measure of caution is warranted in interpreting the results. For example, the pH of the wool products was slightly basic, straw was neutral, and compost was slightly acidic. The acidity of compost is most likely a result of it being comprised of decomposing coniferous wood products and animal manure.

The electrical conductivity (EC) test measures soil salinity or soil salt content. Low levels of salinity (< 4.0 deciSiemen/meter) were observed in all products, however the straw coconut ECB exhibited the highest level of salinity (2.7 deciSiemen/meter). Sodium adsorption ratio (SAR), which reports sodium (Na) quantities relative to a combination of calcium (Ca) and magnesium (Mg), suggests that the there is some variability between the Ca, Mg and Na levels in scoured wool versus carded wool resulting in a comparatively elevated SAR of 8.9 in the carded wool primarily due to the low Ca and Mg levels.

The scoured wool had higher Ca, Mg, and Na values than the wool batting. This may be a result of the additional processing that the batts of wool received – they were scoured, then wet felted in an agitated tub of water which would further removes and leaches nutrients from the raw wool. The straw ECB had moderate levels of Ca, Mg and Na but much less than the compost which was nutrient rich. The percent carbon and organic matter were as anticipated for the product materials.

The amount of macronutrients – nitrogen (N) phosphorous (P) and potassium (K) – measured in the products were often surprising (**Error! Reference source not found.**). Potassium was low in the wool products, but high in the compost and elevated in the straw ECB indicating high amounts of K available for plant uptake in the standard products compared to the experimental wool products. Phosphorous was also lowest in the wool batting and highest in the wood-based compost. The scoured wool had higher P and K values than the wool batting. Wool fiber has no P or K, so the small amounts recorded in the bench tests for wool products are most likely derived from impurities in the wool (i.e., sheep manure, plant material) left after the scouring and/or wet felting processes.

Nitrate (NO_3) is the form of nitrogen that can be readily absorbed by plants for growth and levels were low and similar among the wool batting, scoured wool and straw ECB. Therefore, even though wool fiber is comprised of nitrogen, it is not available for plant growth until it is decomposed. Therefore, the impact of wool's potential nitrogen fertilizing effect will be dependent on the amount of wool material applied to a unit area of soil and the amount of time that it takes for each product to decompose. Compost NO_3 levels were approximately three hundred times higher than the other products indicating it is capable of providing N for plant growth immediately after its application.

The wool materials had 15% total nitrogen (total N) which is comprised of all forms of nitrogen. Total N was much greater in the wool products than the straw ECB or the compost suggesting the wool may provide a long-term source of nitrogen fertility. Similarly, the low carbon to nitrogen

ratio (C:N) values in the experimental wool products compared to the control products indicates much more nitrogen should be available for plant growth over time.

The three major cations that have a basic or alkaline reaction (K, Ca, and Mg) are combined in the measure of saturation or percent base saturation. Saturation is a measure of the product's or a soil's ability to provide nutrition. The percent saturation was high for all products but highest in the scoured wool. The straw ECB control had higher saturation than the wool batting.

In general, the two standard materials currently used by MDT (straw/coconut ECB and compost) had higher water holding capacity than the wool products. Water saturation and water holding capacity (WHC) are interpreted together. Water holding capacity is the total amount of water a soil (or material tested) can hold at field capacity. The field capacity is the amount of water in a soil (or material tested) after the soil/material has been wetted and allowed to drain by gravity. When considering soils, sandy soils have lower water holding capacity than clay soils. Products that hold generous amounts of water are less subject to losses of nutrients by leaching. Products with a lower water holding capacity (i.e. wool products) reach the saturation point sooner than a product with a higher water holding capacity (i.e. straw ECB, compost). After a product is saturated, all of the excess water and some of the nutrients are leached into in the soil profile. The WHC and saturation results indicate wool products hold more water and make the water more readily available to the soil environment (Table 5).

Table 10. Analytical test results for the product materials and study site soil.

Analytical Test[1]	Material Tested			
	Wool Batts	Scoured Wool	Straw/Coconut ECB	Wood–based Compost
pH	8.2	7.8	6.7	5.0
EC (dS/m)	0.1	0.3	1.8	2.7
SAR (unitless)	8.9	1.7	0.4	0.8
Ca (mg/L)	0.5	23	11.6	130
Mg (mg/L)	0.5	9.2	9.4	108
Na (mg/L)	29	37	7.6	55
OC (%)	57	57	56	44
OM (%)	99	98	96	76
K (mg/kg)	38	212	14,500	3,770
P (mg/kg)	<5	41	140	640
NO_3, (mg/kg Dry)	13	14	11	300.0
TKN (mg/kg)	92,900	147,000	1,240	4,720
N-Total (mg/kg)	150,000	150,000	1,300	5,000
N-Total (%)	15.0	15.0	0.1	0.5
C:N Ratio	3.8	3.8	429	88
Saturation (%)	787	943	867	318
Water Holding Capacity (WHC) 0.1 Bar Moisture (wt%)	73	77	190	140
WHC 0.33 Bar Moisture (wt%)	81	55	150	120
WHC 1.0 Bar Moisture (wt%)	93	73	160	84
WHC 15 Bar-DRY(wt%)	90	89	200	84

[1]Unites area as follows: dS/m=deciSiemen/meter; mg/L = milligrams per liter; % = percent; mg/kg = milligrams per kilogram; WHC = water holding capacity; wt% = percent by weight

5 CONCLUSIONS

The woolen reclamation products test results - mass per unit area assessment, standardized ECB laboratory tests and nutritional and water holding capacity tests - provided valuable information on the wool products, their future development, and their deployment on roadside reclamation projects.

Silt Fence

The heavier weight wool silt fence (244 g/m^2) was highly variable in mass per unit area, where as the lighter weight silt fence (140 g/m^2) and wool/burlap silt fence had a more even distribution of mass per unit area. Future development of the heavier weight wool silt fence should focus on a more even distribution of fiber to improve its strengths and eliminate weaker areas in the fence.

ECBs

The woolen ECB products exhibited variability in mass per unit area due to the uneven distribution of their straw, and/or wool fill components that are placed between two layers of sisal netting. However, the standard straw/coconut ECB also had variability in its weight indicating that an even distribution of fill components may not be standard for rolled ECBs. If it is deemed important, future manufacturing improvements could standardize production of the new wool-straw ECB products for more uniform results.

There was some inconsistency with mass per unit area of the wool / straw ECB. It may be worth re-testing three replications of the wool / straw ECB after manufacturing is fine-tuned and can produce a more even distribution of the wool / straw filler layer within the rolled ECB.

The laboratory tests for tensile strength, C-factor and shear stress gave some indication of the wool / straw ECB's performance. These results should be viewed with some caution since only one replication of each test was performed due to the costs of such testing. Normally, transportation agencies would require 3 replications of each test. The wool ECB:

- met MDT tensile strength standards for a short term (Type II B, C) or long term (Type III A) ECB,
- exceeded the minimum shear stress specified in the MDT standard specifications for short term ECB (Type II B) for low level events, but not for high level events, and was lower than the updated minimum shear stress level for short term ECB,
- the C-factor was representative of a short term ECB (Type II C).

In general, the wool/straw ECB was comparable to a short-term (Type II B or C) standard ECB commercially produced and used along MDT roadways. Future product development of the wool/straw ECB should focus on improving the shear strength at high flows so it meets all required Type III specifications.

The analytical laboratory tests showed that the wool-straw ECB has three features that may it improve roadside plant establishment and growth and reduce erosion:

- It has higher nitrogen levels than the standard materials (straw ECB or compost) which may provide a benefit to the establishment and growth of new vegetation over the long term as the wool decomposes.

- The wool/straw ECB has a relatively high percent saturation value which suggests it may hold on to more moisture than the traditional products.
- The wool/straw ECB has a low water holding capacity suggesting it may make the water more readily available for plant growth.

Wool as an Additive to Compost

Due to the total nitrogen level in wool and its water holding capacity and its fibrous nature, cut wool pieces as an additive to compost may serve to help compost blankets perform over the long term. Due to the limited amount of experimentation available in this project to explore this potential, only one ratio of wool to compost was recommended for field tests. Further research will be necessary to more fully understand the ideal mix of wool as an additive to compost.

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