

Material Properties of Used Textiles and Their Reuse Potential in American Industries

A Thesis

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By

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Executive Summary

Used textiles that are discarded pose a threat to the environment and have negative economic impacts. Recycling used textiles into viable products has a positive impact on both the environment and the economy. Qualitative literature has assessed the environmental and economic impact of recycling used textiles that consumers discard and identified product streams and industry areas with the potential for textile reuse. However, quantitative literature is limited on assessing both environmental and economic impacts of recycling post-consumer used textiles. Little is known about the material composition of the post-consumer used textile waste stream, as most thrift stores sort used textiles with respect to the saleable product stream but not by material composition. This research reports on the material composition of post-consumer used textile bales from two thrift store chains, one in Delaware and one in Duluth, Minnesota. The total amount of available post-consumer discarded used textiles by material type was calculated from Delaware thrift store data. In addition, this study carried out an economic input-output life cycle assessment using the discarded textile data available from the Delaware thrift store chain. An efficient textile recycling system will reuse discarded textiles by their material composition and remaining material properties. Thus, this research conducted experiments to find the material properties, tensile strength and permittivity of discarded textiles by material type in order to realistically assess their reuse potential.

One large-scale potential area for reuse of discarded textiles is geotextiles. Desired material properties for geotextiles are known, although more work has been done on nonwoven geotextiles than woven. Most of post-consumer textile waste is woven and knit and very little is nonwoven. Still, the use of woven geotextiles is projected to increase by 2020. Thus, this study investigated the reuse potential of used woven textiles by determining their permittivity and tensile strength properties and comparing them to material property specifications for woven geotextiles. Permittivity and tensile strength were measured since these properties correlate with nearly all of the major functions of geotextiles, i.e. filtration, drainage, separation, cushioning, and reinforcement. For used textile material types that satisfy geotextile material property specifications, the reuse potential of using these discarded textiles as woven geotextiles was determined by

comparing the annual square area of used woven textiles available with that of projected annual sales of woven geotextiles. This study contributes to prior knowledge by presenting information about post-consumer used textile material composition, utilizing a hybrid EIO-LCA model to assess the environmental and economic impacts for different industries by replacing new inputs with used textiles, determining material properties of woven used textiles, and estimating the available square area of used textiles in the U.S. This research found that cotton and polyester used textiles have appropriate material properties and square area availabilities to be utilized as woven geotextiles. The permittivity values were determined for used woven cotton, polyester, and 50/50 cotton-polyester blends and compared with industry specified permittivity values for woven geotextiles. This showed that polyester and mixed cotton-polyester have the potential for reuse in stabilization, separation, filtration/drainage, reinforcement, temporary cover and erosion control applications. The tensile strength was also determined for used cotton, polyester, and 50/50 cotton-polyester in the machine and cross directions and their comparison with industry specified tensile values for woven geotextiles showed that cotton and polyester have the potential for reuse in subsurface drainage and erosion control applications.

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Nomenclature

MSW	Municipal Solid Waste
USD	U.S. Dollars
EPA	U.S. Environmental Protection Agency
Goodwill-DE	Goodwill of Delaware
\$mil	Million USD
TE	Total Economic Impact in \$mil USD
VA	Value Added Economic Impact in \$mil USD
CO ₂ e	CO ₂ Equivalent Emissions in Metric Tons
%Diff	Percentage Difference
NRG	Energy in Terajoules
mfrg	Manufacturing
avg.	Average
EIO	Economic Input-Output
LCA	Life Cycle Assessment
NAICS	North American Industry Classification System
HFC	Hydrofluorocarbons
PFC	Perfluorocarbons
ASTM	American Society for Testing and Materials
DOT	US Department of Transportation
US DOI	US Department of the Interior
AASHTO	The American Association of State Highway and Transportation Officials
AOS	Apparent Opening Size
MNDOT	Minnesota Department of Transportation
DELDOT	Delaware Department of Transportation
NYDOT	New York Department of Transportation
NMDOT	New Mexico Department of Transportation
CALTRANS	California Department of Transportation
MSES	Mechanically Stabilized Earth System
GRSS	Geo-synthetically Reinforced Soil System

PWS	Prefabricated Wall System
ASTM D4491	Standard Test Methods for Water Permeability of Geotextiles by Permittivity
ASTM D5034	Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)
ASTM 4632	Standard Test Method for Grab Breaking Load and Elongation of Geotextiles
ASTM D1776	Standard Practice for Conditioning and Testing Textile

1 Introduction and Research Background

1.1 Used Textile Problem

Used textiles that are discarded in landfills are a large waste problem. Every year, more textile waste is being generated, which increases the textile waste being landfilled as well as load on the environment. The EPA reported that in 2015, 16 million tons of textiles were municipal solid waste, which made 6.1% of total municipal solid waste (MSW) generated that year [1]. In 2015, according to EPA, 10.5 million tons of the MSW of textiles was discarded in landfills, which was 7.6% of total MSW that was landfilled [2]. In 2015, the EPA also reported that of the 25.8% of all MSW that was generated was recycled, and only 15.3% of textile waste generated was recycled [1]. Globally, used textile issues such as dumping second hand textiles in Rwanda and other African nations have led these countries to enact used clothing bans [3]. Also, fast fashion practices lead to greater textile consumption which results in inexpensive clothing that is produced and traded across continents by mass-market retailers. As these poor quality clothes are discarded, this also creates more textile waste [4].

1.2 Global Used Textile Trade

Globally, the used clothing trade has increased and contributes to the generation of textile waste. Annually, the used clothing trade has reached over 1.4 million tons (1.3 million metric tons), and in the decade from 2006 to 2016, it has increased by 106% from \$1.8 billion USD to \$3.7 billion USD [5]. Countries that import these second-hand clothes mostly include sub-Saharan African countries (approximately 20.0%), Pakistan (6.0%), Malaysia (5.8%), and Ukraine (4.9%) [5].

1.3 Environmental Impacts

1.3.1 Waste Creation from Fast Fashion Practices

Fast fashion is the practice to design, create and market cheap fashion trends to make them quickly available to customers [6]. Due to the global fashion revolution, fast fashion

chains are offering new fashion trends at unprecedentedly low prices, thereby also turning fashion into environmentally destructive industry [7]. The fast fashion industry contributes to environmental pollution due to the use of toxic chemicals, dangerous dyes, and synthetic fabrics which seep into water supplies in countries where these cheap textiles are made or consumed [6]. Synthetic textiles almost never break down and release toxic chemicals in air due to the presence of lead, pesticides and numerous chemicals [6]. In fast fashion practices, cheap clothes are produced and traded globally and discarded quickly due to their poor quality [4]. Consequently, fast fashion also leads to 11 million tons of textiles that are landfilled each year in the U.S., which leads to a large carbon impact [6].

1.3.2 Greenhouse Gas Creation from Landfilling Textiles

Textile waste that is landfilled creates a problem for environment by releasing toxic greenhouse gases into the atmosphere that damage the ozone layer and propagate respiratory and health problems as well [8]. Methane (CH₄), a potent greenhouse gas, is released as a by-product with the biodegradation of the fibers from discarded natural textiles [9]. Moreover, when non-biodegradable textiles are rained on for years, the accumulation of chemicals that leach out of the fabrics produce toxic ground water [8]. This toxic ground water damages the natural ecology in the soil and, after evaporation on ground surfaces, also produces acid rain [8].

1.3.3 Greenhouse Gas Reduction from Recycling Textiles

Several qualitative and quantitative studies have examined how recycling used textiles reduces the environmental load. Pursuing new viable products from discarded textiles reduces greenhouse gases which otherwise would be landfilled and add to the environment [10] [11]. One study determined 14.7 tons (13.3 metric tons) of CO₂ equivalent emissions are avoided with recycling a ton of discarded textiles [10]. Another study reported the reduction of CO₂ equivalent emissions to be 3.5 tons per ton (3.4 metric tons per metric ton) of recycling used textiles [11]. These values include greenhouse gas offsets from avoided primary production of new textiles.

1.4 Economic Impacts of Used Textiles

1.4.1 Size of Used Textile Industry in U.S.

The used textile industry (NAICS code: 453310) has a large presence in the U.S. Under this retail trade industry sector, the total number of companies is 62,619 and the estimated number of employees is 208,500 [12]. According to the quarterly update in June 2019, the revenue generated by this industry in U.S. is about \$17.5 billion USD [13].

1.4.2 Size of Global Used Textile Industry

The used clothing industry is large on a global scale. The global exports of used textiles have been increasing consistently for a decade from 1.8 billion USD in 2006 to 3.7 billion USD in 2016 [5]. Global imports of used clothing decreased in 2015 and 2016 [5], which might be attributed to abrupt political shifts worldwide [14]. In 2017, the U.S. was the second largest exporter of used textiles with a percentage share of 15.1%, second only to the European Union [14].

1.5 Combined Environmental and Economic Impacts of Used Textiles

1.5.1 Economic Input Output Life Cycle Assessment (EIO-LCA)

Economic Input Output Life Cycle Assessment (EIO-LCA) is a method of estimating the materials and energy sources that are required to generate the economic activities and also measure the environmental emissions that result from these activities [15]. EIO-LCA also connects economic outputs with material inputs to assess both environmental and economic impacts of an activity [16].

1.5.2 Assessment Studies of Recycling Used Textiles

In order to understand the environmental and economic impacts of recycling used textiles, it is important to do assessment studies of such recycling practices. No hybrid EIO-LCA model has been developed before to examine the impact of recycling used textiles. However, some sustainability assessment studies have been done to look at the recycling of used textiles. Given that there is no textile recycling plant in Sweden, Swedish researchers did a life cycle assessment (LCA) of three different recycling

techniques for a textile waste model of 50/50 cotton-polyester [17]. They reported 8 tons (7.26 metric tons) of CO₂ equivalent reductions and 164 gigajoules (GJ) of primary energy savings per ton of textile waste recycling. Researchers in Sweden also conducted a similar social life cycle assessment to see the impact of recycling textile waste on the environment and society as a whole [18]. A life cycle assessment study in UK looked into reusing donated waste textiles instead of using virgin textile materials as an energy saving perspective [19]. LCA tool was also employed to look into sustainable use of chemicals in textile industry [20] and reduction in carbon footprint associated with recycling of textile materials as well [21].

1.6 Reusing Used Textiles

1.6.1 Recycling Used Textiles into New Products

One of the areas of interest of recycling used textiles is to pursue the manufacturing of recycled viable products instead of virgin materials which would decrease the load on the environment [11], [19], [22]. This practice would further reduce the need for water consumption [10], decreased need for landfill space [23] and lower the need for agricultural land to grow raw materials [24].

1.6.2 Need for Large-Scale Textile Reuse Industry

The textile reuse industry is not a large-scale industry. Although the recycling efforts have been increased for all the materials in the U.S. over the past decade to 25.8% of MSW generated, the percentage of textiles that are recycled is still at 15.3% of textile waste generated [1]. Therefore, in order to handle the large volume of used textiles that are discarded every year, a nation-wide large-scale textile recycling pipeline system should be developed. In order for textile recycling system to improve and have a bigger environmental and economic impact, this phenomenon needs to be examined at the macro-scale of companies instead of the micro-scale of consumers [25].

1.6.3 Geotextiles - A Feasible Reuse Application of Used Textiles

Geotextiles are materials that are permeable and used in applications like increasing soil stability, providing erosion control and assisting in filtration/drainage [26]. Geotextiles are classified into nonwoven and woven geotextiles. Nonwoven geotextiles are felt-like

in appearance and provide planar water flow [26]. The most common type are needle-punched nonwovens, which are manufactured by entangling the staple fibers or continuous filaments with barbed needles [26]. Woven geotextiles are planar textile structures and manufactured by interlacing two or more sets of strands at right angles [26]. Flat slit films and round monofilaments are two types of strands used for making woven geotextiles [26]. Geotextiles are usually synthetic textiles manufactured using virgin materials. Thus, new synthetic material is used in large quantities in a growing industry worldwide. However, due to the high demand for geotextiles, these virgin materials might be replaced with used textiles as a feasible reuse application.

1.7 Geotextiles

1.7.1 Global Market

Globally, the demand for geotextiles increases every year due to the multiple performance advantages of geotextiles over layers of soil and rock aggregates, poured concrete and precast concrete forms [27]. The demand for synthetic geotextiles is projected to grow at an annual rate of 5.6% through 2019 [27]. Also, in 2014, the North American region had the second largest demand for geosynthetics, next to the Asia/Pacific region, with 22.4% of 4.8 billion square meters demand in the world [27]. The demand in North America is also projected to grow from more than 762 million square meters in 2014 to 920 million square meters through 2019 [27]. With this ever-increasing demand for synthetic geotextiles, this study explored the opportunity to investigate the feasibility of meeting this demand with used textiles.

1.7.2 U.S. Market

In the U.S., the geotextile market increases every year as well. In 2014, the consumption of geotextiles was estimated to be 890 million square yards (744.15 square kilometers) at a monetary value of 827 million USD [28]. This value is projected to increase to 1,032 million square yards (862.88 square kilometers) at a monetary value of 965 million USD [28]. The market for woven geotextiles is also booming, and their growth rate is projected to be 2.6% between 2015 and 2020, as opposed to a 2.1% growth for nonwoven geotextiles within the same timeframe [28]. The market share of woven geotextiles is

projected to increase by 1% from 75% to 76% between 2014 and 2020 [28]. Due to this increasing demand for woven geotextiles in the U.S., the authors of this research examined the feasibility of reusing used woven textiles as woven geotextiles.

1.7.3 Geotextile Functions

Geotextiles are used in many industrial applications due to their unique characteristics and functions. Some of the geotextile functions include drainage, filtration, separation, cushioning and reinforcement [29]. The drainage function is the hydraulic property of geotextiles with in-plane flow capacity for applications like accelerating consolidation in soft grounds, capillary barriers in area of frost, salinity, and/or aridity; and in leakage and gas collection systems of landfills [29]. In regard to the filtration function, geotextiles retain the particles without affecting the drainage capacity of the systems and are used as horizontal filters for roads, railways and other embankments and covered by fill on top; vertical filters for drainage trenches in walls and river and coastal filter applications [29]. Geotextiles also act as separators when a flexible porous textile is placed between two dissimilar materials which preserves their integrity and functions and prevent these materials from affecting each other [29]. Some of the areas where geotextiles act as separators include applications beneath sidewalk slabs and sport and athletic fields, or between landfills, stone base courses, and foundations and embankment soils for roadway fills [29]. Geotextile cushions are installed above and/or below geomembranes to protect them from tearing or puncturing during construction or damage during their service life [29]. In reinforcement applications, geotextiles act as two dimensional tensile structures which hold together aggregate or soft soils [29]. The reinforcement function of geotextiles involves other functions and some of the reinforcement applications include reinforcing paved and unpaved roads, walls, berms, and slopes as well as soft soil foundations [29].

1.7.4 Material Properties Important for Geotextiles

Geotextiles have different properties such as physical, mechanical, and hydraulic properties. The physical properties of geotextiles reflect the raw materials and manufacturing process that is used to fabricate them [29]. The mechanical properties of geotextiles are important for analyzing their performance in structural roles, and areas

where they are subjected to localized stresses or installation damages [29]. The hydraulic properties of geotextiles are essential for determining their filtration or drainage performance [29]. The mechanical and hydraulic properties are crucial to understanding the true performance and functionality of geotextiles. In that regard, determining the tensile strength is important because it is an essential characteristic that influences all functions of geotextiles regardless of their applications, as geotextiles are always exposed to stresses during installation or by any other means [29]. Moreover, almost all geotextiles are permeable fabrics, so it is important to determine their permittivity properties; however, for filtration/drainage applications, hydraulic specifications must be met [29]. The authors of this study tested the used textile materials for tensile strength and permittivity.

1.7.5 Permittivity of Geotextiles

The authors of this study used a standard method described in ASTM D4491 to determine the permittivity of used textiles [30]. The standard test method for water permeability by permittivity describes the procedure to determine the hydraulic conductivity of geotextiles in terms of permeability and permittivity in an uncompressed state under standard testing conditions [30]. According to the standard, the permittivity of geotextiles is the volumetric flow rate of water per unit cross sectional area per unit head under laminar flow conditions, in the normal direction through a geotextile [30].

1.7.6 Tensile Strength of Geotextiles

Standard methods used to determine the tensile strength of geotextiles and textile fabrics are ASTM D4632 [31] and ASTM D5034 [32], respectively. The tensile strength of a material is measured by determining the breaking force and according to both standards it is the maximum force applied to a material until it ruptures [31], [32]. The authors of this study used the ASTM 5034 grab test for testing woven fabrics to measure the break force of used garments. Since tensile strength of a material is the maximum amount of tensile stress that a material can withstand, the force that relates to that tensile stress is the breaking force which is measured using this standard. The tensile stress formula is given below in equation 1.

$$\text{Tensile Stress} = \text{Force}/\text{Area} \quad (1)$$

$$\text{Maximum Tensile Stress} = \text{Break Force} / \text{Area}$$

1.7.7 Geotextiles Made from Recycled Materials

Geotextiles are usually manufactured synthetically using new virgin materials. Studies have looked at manufacturing geotextiles from natural and recycled materials instead and the positive impacts on the environment and economy this might have [33], [34], [35], [36], [37], [38], [39]. Most of the studies have investigated recycling textile waste into nonwoven geotextiles, and little is known about the use of discarded textiles as woven geotextiles. This study aims to assess the feasibility of recycling used woven textiles into woven geotextiles for industrial applications by providing bale case study data and determining material properties.

1.8 Motivation

Used textiles are a global problem that poses serious problems such as increased landfilling of used textiles globally and locally in the U.S., increased exports to undeveloped countries, and emissions of greenhouse gases from landfilled textiles. Textile manufacturing locally and globally also contributes to carbon emissions due to fast fashion practices. It is necessary to increase the recycling efforts for used textiles to enhance environmental sustainability. However, the literature is limited on the combined environmental and economic impacts of recycling used textiles. Therefore, a hybrid EIO-LCA case study was carried out to examine the combined environmental and economic impacts of recycling used woven textiles. Also, the material types and amounts of used textiles are largely unknown and need investigation for assessing the reuse potential of used textiles. Similarly, the material properties of used textiles are largely unknown. Knowing the material properties, specifically permittivity and tensile strength, allows us to answer whether used textiles made of specific materials can be used as geotextiles.

1.9 Scope of Work

To determine the material composition of annually discarded used textiles, Goodwill of Delaware and Duluth, Minnesota, each donated a bale of used clothing to this research. The bales were manually sorted by reading the material tags. After sorting, it was determined that used cotton was the largest by percentage weight in both bales. Polyester

and blends of natural (e.g. cotton) and synthetic (e.g. polyester) fibers were also a large part of the material composition of the used textile bales. A hybrid EIO-LCA model was established by material and monetary flow values associated with recycling Goodwill of Delaware's annual unsold used cotton textiles to assess the potential environmental and economic impacts of reusing these textiles in different American industrial sectors. Permittivity and tensile strength material properties of used clothing made of cotton, polyester and 50/50 cotton-polyester blends from the bales from both locations were measured using samples from these used textiles.

1.10 Thesis Structure

1.10.1 2: Literature Review

- Environmental and economic impact of used textile recycling
- Background of Economic Input-Output Life Cycle Assessment (EIO-LCA) studies of single industries
- Description of background literature on used textile recycling
- Background literature on geotextiles from recycled materials
- Background literature on permittivity and tensile testing of woven and nonwoven geotextiles
- Summary of permittivity and tensile property values from Department of Transportations and the U.S. Department of the Interior
- Background literature on geotextile functions and applications
- Identification of the problem summary and research gap covered in this study

1.10.2 3: Reuse Potential of Used Textiles for American Industries (Publication for IDETC-CIE 2019 Conference in Its Entirety)

- Selection of industrial sectors for potential reuse of used textile
- Overview of bale case study, annual textile weight and EIO-LCA model methodology
- Analysis and discussion of EIO-LCA hybrid model results

1.10.3 4: Material Properties of Used Textiles (In Preparation for a Journal Paper to be Submitted to Geotextiles and Geomembranes)

- Selection of fabric types and samples
- Detailed description of permittivity and tensile testing methods of used fabric samples
- Analysis of the results of material testing

1.10.4 5: Reuse Applications of Used Clothing as Geotextiles (Paper in Preparation for IDETC-CIE 2020 Conference)

- Identified the monetary relation between geotextiles sales and square area
- Overview of annual bale textile weight and annual U.S. used textile weight estimates
- Estimation of U.S. market shares of used cotton and polyester in \$mil/km² and annual square kilometers and their comparison with 2020 market projections

1.10.5 6: Conclusions and Future Work

- Identified the impact of this study
- Recommendation for future work

1.10.6 Appendices

- Sample force-displacement plots for cotton, polyester and mixed used clothing samples in machine and cross directions
- Calculation of annual weight, market share of used textiles in \$mil/km² and square kilometers and their comparison with 2020 woven geotextiles market

2 Literature Review

2.1 Introduction

In order to assess the feasibility of reusing used textiles it is important to determine their material composition and material properties. In this context, this chapter describes the background studies that have been conducted to look at the environmental and economic impact of reusing the recycled textiles. The chapter also provides an overview of studies on recycling materials into geotextiles, permittivity and tensile strength properties of geotextiles, material property standards used in industry and geotextile applications. A problem summary is provided, and the research gap is identified.

2.2 Environmental Impact of Used Textile Recycling

Researchers have looked at the environmental impacts of recycling used clothing. One descriptive and qualitative study looked at the environmental benefits of textile recycling [23] and another study assessed the feasibility of using recycled textile products instead of virgin materials [22]. Some studies are more quantitative and have also calculated the reduction in greenhouse gas emissions from recycling or reusing the used textiles.

According to one study, 14.7 tons (13.3 metric tons) of CO₂ equivalent emissions are avoided per ton of discarded textiles recycled [10]. These CO₂ savings are achieved by replacing new clothing and include materials, production and transport [10]. Fabricating new viable products made from used textiles has the benefit of reducing the environmental load from greenhouse gases [10], [11]. Additional advantages of recycling discarded textiles results in reducing water consumption [10], decreasing the need for landfill space [23], and decreasing the need for agricultural land [24].

2.3 Economic Impact of Used Textile Recycling

Very few studies have investigated the economic impact of recycling used textiles. Hawley [23], [40] conducted a qualitative study and described how various actors in the recycled textile supply chain can gain economic benefits from textile recycling systems and also contribute to corporate social responsibility. She concluded that, for a textile recycling system to result in economic and environmental improvements, an alliance is

needed between supply chain actors [40]. Therefore, it is necessary to have a sustainable system in place to direct the flow of used clothing and textile wastes into a recycling pipeline globally as well as in the U.S. Ekström and Salomonson recommended that in order to improve textile recycling system, it should be looked on a macro scale (industry wide), instead of a micro scale (company) or individual actor basis (consumer) [25]. However, the authors only considered reuse within the apparel industry. Truly considering all sectors within the economy at a macro scale, that could reuse available textiles, would address the reuse and recycling problem.

2.4 EIO-LCA Studies of Single Industry

Economic Input Output Life Cycle Assessment (EIO-LCA) is a tool that allows the comparison of economic and environmental impacts for decision-making by connecting the material or supply inputs with product generated as a result [16]. A hybrid EIO-LCA model was customized to allow changes to be made to economic inputs and outputs within industrial subsectors, for assessments of environmental and economic impacts to other sectors [41]. Relatively few studies utilize the hybrid EIO-LCA method rather than conventional EIO-LCA.

Several hybrid EIO-LCA studies have only considered a single industry. Meisterling et al. analyzed an organic vs conventional wheat growth agricultural system to compare the impacts of energy use and the Global Warming Potential (GWP) [42]. Meier et al. also developed a model to assess environmental impacts of a sustainable high yielding agricultural system [43]. Similarly, EIO-LCA studies looked at the environmental impacts of single industries like cob construction [44], hotel textiles [45] and multiple construction projects [41], respectively. A study also considered all sectors within one U.S. region to assess the economic impact of a final product and concluded that no major differences are found at a regional and national level [46]. This thesis paper considered a national rather than regional economic scale based on the conclusions of this study. Ritchie et al. investigated how investment decisions impact carbon footprints across all industries and increased investments negatively impact the environment [47]. However, the study does not consider actual material flows to be replaced but simply focuses on monetary flows. Our study contributes to previous EIO-LCA studies by utilizing a cross-

industry approach, offsetting new virgin materials with recycled textiles at a national scale and compares the monetary flows before and after this change.

2.5 Used Textile Recycling

Several qualitative studies have looked at how pursuing recycled textile inputs have positive environmental impacts. However, little is known about the combined environmental and economic impact of recycling used textiles. Also, little quantitative data exists about discarded textile collection and sorting processes. A study described a sorting and quality methodology in Denmark for reusing textile collected from MSW [24]. Sandin and Peters emphasized the need for collecting verifiable data on used textiles and primary sources for sorting [48]. It is important to have the sorting data of discarded clothing available from various locations for better feasibility of reusing used textiles.

2.6 Geotextiles from Recycled Materials

A substantial amount of literature is available on the manufacturing of non-woven geotextiles from textile waste. However, these studies differ from one another regarding the type of textile waste that is used to make geotextiles and applications of the geotextiles. Some studies have looked at manufacturing geotextiles from natural fibers like jute [33], a blend of recycled natural and synthetic fibers [34] and low cost reclaimed fibers from plastics and polyethylene terephthalate (PET) [49]. All these studies mention geotextile use in reinforcement, protection of slopes and protection against soil erosion. One study looked at geotextiles that consist of meandrically-arranged coarse ropes made from nonwoven waste and used in roadside ditch protection in clay grounds [50]. A study from Romania described recycling knitted polyacrylonitrile used clothing and woven polyester patches into nonwoven geotextiles [36]. This study provided a technical solution to support the circular economy by minimizing waste and making the most of resources and addressed the positive economic impacts of manufacturing geotextiles from textile waste. Another qualitative study was conducted about converting old industrial textile waste into fibers which can be used for nonwoven geotextile applications [37]. Several other studies have also examined the recycling of postconsumer fibers and

plastics for manufacturing of geotextiles which can be used for roadbed applications and pond liners [38],[39]. Overall, all these studies found that recycling textile waste into nonwoven geotextiles is feasible.

2.7 Permittivity Testing of Geotextiles

Substantial quantitative studies on permittivity, filtration and drainage properties of different geotextile material types, specifically nonwovens, are available. It is imperative to study these properties in order to assess the performance capabilities and effectiveness of geotextile fabrics used in various industrial applications. The interest in determining the filtration properties of geotextiles under tensile stress, soil confinement and different parameters has been gaining importance as geotextiles used in various applications experience lateral tensile stresses and are exposed to different soil conditions. Correlating to drainage and filtration functions, Palmeira et. al, Hong et. al, Pak et al. and Wu et al. examined the influence of various loads and stress level on physical and hydraulic properties of nonwoven geotextiles [49], [50], [51] and [52] respectively. Bezuijen et al. provided a quantitative study on geotextile permittivity as a function of temperature and presented results of constant and falling head permittivity tests [53]. Moreover, Xiao et al. conducted simulative study to reveal the effects of clogging of soil particles on permittivity of nonwoven geotextile filter media [54]. Additionally, researchers have studied the permittivity characteristics of geotextiles under soil confinement for filtration applications [55], [56]. One journal study examined the geotextile filtration behavior and its effects on the structure performance of a nonwoven geotextile-reinforced soil wall [57]. A similar study analyzed the results of large-scale tests on inclined slopes using a wave tank and three types of nonwoven geotextiles and a conventional granular layer as filters between the protective layer on the slope and base soil slope [58].

These studies have in common that they consider permittivity of nonwoven geotextiles; however, there are some studies that also analyze these properties for woven geotextiles, but the literature on this subject is limited. A quantitative study has been conducted to determine the permittivity behavior of a woven polypropylene geotextile under tension [59]. Blair et al. conducted a study to investigate the fabric permittivity of both woven and non-woven geotextiles, analyzed the factors that affect it, and recommended a

method for measuring fabric permittivity [60]. Nahar et al. conducted a study to fabricate and install an apparatus according to ASTM D4491 and showed it to work for both types of geotextiles [61]. Other studies looked at the filtration behavior of woven and nonwoven geotextiles in municipal water [62] and sludge system [63]. Overall, studies have consistently looked at the permittivity characteristics of nonwoven geotextiles and literature is also available for woven geotextiles. The authors of this thesis have determined the permittivity characteristics of used woven textiles for assessing their reusability as woven geotextiles and compared of these values with industry-specified permittivity values for woven geotextiles.

2.8 Tensile Testing of Geotextiles

Similarly, to assessing the permittivity of geotextiles, several quantitative studies have been conducted and presented in order to assess their tensile strength properties that are used in various construction and industrial applications. Determining tensile strength properties of geotextiles under different applications as well as assessment of parameters like temperature, humidity and soil conditions that affect these properties is crucial to estimate the performance and effectiveness of geotextiles. Most of the studies about tensile strength are limited to nonwoven geotextiles. One study analyzed the stress strain parameters of a tensile test to better understand the behavior of nonwoven geotextiles in construction [64]. Another study examined the tensile properties of nonwoven geotextiles under confining pressure by comparing the data values with tests without confining pressure [65]. A different study examined the tensile properties of nonwoven geotextiles and how these properties are important to the soil filtration characteristics of these geotextiles [66]. Richardson and Bove reviewed the parameters that affect the apparent tensile strength properties of nonwoven geotextiles and made recommendations to accurately assess geotextile-soil interaction [67]. Rosete et al. determined the influence of abrasion laboratory tests on tensile strength properties of nonwoven geotextiles [68]. A study also evaluated the in-soil tensile strength properties of geotextiles by conducting tests on an in-soil laboratory tester [69].

In addition to studying tensile strength properties of nonwoven geotextiles, several studies also analyzed these properties for woven geotextiles. A study assessed the effects

of seam type, puncture, and clamping techniques on tensile strength properties of both woven and nonwoven geotextiles [70]. Zhao and Tang determined the influence of pore size deformation coefficient and textile shrinkage coefficient on tensile strength properties of woven geotextiles by using image analysis technique in a uniaxial tension test [71]. One study also examined the effects of temperature on tensile strength properties of woven geotextiles by performing tensile tests at different temperatures [72]. Another study has devised a plane strain hydraulic tensile test to better test the geotextiles [73]. The results of this study were compared to laboratory tests developed for textiles intended for use as clothing, household goods and specific industrial uses [73]. Studies have consistently looked at determining tensile strength properties of nonwoven geotextiles and literature is also available for woven geotextiles. The authors of this study determined tensile strength properties of used woven textiles for assessing the feasibility of reusing them as woven geotextiles and compared these determined values with industry-specified tensile strength values for woven geotextiles.

2.9 Geotextile Material Properties Needed by Standards

In order to better understand the reuse potential of discarded woven textiles, a comparison of their permittivity and tensile strength values with the standards for woven geotextiles used by state Department of Transportations (DOTs) across America [74] and from the US Department of the Interior (US DOI) [75] was done. Table 1 and Table 2 shows the permittivity and tensile strength values of woven geotextiles from DOTs and US DOI respectively. These tables also specify these values by ASTM standard, test type, geotextile functions, geotextile type, and class.

Table 1 Permittivity Values for Woven Geotextiles from DOTs Standards [74]

Sr. No	Source	ASTM Standard	Test Type	Geotextile Function	Geotextile Type	Geotextile Class	Values				
1	AASHTO	ASTM D4491	Permittivity (1/s)	Stabilization and separation application	Slit film woven geotextile	US 200	0.05 1/s				
				Permanent Erosion Control & Subsurface Drainage	Monofilament woven geotextile	US 670	0.28 1/s				
				Filtration/Drainage	Woven	US 230C	0.70 1/s				
2	WIDOT (utilizes AASHTO with modifications for AOS)	ASTM D4491	Permittivity (1/s)	Filtration/Drainage	Woven	US 230C/ Type R (Riprap)	0.70 1/s				
				Filtration/Drainage	Woven	US 230C/ Type HR (Heavy Riprap)	0.70 1/s				
3	MNDOT (Does not follow AASHTO)	ASTM D4491	Permittivity (1/s)	Stabilization and separation application	Woven	US 200/Type 5	0.05 1/s				
4	DELDOT	ASTM D4491	Permittivity (1/s)	Stabilized Construction Entrance	Woven	Class 1/ US 315	0.05 1/s				
				Separation	Woven	Class 1/ US 250	0.05 1/s				
				Stabilization Fabric	Woven	Class 1/ US 315	0.05 1/s				
				Underdrain	Woven	Class 2/ US 230	0.90 1/s				
				Underdrain	Woven	Class 2/ US 670	0.28 1/s				
5	NYDOT (Follows ASHTO)	ASTM D4491	Permittivity (1/s)	Bedding	Woven	US 230	0.90 1/s				
				Bedding & Filtration	Woven	US 670	0.28 1/s				
				Separation	Woven	US 250	0.05 1/s				
				Stabilization	Woven	US 315	0.05 1/s				
				MSES Geotextile	Woven	US 250	0.05 1/s				
				MSES Subsurface Drainage System	Woven	US 670	0.28 1/s				
				GRSS Geotextile face Wrap	Woven	US 250	0.05 1/s				
				GRSS Drainage System	Woven	US 670	0.28 1/s				
				PWS Geotextile	Woven	US 250	0.05 1/s				
				PWS Drainage Geotextile	Woven	US 670	0.28 1/s				
				6	NMDOT (Follows AASHTPO)	ASTM D4491	Permittivity (1/s)	Erosion Control Geotextile Class 2 < 15% Fines (Woven Option)	Woven	US 230	0.90 1/s
								Erosion Control Geotextile Class 2 > 15% Fines (Woven Option)	Woven	US 670	0.28 1/s
Separation Geotextile	Woven	US 250 Class 2	0.05 1/s								
Separation Geotextile	Woven	US 200 Class 3	0.05 1/s								
Stabilization Geotextile	Woven	US 315	0.05 1/s								
7	CALTRANS	ASTM D4491	Permittivity (1/s)	Geotechnical Subsurface Reinforcement	Woven	US 200	0.05 1/s				
				Sediment Filter Bag	Woven	US 1540	2.10 1/s				
				Temporary cover	Woven	US 200	0.05 1/s				
				Subgrade Enhancement B1	Woven	US 4800	0.138 1/s				
				Subgrade Enhancement B2	Woven	US 230	0.90 1/s				

From Table 1, the American Association of State Highway and Transportation Officials (AASHTO) and all the state Department of Transportations (DOTs) except the California Department of the Transportation (CALTRANS) have reported the lowest standard value of acceptable permittivity at 0.05 1/s for stabilization and separation applications. However, the New York Department of Transportation (NYDOT) has also reported 0.05 1/s as the lowest permittivity value for drainage and reinforcement applications. The California Department of Transportation (CALTRANS) has reported 0.05 1/s as the lowest permittivity value for reinforcement and temporary cover applications. In Table 1, the lowest permittivity value of 0.05 1/s is followed by 0.28 1/s and 0.70 1/s values reported by the AASHTO for erosion control and filtration/drainage applications and by NYDOT for drainage applications respectively. The Wisconsin Department of Transportation (WIDOT) has also reported permittivity standard value of 0.7 1/s for filtration/drainage applications and the New Mexico Department of the Transportation has reported permittivity value of 0.28 1/s for erosion control applications. This study will compare these three lowest standard values of 0.05 1/s, 0.28 1/s and 0.7 1/s with the determined permittivity values of used woven textile articles to assess their reuse for

stabilization, separation, reinforcement, temporary cover and filtration/drainage applications.

Table 2 Tensile Strength Values for Woven Geotextiles from DOTs Standards [74] and US DOI [75]

Sr. No	Source	ASTM Standard	Test Type	Geotextile Function	Geotextile Type	Geotextile Class	Values
1	US Department of Interior Bureau of Reclamation (June 2014)	ASTM D4632 (AASHTO 1996)	Tensile Grab Test	Subsurface drainage	N/A	N/A	800.68 N
				Subsurface drainage			355.86 N
				Armored erosion control			889.64 N
				Armored erosion control			400.34 N
2	AASHTO	ASTM D4632	Tensile Strength	Stabilization and separation application	Slit film woven	US 200	890 N
				Permanent Erosion Control & Subsurface Drainage	Monofilament woven	US 670 (Class 2 & 3)	1646 x 1112 N
					Woven	US 230C	1424 x 1424 N
3	WIDOT (utilizes AASHTO with modifications for AOS)	ASTM D4632	Tensile Strength	Filtration/Drainage	Woven	US 230C/ Type R (Riprap)	1424 x 1424 N
				Filtration/Drainage		US 230C/ Type HR (Heavy Riprap)	1424 x 1424 N
4	MNDOT (Does not follow AASHTO)	ASTM D4632	Tensile Strength	Stabilization and separation application	Woven	US 200/Type 5	890 N
5	DELDOT	ASTM D4632	Tensile Strength	Stabilized Construction Entrance	Woven	Class 1/ US 315	1402 N
				Separation		Class 1/ US 250	1112 N
				Stabilization Fabric		Class 1/ US 315	1402 N
				Underdrain		Class 2/ US 230	1780 x 1423 N
				Underdrain		Class 2/ US 670	1646 x 1112 N
6	NYDOT (Follows ASHTO)	ASTM D4632	Tensile Strength	Bedding	Woven	US 230	1780 x 1423 N
				Bedding & Filtration		US 670	1646 x 1112 N
				Separation		US 250	1112 N
				Stabilization		US 315	1402 N
				MSES Geotextile		US 250	1112 N
				MSES Subsurface Drainage System		US 670	1646 x 1112 N
				GRSS Geotextile face Wrap		US 250	1112 N
				GRSS Drainage System		US 670	1646 x 1112 N
				PWS Geotextile		US 250	1112 N
				PWS Drainage Geotextile		US 670	1646 x 1112 N
7	NMDOT (Follows AASHTO)	ASTM 4632	Tensile Strength	Erosion Control Geotextile Class 2 < 15% Fines (Woven Option)	Woven	US 230	1780 x 1423 N
				Erosion Control Geotextile Class 2 > 15% Fines (Woven Option)		US 670	1646 x 1112 N
				Separation Geotextile		US 250 Class 2	1112 N
				Separation Geotextile		US 200 Class 3	890 N
				Stabilization Geotextile		US 315	1402 N
8	CALTRANS	ASTM D4632	Tensile Strength	Geotechnical Subsurface Reinforcement	Woven	US 200	890 N
				Sediment Filter Bag		US 1540	1624 x 890 N
				Temporary cover		US 200	890 N
				Subgrade Enhancement B1		US 4800	2448 x 2448 N
				Subgrade Enhancement B2		US 230	1780 x 1423 N

From Table 2, US DOI has reported the lowest acceptable values for breaking strength at 356N and 400 N for subsurface drainage and erosion control applications respectively. The tensile strength values of woven geotextiles in this study was compared with these two lowest standard values to assess used textiles reuse potential for subsurface drainage and erosion control applications.

2.10 Geotextile Applications

Geotextiles are used in numerous industrial applications based on their functions and properties. These applications include transportation, construction, environment and coastal defense. Some of these applications are described below.

2.10.1 Geotextiles in Transportation

Geotextiles are widely used in transportation applications [76]. Geotextile transportation applications include road construction, drainage applications and pavement overlays. Additional newer transportation applications of geotextiles include acting as a moisture barrier, limiting overflow of stormwater underground, separating pavement and secondary containment as a backup to protect against leakage [77]. Two studies examined the use of synthetic geotextiles in pavement construction for transportation applications [78], [79]. Koerner lists the transportation engineering applications of geotextiles in modified roadways, trenchless pipe remediation and erosion control of systems [80]. One of the advantages in transportation applications of geotextiles is the prevention of permafrost degradation [81]. In this context geotextiles including woven geotextiles are used in reinforcement applications and embankment stability on the side-slopes of highways [81].

2.10.2 Geotextiles in Construction

Geotextiles are widely used for construction applications. Nonwoven geotextiles are mostly used for construction applications and very few studies mention use of woven geotextiles for these applications. Nonwoven geotextiles are used in wall reinforcement applications because of their ease of construction, expediency and low cost [82]. Because of their widespread use in construction, in-field performance of geotextile reinforcement was analyzed in embankment applications over weak foundations [83]. A study also examined the damage that occurs to nonwoven geotextiles in road construction [84]. Some studies have analyzed and evaluated the behavior of both woven and nonwoven

geotextiles in sediment control [85], slope stabilization [86] and rural road pavement construction [87].

2.10.3 Geotextiles in Environmental Applications

Geotextiles have environmental applications for the purpose of soil conservation and treatment of sewage. The effectiveness of vegetation cover acting as biological geotextiles in reducing runoff and soil loss was analyzed under controlled laboratory tests and in-field tests [88], and in-field run off and soil loss data of different biological geotextiles was compared for regions across Europe [89]. Geotextile tubes are a low cost and efficient means of dewatering waste in a sewage treatment plant (STP) [90] and a study analyzed the use of geotextile tubes, geotextile containers and geotextile bags in hydraulic and marine applications [91]. Moreover, behavior of biodegradable geotextiles, such as coir fiber was investigated for the application of reinforcement of embankments on soft ground [92]. A study also assessed the engineering and environmental impacts of using the recycled construction and demolition materials along with geotextiles for permeable pavements and trapping pollutants [93].

2.10.4 Geotextiles in Coastal Protection

Products made from geotextiles such as geotextile bags, tubes and containers are ecofriendly, construction friendly and cheap, used for coastal, river and offshore protection [94]. A study was conducted to find out the feasibility for the protection of coastal erosion with the use of geotextile tubes and artificial beach rock [95]. The placement of geotextile tubes in terms of depth and alignment is crucial to their functionality and life span for coastal protection measures [96]. Lee et al. presented case studies to examine the feasibility of using geotextile tubes in sandy and muddy coasts [97]. They also considered different factors such as placement of tubes that affect their functionality in those conditions [97]. A study conducted in Poland also assessed different parameters of geotextiles including their tensile and permittivity properties for the coastal protection application [98]. As an alternative geotextile wrap-around revetment structures are also being used for coastal protection [99]. This study provides

quantitative data for both woven and nonwoven geotextile to show that geotextile wrap-around revetments have greater stability and more resistance to erosion [99].

2.10.5 Used Textiles Reuse Potential for Geotextile Applications

In the context of various applications of geotextiles, with some modification, used textiles may have the potential to be used for erosion control, ditch protection, and reinforcement applications in transportation and construction industries. Moreover, they could also be used in environmental applications for treating sewage and protection of coastal erosion. However, determining the material properties and their comparison with the material property values that come from different agencies can give more insight in the reuse potential of used textiles for different applications.

2.11 Problem Summary

Literature on the combined environmental and economic impact of recycling discarded textile is limited. Also, little is known about the material composition of discarded textiles. In order to completely assess the reuse potential of discarded textiles, determining the material composition of used textiles is needed. A hybrid EIO-LCA model was developed to understand the combined environmental and economic impacts of recycling used cotton textiles.

Moreover, studies have consistently considered the material properties of nonwoven geotextiles and literature on applications and material properties of woven geotextiles is limited. To fully assess the reuse potential of discarded woven fabrics as woven geotextiles, used textiles' material properties should be determined and compared with standards for acceptable material properties that came from agencies such as DOTs and the US DOI.

2.12 Research Gap covered

This thesis:

- 1) estimates the availability of used textiles in the U.S. by providing case study data on the material composition of used textiles that were obtained from thrift store wholesalers in two regions of the U.S.;
- 2) modifies the hybrid EIO-LCA method by utilizing case study data to replace new material production from cotton farming with used cotton textile recycling from thrift store wholesalers as the input value; and
- 3) identifies different industrial subsectors for the reuse potential for utilizing discarded textiles due to economic and environmental effects of replacing new material production processes with used textile processes [100];
- 4) determines the permittivity and tensile properties of used woven textiles;
- 5) identifies the reuse potential of the used woven textiles as geotextiles by comparison of material property values determined through experimentation, with standard material property values used by U.S. agencies.

3 Reuse Potential of Used Textiles for American Industries (Publication for IDETC-CIE 2019 Conference)

3.1 Introduction

This chapter has already been published for the 2019 International Design Engineering Technical Conference [101]. Used clothing is a global and local problem. Annually, goods produced by textile, leather and footwear manufacturers in China, one of the largest textile producers globally, export more than 300 million tons of embodied carbon emissions [102]. Poor quality clothes boost fast fashion practices in retail sales because they promote faster purchase and discard rates [7], [10], [5]. These cheaply made used clothes are sent to overseas markets in Africa, Asia, and Eastern Europe leading multiple countries to pursue bans on used clothing imports [4].

Various studies have been conducted to look at the environmental impacts of recycling used clothing. Some of these discussions are descriptive and qualitative and consider the environmental benefits of textile recycling [23] and of using these products instead of virgin materials [22]. Other studies are more quantitative and calculate how recycling or reusing textiles specifically reduces greenhouse gas emissions. According to one study 14.7 tons (13.3 metric tons) of CO₂ equivalent emissions are avoided per ton of discarded textiles recycled [10]. Manufacturing new viable products made from discarded textiles is another way to reduce environmental load from greenhouse gases [10], [11]. This practice has the additional advantages of reducing water consumption [10], decreasing the need for landfill space [23], and decreasing the need for agricultural land [24].

Very few studies have examined the economic impact of recycling used textiles. Hawley [23], [40] provides qualitative descriptions of how various actors in the recycled textile supply chain economically benefit from textile recycling systems and contribute to corporate social responsibility. Hawley concludes that collaboration in textile recycling between supply chain actors can result in economic and environmental improvements [40]. Therefore, embracing a system to direct the clothing and textile waste into a recycling pipeline in the U.S. as well as globally is paramount for sustainability. Ekström and Salomonson consider how reusing and recycling used clothing at a macro scale

(industry wide), instead of a micro scale (company) or individual actor basis (consumer), can lead to improvements [25]. However, the authors only considered reuse within the apparel industry. Considering all sectors within the economy that could reuse available textiles would truly account for taking a macro view of the textile reuse and recycling problem.

Globally the used clothing trade has increased by 106% in the past decade from \$1.8 billion USD in 2006 to \$3.7 billion USD in 2016 and has reached over 1.4 million tons (1.3 million metric tons) annually [5]. Most used clothing exports go to sub-Saharan African countries (approximately 20.0%), Pakistan (6.0%), Malaysia (5.8%), and Ukraine (4.9%) [5]. The trade of used textiles may stop abruptly due to political conflicts [14]. In 2015, Goodwill-DE contacted university researchers in an effort to find new manufacturing opportunities for used textiles under the Recycled Goods Manufacturing Initiative. Used textiles, like any recycled commodity, experience large price swings. The sales price for used clothing had fallen from approximately \$0.23 to \$0.05 USD per pound (\$0.51 USD to \$0.11 USD per kg) from 2012 to 2014, the year in which Goodwill-DE opened their textile recycling center [103]. This decline in price may be attributed to political, economic or health crises (ebola outbreak) in multiple regions around the world including large used textile importing regions such as Ukraine and western Africa [14]. When used textiles fluctuate at the lower end of price extremes, thrift store franchises may decide it makes more financial sense to dispose of unsold used textiles in landfills and pay tipping fees of over \$80 per ton rather than continue paying for storage. Establishing an efficient industrial textile recycling system and maximizing the reuse potential of discarded clothing can alleviate this problem.

The U.S. EPA calculated in 2015, the most recent year of data available, textiles discarded in landfills made up over 7.6% of total landfilled MSW in the U.S. Of the 16 million tons of textiles discarded in 2015, only 15% or more than 2 million tons of textiles were recycled [1]. Textiles are almost completely recoverable. The Secondary Materials and Recycled Textiles Industry Association estimates textiles are 95% recyclable, either for remanufacturing new products such as rags and wipers or through industrial composting [104]. Similar to composting, discarded natural textiles in landfills breakdown the biodegradable fibers which creates methane (CH₄), a potent greenhouse

gas as a byproduct. In contrast, recycling or reusing textiles is found to reduce 3.5 tons (3.4 metric tons) of CO₂ equivalent emissions per metric ton of discarded textiles recycled, which includes emissions avoided from primary production of new textiles [11]. Clearly, the economic and environmental impacts of textile recycling demand attention.

Economic Input Output Life Cycle Assessment (EIO-LCA) connects economic inputs (material or supply) and economic outputs (product) from different industrial subsectors across an economy to allow comparison of economic and environmental impacts for decision-making [16]. A hybrid EIO-LCA allows changes to be made to the industrial subsectors that act as inputs and outputs for other economy-wide subsectors for comparisons of potential environmental and economic changes [41]. Relatively few studies utilize the hybrid EIO-LCA method rather than conventional EIO-LCA.

Several hybrid EIO-LCA studies have only considered a single industry. Meisterling et al. analyzed an agricultural system to compare the impacts of energy use and the Global Warming Potential (GWP) associated with the growth of organic and conventional wheat in the U.S. in order for policy makers to minimize GWP [42]. Meier et al. considered organic and conventional agricultural products to develop a sustainable high yielding agricultural system with the least possible impact on the environment [43]. Similarly, single industry EIO-LCA studies considered the environmental impacts of cob construction [44], hotel textiles [45] and multiple construction projects [41], respectively. Cicas et al. investigated all the industries within a single U.S. region and found no major differences on national and regional levels between economic activities generated by the same final demand [46]. The researchers of this paper consider a national rather than regional economic scale based on the conclusions of Cicas et al. Ritchie et al. considered how investment decisions impact carbon footprints across all industries and found that increased investments lead to more profits but also more environmentally detrimental effects [47]. However, the study does not consider actual material flows to be replaced, simply monetary flows. In this context the researchers of this paper also utilize a cross-

industry approach for monetary flow replacement associated with recycled textiles at a national scale, something very few previous hybrid EIO-LCAs have considered.

Substantial amounts of studies have looked at the environmental impact of discarded textile recycling along with the replacement of new textile inputs with used textile inputs. However, the literature on the economic impact or combined environmental and economic impacts of replacing new textile inputs with used textile inputs is limited. Also, little quantitative data exists about discarded textile collection and sorting processes.

Researchers in Denmark developed a sorting and quality methodology for characterizing textile reusability out of MSW collected from the Jutland region [24]. Sandin and Peters identified the need for verifiable data on used textile collection and sorting from primary sources [48]. Comparison of discarded textiles from more than one location allows for a more feasible assessment of reuse potential for used textiles. The authors of this research address a research gap for textile reuse and this paper adds to existing work by examining the interconnectedness of economic and environmental effects in three ways. This paper:

- 1) estimates the availability of used textiles in the U.S. by providing case study data on the material composition of used textiles that were obtained from thrift store wholesalers in two regions of the U.S.;
- 2) modifies the hybrid EIO-LCA method by utilizing case study data to replace new material production from cotton farming with used material recycling from thrift store wholesalers as the input value; and
- 3) identifies different industrial subsectors for the potential of utilizing discarded textiles due to economic and environmental effects of replacing new material production processes with used textile processes [100].

The modified hybrid assessment model was applied to three main industries: 1) vehicles and other transportation equipment; 2) furniture, medical equipment, and supplies; and 3) textiles, apparel, and leather. Within these three main industrial sectors, seven subsectors are considered. For each subsector, new material inputs were replaced with used/recycled inputs for a real, feasible monetary value. The subsector output depended on the availability and cost of the used/recycled materials. Specifically, the replacement of virgin cotton textiles was achieved by shifting the economic value from cotton farming inputs to used textile inputs by utilizing the thrift store wholesale

industrial subsector. Goodwill-DE thrift store and Goodwill of Duluth thrift store both donated a bale of used clothing for sorting based on material composition. The authors of this paper used Goodwill-DE used textile bale generation data and material composition measurements of the two bales to create a realistic estimate of used cotton weight annually available in bales and the monetary value of this used cotton. The hybrid EIO-LCA model was run by replacing the monetary flow of new cotton textile materials into the seven individual industrial subsectors with used cotton textiles to determine what, if any, environmental and economic effects occur from this change in material inputs.

3.2 Materials and Method

3.2.1 Selection of Industrial Sectors

To better determine the reuse potential of discarded clothing in U.S. industries, seven industrial subsectors were selected based on the proposition that they could replace new textile inputs with the recycled cotton textile products. These subsectors include:

1. Cut and sew apparel contractors (NAICS code: 315210)
2. Women's and girls' cut and sew apparel manufacturing (NAICS code: 315240)
3. Men's and boys' cut and sew apparel manufacturing (NAICS code: 315220)
4. Aircraft seats manufacturing (NAICS code: 336360)
5. Upholstered household furniture manufacturing (NAICS code: 337121)
6. Automobile seat covers manufacturing (NAICS code: 336360)
7. Textile bag and canvas mills (NAICS code: 314910).

All three cut and sew apparel subsectors involve the cutting of purchased textile fabrics and sewing it together to make apparel and accessories for different types of clients/consumers. Aircraft and automobile seat manufacturing subsectors consist of establishments that are engaged in fabricating motor vehicle seating, seats, seat frames, seat belts and interior trimmings. Upholstered household furniture subsector comprises establishments involved in manufacturing household furniture. The furniture may be made on a stock or custom basis and includes the upholstered seats and backs of wood or metal kitchen and dining room chairs. Textile bag and canvas mills use textiles in covers (boats, swimming pool, trucks etc.), laundry bags (made usually from purchased woven

or knitted material), or textile bags like women's handbags (made usually from purchased woven or knitted material). All of these industrial subsectors use cotton material.

3.2.2 Bale Case Study and Sorting Methodology

To better understand the reuse potential of discarded textiles one needs to determine the composition of used textiles. To determine the material type of used textiles, the clothes were manually sorted by the material composition stated on the textile tags. This approach has been successfully carried out by other researchers [24]. Sorting in the thrift store industry is usually a manual process in order to generate different saleable product streams [4]. Different product streams include vintage name brand clothing, jeans, insulation, upholstery cushioning or cotton textiles for rags and wipes [105]. Automated sorting is rare in the thrift store industry. Chavan discusses the textile for textile (T4T) project for which an automated industrial sorting line with near-infrared (NIR) spectroscopy quickly and accurately sorts textile waste based on composition and color [10]. This study adds to previous work by considering textiles discarded to MSW handlers and assessing material composition and quality but for donated used textiles.

In order to determine which textile materials are commonly discarded, the authors of this study pursued collaboration with Goodwill-DE (2016) and later Goodwill of Duluth (2017). Each thrift store franchise donated a bale of used clothing that had not sold (Figure 1). Normally, unsold donated textiles are baled and sold by the semi tractor-trailer load (approximately 18 bales per load) to wholesalers who sell the bales around the globe [105].

A baler machine can compress a half ton to one ton of used clothing with wire ties. Once opened each bale of used clothing fits into two to four cardboard gaylords which are 3 foot wide by 3 foot long by 3 foot high shown in Figure 1 and Figure 2.

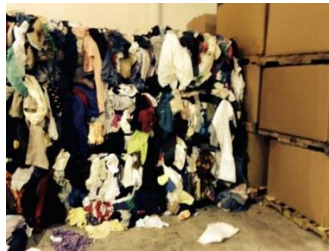


Figure 1 Bales Stacked Three High for Storage and Gaylord (Authors' Photo)



Figure 2 Bales Filled with Used Textiles (Authors' Photo)

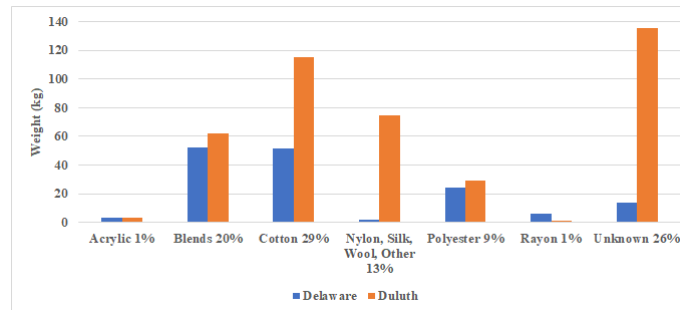


Figure 3 Delaware and Duluth Bale Materials Percentage by Weight 2016 and 2017 (Goodwill of Delaware sorting done by Isabella Aswad and Eric Johnson and Goodwill of Duluth-Minnesota bale sorting done by Ben Zbornik)

Sorting of bales from these two regions, Delaware and Duluth, Minnesota, provided insights into the material composition of discarded textiles. Many articles of used textiles no longer had tags, hence were marked as unknown material composition. More clothing without tags of unknown material were found in the bale from Duluth. This difference could be random or reflect a difference in preference for cutting out tags between consumers in Duluth and Delaware.

Figure 3 shows the material composition of different bales by percentage weight. The different locations, Duluth and Delaware had different weights and percentages of materials. Figure 3 also shows cotton has the highest availability for single material composition textiles in both locations. The Delaware bale yielded more blends than cotton, but in Duluth, cotton was the highest single material type present. These different material compositions by location may reflect different styles, aesthetic tastes or even climate. Despite any differences between both locations, they showed a surprisingly similar use of textiles, with cotton being a large material category found in both locations. Due to these similarities in material content, it can be stated with caution that these two areas are somewhat representative of the U.S. as a whole. Future work, outside of the

scope of this project, could procure more bales from diverse geographic regions across the U.S. for material content analysis.

3.2.3 Quality Rating

Due to the time required to assess quality, a selection of garments was graded using a decision matrix designed to assign a quality rating (Table 3). Quality was rated from 1 to 4, with 1 representing textiles unable to be reused and 4 representing textiles that were completely new. Quality was evaluated by the garments' flaws, fading, and wear. Minor flaws were differentiated from significant flaws by size and number, where less than one cm in size and fewer than two flaws were considered minor, and more were considered significant. Mild fade was considered a lightening of color between the exterior and interior of the garment, while significant fade was considered an unrecognizable color difference between these two textile layers. Wear was assessed by evidence of wash and wear for minor and the presence of fabric pilling for significant wear.

Table 3 Quality Decision Tree

	4	3	2	1
Wearable?	Yes			No
Flaws?	None		Minor	Significant
Fade?	None	Mild	Significant	
Worn?	Not worn	Yes	Yes, pilling	

3.2.4 Annual Textile Weight and Economic Study

Data collected by Goodwill-DE about the weight of unsold textiles from 2012-2014 was analyzed and averaged into an annual value of unsold textiles by number of bales. This annual rate of discarded textiles was multiplied by the average weight of the bales and the percentages of cotton present (Figure 3). Close to 20% of the most prevalent material types in the Delaware bale, specifically cotton and polyester, were measured for usable area of the garment (excluding sleeves and other small sections). The usable square area was assessed by measuring the width and length of the largest continuous area for

randomly selected garments of a specific material type. The measured garments were weighed to assess an average weight per area for a material.

This weight per area was used to assess the annual square area available by different textile material types at Goodwill-DE (Table 4). Goodwill-DE has nineteen thrift stores, and a recycling center which sells textiles by the pound. Goodwill of Delaware is one of 153 Goodwill thrift store chain franchises across the U.S. and is described as middle-sized compared to other franchises.

As seen from Table 4, the annual average weight of discarded cotton textiles from Goodwill-DE is 1,113 tons (1,010 metric tons). An assumption that used cotton textiles could replace new cotton inputs priced at \$28.80 per ton (\$31.75 USD per metric ton) was used. Utilizing this figure allows the calculation of the total economic value of Goodwill-DE’s used cotton textiles annually. Thus, the annual economic value of Goodwill-DE discarded cotton textiles is \$32,069 or 0.032 \$mil.

Table 4 Annual Goodwill-DE Cotton and Polyester (Data collected from Goodwill of Delaware by Isabella Aswad, Abigail Clarke-Sather, and Eric Johnson in metric and imperial Units)

Textile Type	Mass per Area kgm^{-2} (lbft^{-2})	Annual Weight metric tons (tons)	Annual Area km^2 (square miles)	Average Quality
Cotton	0.46 (0.09)	1010 (1,113)	2.2 (0.85)	1.9
Polyester	0.36 (0.07)	482 (331)	1.3 (0.50)	2.5

3.2.5 EIO-LCA Model Methodology

A hybrid product model was made for Goodwill-DE’s annual discarded textiles monetary value using Carnegie-Mellon’s Economic Input-Output Life Cycle Assessment (EIO-LCA) method tool to show the impact of reusing textiles on U.S. industries [100]. From the EIO-LCA U.S. 2002 (428 sectors) producer model, the following three broad U.S. economic industrial sectors that use cotton textiles were chosen for modification:

- Vehicles and other transportation equipment
- Furniture, medical equipment, and supplies

- Textiles, apparel, and leather

Because of extensive documentation of the background for the 2002 EIO-LCA model parameters, the 2002 model was used instead of the 2007 model [100]. The three broad sector groups selected: automotive, furniture, and apparel industries, all use textiles in large quantities. Within these three large sector groups, the following seven subsectors were chosen:

- Aircraft seat manufacturing,
- Automobile seat manufacturing,
- Upholstered household furniture manufacturing,
- General cut and sew apparel manufacturing,
- Men's and boys' cut and sew apparel manufacturing,
- Women's and girls' cut and sew apparel manufacturing,
- Textile bag and canvas mills.

For the seven subsectors a total of 1 million USD of economic activity was considered as the output. Four different model outputs or indicators, which are reflective of the main categories of the EIO-LCA model, were considered that encompassed both economic and environmental impacts. Economic indicators were based on total economic activity generated and included total purchases (TE) and total profits (VA). Environmental indicators encompassed global warming potential (GWP) and energy use (NRG) [9]. All these main indicators are the summation of sub-indicators within the same categories. Total purchases (TE) is the complete economic supply of direct and indirect purchases needed for production which includes labor costs and taxes paid but excludes profits which are treated as a separate indicator. Profits (VA) are the portion of value added which are not used for supply purchases. Global Warming Potential (GWP) is indicated by the total tCO_{2e} in metric tons of CO₂ equivalent emissions. GWP is a weighting of greenhouse gas emissions into the air from the production of each sector. Total tCO_{2e} is the sum of sub-indicators from CO_{2e} created from fossil fuel combustion sources, process emissions (sources other than fossil fuel combustion), methane (CH₄) emissions, nitrous oxide (N₂O) emissions, and hydrofluorocarbons (HFC) or perfluorocarbons (PFC) emissions. Total Energy (NRG) is the total energy use in terajoules (TJ) from all fuels and electricity. The main indicator of energy is a sum of sub-indicators related to coal,

natural gas, gasoline, biomass/waste, and non-fossil electricity sources. In order to maintain model simplicity, the sub indicators were neglected and only the four summary indicators for the demonstration of environmental and economic impact on the selected seven industrial subsectors were chosen.

A hybrid product model was then created to reveal the impact of replacing new textiles with recycled used textiles, in this case cotton, for these seven sectors. This replaces new material inputs and thus the materials production necessary to create new cotton textiles. The assumption of used cotton textiles as new cotton textile input has been shown to be technologically feasible and cotton recycling via shredding has recently shown promise for recycling into new yarns [106].

For both Delaware and Duluth, used cotton textiles took up the largest or a large percentage of total bale weight (Figure 2). Hence it is assumed that cotton would be the main type of textile in discarded clothing at a national level. Also, compendious studies have been done on the reuse potential of cotton waste and its benefits for environmental impacts associated with cotton production [10], [103], [107], [108], [109], [110], [111].

The economic category which was presumed to be replaced by the used cotton textile inputs is cotton farming (NAICS 111920). Additionally, the added economic activity associated with the sale of used textiles was considered as textile waste material wholesalers (NAICS Code 423930), which was assumed to replace the economic activity in cotton farming based on the availability of Delaware used cotton.

The base model for each of the seven industrial subsectors was run without any changes. Then a 0.032 \$mil value of annual discarded cotton textile was subtracted from economic activity for cotton farming and added to the wholesale trade for each run. Equation 2 shows how the differences shown in Figures 3, 4, 5 and 6 were calculated. The percentage differences (*%Diff*) between the original indicator (*Indicator_O*) and the indicator after modifying the economic activities in cotton farming and wholesale trade (*Indicator_M*) was compared to the original indicator value. All percentage differences were calculated the same way for each of the four indicators

$$\%Diff = \frac{Indicator_O - Indicator_M}{Indicator_O} \quad (2)$$

3.3 Results

For the seven industrial subsectors, the percent difference between these two models was plotted for each of the four indicators in Figures 4, 5, 6 and 7. The summary of percentage difference of these indicators is shown in Table 5. The average quality of cotton for 39 garments was just below 2, thus some cotton items were not reusable. The average quality of polyester for 30 garments was over 2, deemed reusable.

Figure 4 shows purchase savings for all industrial sectors. Women's and girls', men's and boys' and cut and sew apparel contractors manufacturing industrial subsectors show the greatest percentage of purchase savings. Figure 5 shows the profits losses for the sectors. These cut and sew apparel industries show the greatest profit loss. However, the profit losses are offset by the purchase savings and the cut and sew apparel sectors have net positive economic gain of 1.4%. Figure 6 shows the energy savings in the seven industrial subsectors. The three cut and sew apparel subsectors combined save around 0.182 terajoules of energy. Figure 7 shows the reduction in CO₂e emissions in all seven industrial sectors. The three cut and sew apparel industrial subsectors show the greatest reduction in CO₂e emissions of 29.4%. Figure 8 shows the economic and environmental impact for all indicators and industrial subsectors. Overall, cut and sew apparel industrial subsectors shows the greatest promise for potential reuse of discarded cotton textiles.

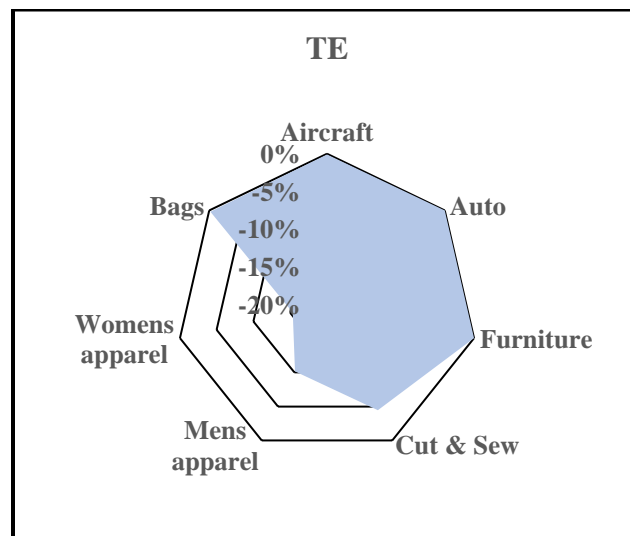


Figure 4 Percentage Change in Total Supply Purchases

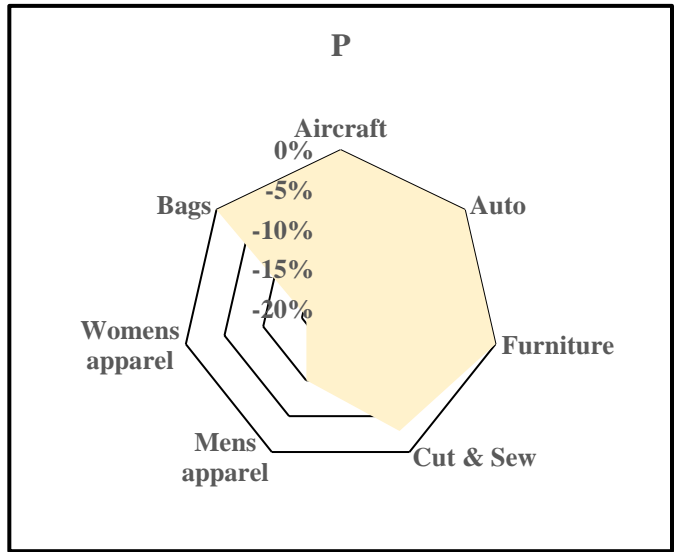


Figure 5 Percentage Change in Total Profits

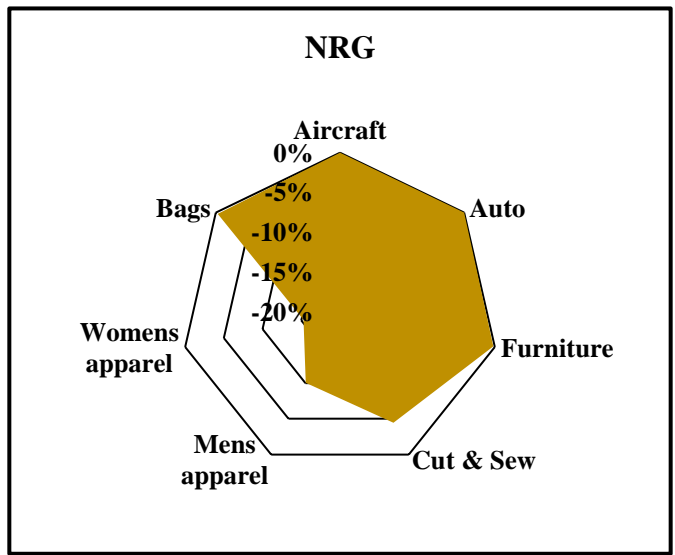


Figure 6 Percentage Change in Total Energy Use

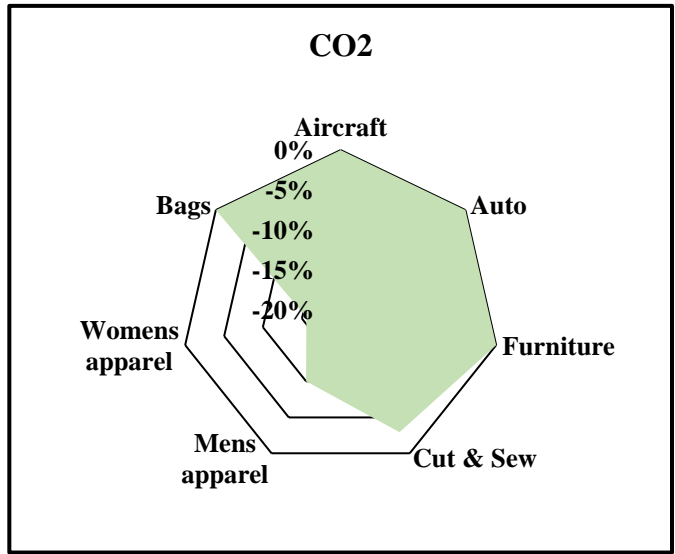


Figure 7 Percentage Change in CO₂e

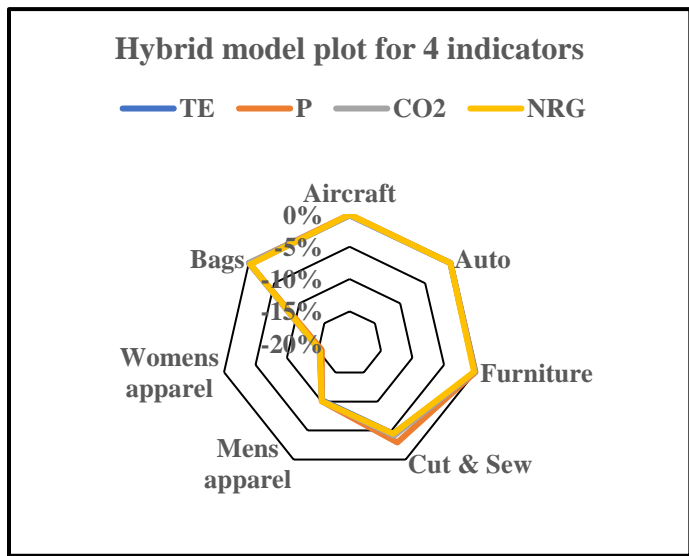


Figure 8 Percentage change in all indicators

Table 5 EIO-LCA Indicator Differences After Reuse of Goodwill-DE Cotton Textile

Sectors (NAICS Code)	%Diff TE	%Diff. Profit	%Diff CO2e	%Diff. NRG
Aircraft seats mfrg (336360)	-0.1%	0%	-0.1%	0%
Automobile seats mfrg (336360)	0%	0%	0%	0%
Upholstered household furniture mfrg (33712)	0%	0%	-0.1%	-0.2%
Cut and sew apparel mfrg (315210)	-4.5%	-2.9%	-4.1%	-4.5%
Men's' and boys' apparel (315220)	-10.2%	-10%	-10.1%	-10%
Women's' and girls' apparel (315240)	-15.3%	-15.6%	-15.2%	-15.3%
Textile bags and canvas mills (314910)	-0.2%	0%	0%	-0.30%

3.3.1 Economic Impacts

Economic impacts were measured by supplier purchases and profits. In regard to total supplier purchases, the women's and girls' cut and apparel manufacturing subsector shows the greatest percentage in savings. The men's and boys' cut and sew apparel and

cut and sew apparel contractors subsectors have the second and third greatest percentage savings respectively in supplier purchases (Table 5). Textile bag and canvas mills as well as aircraft manufacturing subsectors show lower purchase savings, while automobile and upholstered household furniture subsector show no purchase savings after reuse of discarded cotton.

Regarding profits, the women's and girls' cut and sew apparel manufacturing subsector show the greatest percentage losses in profits, with men's and boys' and cut and sew apparel contractors manufacturing industrial subsectors having the next greatest percentages of profit losses respectively. The rest of the industrial subsectors show no profit loss after reuse of discarded cotton textiles as shown with 0% difference in Table 5. Overall, all three cut and sew apparel manufacturing industrial subsectors save approximately 30% in supplier purchase costs and lose 28.6% in profits for a net economic gain of +1.4%. It can be observed that the cut and sew apparel subsectors, even after losing profits, are still net positive economically. Thus, replacing new cotton with used cotton textiles appears to have a positive economic impact for US apparel industrial subsectors.

3.3.2 Environmental Impacts

The recycling of discarded textiles, specifically cotton, and its reuse in U.S. industries may have positive environmental impacts, as shown from the seven industrial subsectors selected and investigated with the hybrid EIO-LCA model. With the reuse of annual Goodwill-DE used cotton textiles, the women's and girls' cut and sew apparel manufacturing industrial subsector has the greatest energy savings and reduction in CO_{2e} emissions. Men's and boys' apparel and cut and sew apparel contractors manufacturing industrial subsectors have the second and third position in terms of reducing CO_{2e} emissions and energy consumption. Overall, after reuse of the annual amount of Goodwill-DE's discarded cotton textiles, these industries reduce 29.4% CO_{2e} emissions for every \$1 million USD output.

The aircraft subsector is only marginally impacted in terms of reducing CO_{2e} emissions while showing no change in energy savings. The upholstered household furniture subsector also shows very little change in environmental impact. Likewise, the textile bags and canvas mills manufacturing industrial subsector shows no change for

CO₂e emissions but has a very small 0.3% decrease in energy consumption. Recycling discarded textiles has the greatest effects on the environmental impact of the three cut and sew apparel manufacturing industrial subsectors.

3.4 Discussion

A hybrid EIO-LCA model was run for the reuse potential of discarded cotton textiles within seven selected industrial subsectors. These industrial subsectors were selected since all could accept used cotton textile as a replacement for new cotton textile inputs. Four indicators were selected to model the combined economic and environmental impacts of total supply purchases (TE), profits (P), metric tons of CO₂ equivalent emissions avoided (tCO₂e) and energy used in terajoules (NRG) respectively.

3.4.1 Economic Impacts

Recycling Goodwill-DE's is 1,113 tons (1,010 metric tons) annual discarded cotton textile valued at \$0.03 mil USD within the cut and sew apparel industrial subsectors show the greatest positive impact for the environment with a relative minor decrease in profits offset by a greater decrease in supply purchase costs. All three apparel industries combined together save \$0.29 mil USD in economic supply of purchases while they lose \$0.05 mil USD in profits which is still \$0.24 mil USD net positive. The aircraft industry subsector shows no profit decrease as well as no energy savings; however, this subsector shows a very small \$0.001 mil USD savings on supply purchases. The textile bag and canvas mill subsector show no change in profits while saving a very small amount of \$0.002 mil USD in supply purchases. The automobile and upholstered household furniture subsectors are not impacted economically.

3.4.2 Environmental Impacts

In terms of environmental impact, the women's and girls' cut and sew apparel manufacturing industrial subsector reduces 3.9 tons (3.5 metric tons) of CO₂e emissions while saving 93.9 million BTUs (0.099 TJ) of energy. Men's and boys' and cut and sew apparel contractor manufacturing industrial subsectors follow this same trend for CO₂e emissions and energy savings. Combined together the three apparel industrial subsectors reduce (5.3 metric tons) of CO₂e emissions and save 172 million BTUs (0.182 TJ) of

energy after recycling 1,113 tons (1,010 metric tons) of Goodwill-DE textile within these subsectors. Compared to 3.5 tons per ton (3.4 metric tons per metric ton) of CO_{2e} emissions reductions for recycling instead of landfilling discarded textiles reported in other research [8], all three cut and sew apparel industries reduced a much smaller amount 5.29 kg CO_{2e} per metric ton. The EIO-LCA is a highly simplified model of the economics and environmental impacts of this system. However, the great difference between these values seems surprising and likely comes from different assumptions and life cycle system boundaries.

The upholstered household furniture subsector reduces 22 lbs (10 kg) of CO_{2e} emissions and saves 0.95 million BTU (1,000 MJ) of energy. The aircraft subsector also reduces 22 lbs (10 kg) in CO_{2e} emissions. The textile bags and canvas mills subsector show no change in CO_{2e} emissions, however, saves 1.99 million BTU (2,000 MJ) of energy. The aircraft, upholstered household furniture and textile bag industrial subsectors show relatively little economic or environmental improvements by replacing new with used cotton textile inputs. The automobile subsector shows no change in any factor when utilizing used cotton textile inputs.

Overall, the three cut and sew apparel subsectors show the most positive impact in terms of economic and environmental indicator improvement. Ekström and Salomonson also focused on improving reuse and recycling of clothing and textiles in the apparel industry in Sweden [8]. Our research confirms that focusing on the apparel industry as the primary acceptor of discarded cotton textiles makes both economic and environmental sense.

3.5 Conclusion

An EIO-LCA hybrid model was created to see the impact of recycling the annual Goodwill-DE discarded cotton textile output within seven individual industrial subsectors. Three cut and sew apparel manufacturing industrial subsectors show the most promise for utilizing discarded textiles in the future because of the positive impact in terms of purchase and energy savings, reduction of greenhouse gas emissions with relatively little profit loss.

This research confirms that focusing on the apparel industry as the primary acceptor of discarded textiles makes economic and environmental sense. Aircraft, upholstered, and textile bag mill subsectors showed some positive economic and environmental impacts, but the automobile seat manufacturing subsector showed no impact whatsoever.

Further research could lead to a more realistic approach to modeling U.S. national impacts by collecting discarded used textile data nationally and then modeling the impacts of used textiles. Modeling a greater variety of indicators would reflect more detailed economic and environmental impacts. Some U.S. industries will be positively impacted by utilizing used cotton textiles. Recycling discarded textiles helps reduce waste in the U.S. society as a whole.

4 Material Properties of Used Textiles (In Preparation for a Journal Paper to Be Submitted to Geotextiles and Geomembranes Journal)

4.1 Introduction

Discarded used textiles pose a serious problem to the environment, and textile manufacturing locally and globally also contribute to carbon emissions. Annually, goods produced by textile, leather and footwear manufacturers in China, one of the largest textile producers globally, account for more than 300 million tons of embodied carbon emissions [102]. Additionally, poor quality clothes used in fast fashion practices in retail sales promote faster purchase and discard rates [7], [10], [5]. Therefore, the issue of used textiles must be dealt with in order to have a positive impact on the environment and reduce the environmental load from greenhouse gases. The authors of this paper aim to study the feasibility of recycling used textiles, particularly cotton, polyester and mixed cotton polyester textiles, into woven geotextiles by determining their material properties. Geotextiles are widely used in numerous applications based on their functions of drainage, filtration, separation, cushioning and reinforcement [29]. The literature on assessing the reuse and recycling potential of used textiles into geotextiles, specifically by determining the material properties of used textiles, is limited and confined to nonwoven geotextiles manufactured from textile waste. It provides a qualitative assessment of nonwovens in an application but does not determine the material properties of the used textiles. The authors of this research bridge this gap by determining the reuse potential of used woven textiles. They specifically investigated the permittivity and tensile strength properties of used woven cotton, polyester and mixed cotton polyester and compared the data with standard values for woven geotextiles obtained from several departments of transportation (DOT) across America.

4.2 Methodology and Testing Procedures

4.2.1 Sorting Methodology

In order to assess the reuse potential of discarded used textiles, a manual sorting methodology was used [101]. Goodwill of Delaware and Goodwill of Duluth-Minnesota, each thrift store donated a bale of used textiles. The bales were sorted to determine the material composition of each textile type by percentage weight. The material composition after sorting is shown in Figure 9.

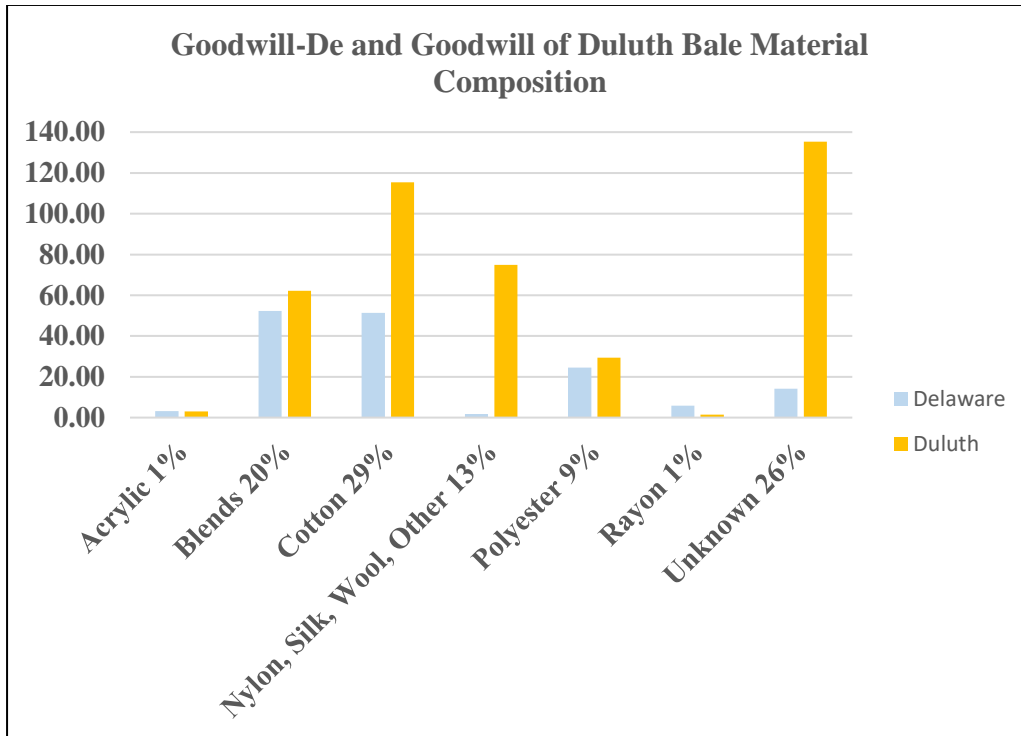


Figure 9 Delaware and Duluth Bale Materials Percentage by Weight 2016 and 2017 (Goodwill of Delaware sorting done by Isabella Aswad and Eric Johnson and Goodwill of Duluth-Minnesota bale sorting done by Ben Zbornik)

4.2.2 Selection of Fabric Types

After the sorting of bales, three different categories of woven garments, namely 100% cotton denim jeans, 100% polyester and 50% cotton/50% polyester garments, were selected. In Figure 9, from both locations, the major category of discarded textiles by percentage weight was cotton at 29%. Polyester had a considerable percentage around 9% and blends at 20%. The composition category of nylon, silk, wool, and other composites considers a variety of materials for manufacturing these textiles and is thus

not representative of a single material category that can be tested. Also, the unknown category refers to textiles with no tags; therefore, no information on the material composition of these textiles was known and they were avoided for testing. Most of the used clothing from the bales was either woven or knit, and very few nonwovens were encountered. Tensile testing of knit clothing is difficult to assess as knitted garments have a high stretch of 11% for which the common texting testing method ASTM D5034 becomes invalid. Therefore, instead of knit materials, woven discarded textiles were selected for this research,

4.2.3 Permittivity Samples

For permittivity testing of 100% denim clothing samples, nine discarded denim garments from Goodwill of Delaware and five discarded denim garments from Goodwill of Duluth were selected. Denim was chosen to see if more uniform sample results could be found by choosing a single garment type. Denim is a heavy-duty cotton garment manufactured from rugged tightly woven twill in which the weft passes under two or more warp threads. Also from Goodwill of Duluth, Minnesota, nine polyester and nine 50/50 cotton-polyester blend garments were selected for permittivity. Polyester fabrics are made from weaving of either filament or spun yarns. 50/50 cotton-polyester articles were chosen because they have the properties of both 100% cotton and 100% polyester. Four 3-inch diameter round samples were cut out from each fabric. The Duluth denim samples for permittivity were named as m.D.XY and the Delaware samples as D.XY. Polyester samples were named as P.XY and mixed cotton/polyester samples were named as CP. XY where X = 1,2,3,4,5 and Y = a,b,c and d. A fabric sample for permittivity testing is shown in Figure 10 below:



Figure 10 Denim 3-inch Diameter Samples

4.2.4 Tensile Testing Samples

From Goodwill of Duluth sorted textiles, five garments were selected for tensile testing across three categories. The number of samples that were cut out from each textile article were determined according to ASTM D5034. The selected five textiles across each category already had their corresponding permittivity tests conducted on them. Out of each textile article, five samples of 4 x 7 inches in machine direction and eight samples of the same dimension in cross direction of the garment were cut out. The tensile samples were named as m.D. X MY and m.D.X CZ for denims, P XMY and P XCZ for polyesters, C.P XMY and C.P XCZ for mixed cotton polyester where X = 1,2,3,4 and 5 and MY (machine direction) = M.1, M.2, M.3, M.4 and M.5 and CZ (cross direction) = C.1, C.2, C.3,....., C.8. The methodology for permittivity and tensile testing is explained below in section 4.2.5 and 4.2.6 respectively. A fabric sample for permittivity and tensile testing is shown in Figure 11 below.



Figure 11 Tensile 4 x7 Inches Samples

4.2.5 Permittivity Testing

For the permittivity testing of the garment samples, an ASTM D4491 standard method was used. This method is used to determine the hydraulic conductivity of geotextiles in terms of permittivity (1/s) under standard testing conditions in an uncompressed state [30]. The method uses three procedures: 1) constant head 2) falling head and 3) air flow method using air flow apparatus [30]. This study used the constant head method for determining the water permittivity of used textile articles. The permittivity is calculated with Equation 3 [30].

$$\Psi = QR_t / hAt \quad (3)$$

where:

Ψ = permittivity, s^{-1}

Q = quantity of flow, mm^3

h = head of water on the specimen, mm,

A = cross-sectional area of test area of specimen, mm^2 ,

t = time for flow (Q), s, and

R_t = temperature correction factor determined using equation ...

$$R_t = u_t/u_{20c}$$

where:

u_t = water viscosity at test temperature, millipoises, as determined from Table 6, and

u_{20c} = water viscosity at 20 degree Celsius, mP.

Table 6 Viscosity of Water Versus Temperature [30]

Temperature (Degree Celsius)	Viscosity ($\times 10^{-3}$ kg/s . m)	Correction Factor, R_t^A
19	1.027	1.025
20	1.002	1.000
21	0.978	0.976
22	0.954	0.952
23	0.932	0.931

^A Alternatively, the correction factor, R_t , can be calculated with: $R_t = 1.4751 - 20.0237 * T$, where T is in degrees centigrade.

According to the ASTM D4491 standard and as seen from the table, the water temperature range should be from 19 to 23 degree Celsius, and the dissolved oxygen level of the deaired water should be below 6 parts per million (ppm). The ASTM standard method was followed with the exception of the backfilling method. Instead of using the ASTM standard method of backfilling the apparatus from the outlet pipe, a sample was placed between the flanges first, and then the apparatus was filled with the deaired water from the outlet pipe. Due to the low permittivity of the textile samples, specifically denim, the deaired water would not pass through the sample in a timely fashion if the whole apparatus was filled from the outlet pipe. Therefore, the apparatus was filled with deaired water mostly from the head pipe, and deaired water was also poured at the outlet

end by removing the outlet elbow and filling that end with water until it started to flow out. Once the tester was filled, air bubbles could be seen trapped in the apparatus. To remove these bubbles, first the outlet elbow pipe was placed back on that outlet end, and then the tester was elevated from the outlet end to remove the trapped bubbles from that side. Then the outlet gate valve was closed, and the apparatus was elevated from the inlet side to let the trapped bubbles escape. After that, no bubbles were observed in the apparatus.

As seen in the Figure 12, a constant head lab tester with horizontal flow was built for permittivity testing of fabric samples. Dr. Abigail Clarke-Sathers' laboratory including Mathew Lee, Jeffrey Kangas and I built and calibrated the permittivity tester. The tester scheme is shown below in Figure 12.

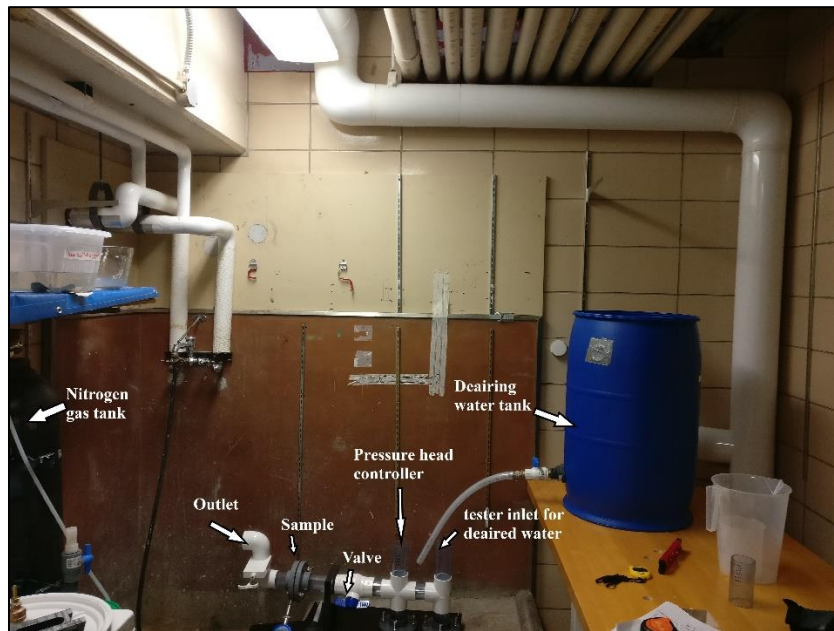


Figure 12 Horizontal Flow Permittivity Tester

The testing apparatus was calibrated with a No. 200 standard U.S. mesh sieve. The sieve was tested under a 10 mm head, and five runs were conducted. The procedure was repeated, and the head increased by 5 mm after each five readings until 75 mm. The same procedure was repeated on the apparatus without the sieve, and a calibration curve was plotted for flow rate (mm/s) versus head (mm).

The calibration curve after conducting these runs is shown in Figure 13.

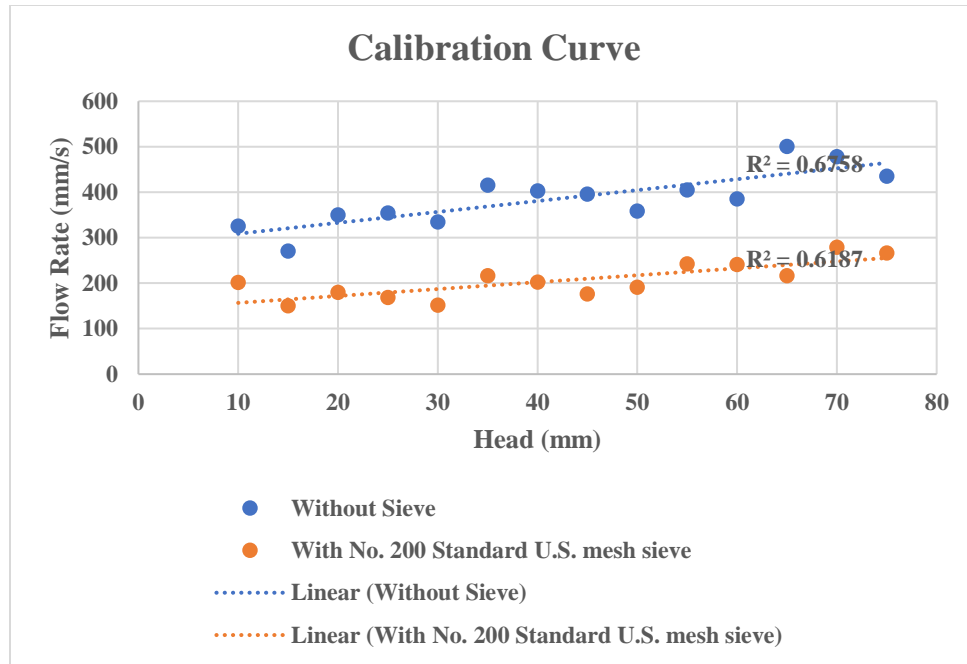


Figure 13 Permittivity Tester Calibration Curve

In Figure 13, the curve shows that the volumetric flow at different heads of the apparatus for the tests without the sieve is above the trendline for tests with the sieve. This means that the apparatus did not hinder the flow and was calibrated. Calibration was achieved by testing the apparatus for permittivity of 5 s^{-1} for the mesh sieve and this value was achieved. In Fig 13, the linear portion of the curves for both with and without No. 200 standard mesh sieve shows that head pressure and flow rate were directly proportional to each other. This direct proportionality means that as the head increased, the flow rate also increased with little to no hindrance to flow, thus showing a laminar flow region under linear plot as per ASTM D4491. The R squared value for tests without sieve was greater than that for tests with sieve, therefore the linear relationship between flow rate and head was more significant for tests without sieve and resulted in a smoother flow. However, the R^2 value on the calibration curve in Fig 13 was fairly low (~ 0.6), which may indicate that a turbulent flow existed. Laminar flow is needed for accurate permittivity results per ASTM D4491. Thus, the possible turbulence of the flow may have impacted the permittivity results. Before the samples were tested, they were conditioned in deaired water in an air-sealed container for at least two hours as shown in Figure 14 below.



Figure 14 Airtight Container for Conditioning

Deairing of water was done by bubbling nitrogen gas through water tank as shown in Figure 15. We made sure that the water temperature before deairing was between 19-23 degree Celsius as per ASTM standard. All of the tests were conducted successfully using this procedure, and the water temperature values were within the 19 to 23 degree Celsius range, and the dissolved oxygen values were below 6 ppm measured by an AMTAST probe. Also, at the start of the day of testing fabric samples, the AMTAST probe was calibrated as well and a No. 200 standard mesh sieve was tested for permeability. The permittivity values of the sieve testing were between the range of 3.7 1/s and 6.3 1/s as per ASTM standard and are reported in Table 7.

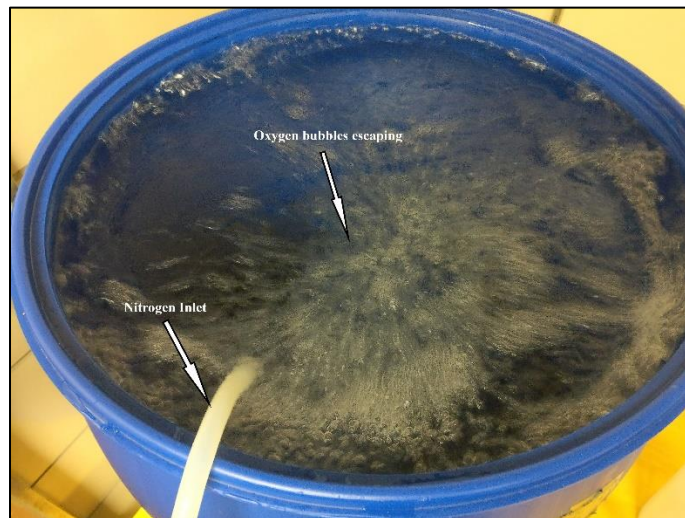


Figure 15 Deairing by passing Nitrogen Gas

Table 7 Permittivity Data of Sieves Tested

Date	Mesh Sieve US Standard No.200	Permittivity (1/s)	Within Acceptable Range
06/07/2019	Sieve 1	4.18	Yes
06/08/2019	Sieve 2	4.34	Yes
06/09/2019	Sieve 3	4.55	Yes
06/13/2019	Sieve 4	4.28	Yes
06/14/2019	Sieve 5	4.40	Yes
06/15/2019	Sieve 6	4.09	Yes
06/16/2019	Sieve 7	3.84	Yes
06/17/2019	Sieve 8	4.25	Yes
06/25/2019	Sieve 9	4.14	Yes

The permittivity values measured for woven clothing samples are mentioned in results section 4.3.1.

4.2.6 Tensile Testing

For the tensile testing of the used garment samples, an ASTM standard of D5034 was used. As opposed to ASTM 4632, which uses smaller sample size, this standard was used because it requires more samples and also because this is a standard for tensile testing textiles. Due to the limitation of the standard that the stretch value should not exceed 11%, knit materials were not selected. As the stretch value of woven textiles is below 11% so they were selected. For each piece of clothing material from the three categories of woven fabrics, 13 samples were cut out, five in machine direction and eight in cross direction. Machine direction in a textile is parallel to the direction of movement the fabric followed in the manufacturing process and cross direction is perpendicular to the machine manufactured direction [112]. Machine and cross direction in a textile are shown in

Figure 16 below [113]. Generally, the machine direction is the stronger direction because of the parallel orientation of the longer fibers resulting in increased strength. These samples were tested on an MTS machine (Model #: 39-075-103, Sr #: 843328). The tester setup is shown in Figure 17 below.

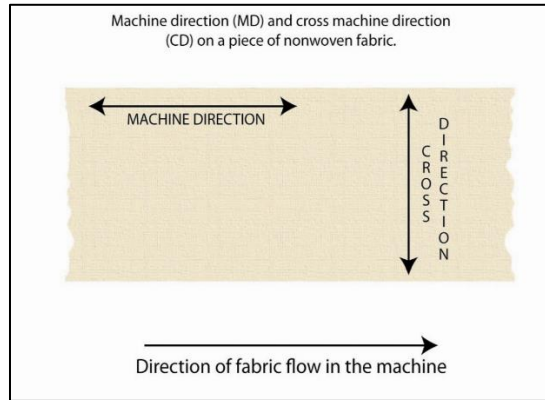


Figure 16 Machine and Cross direction in a Fabric Sample

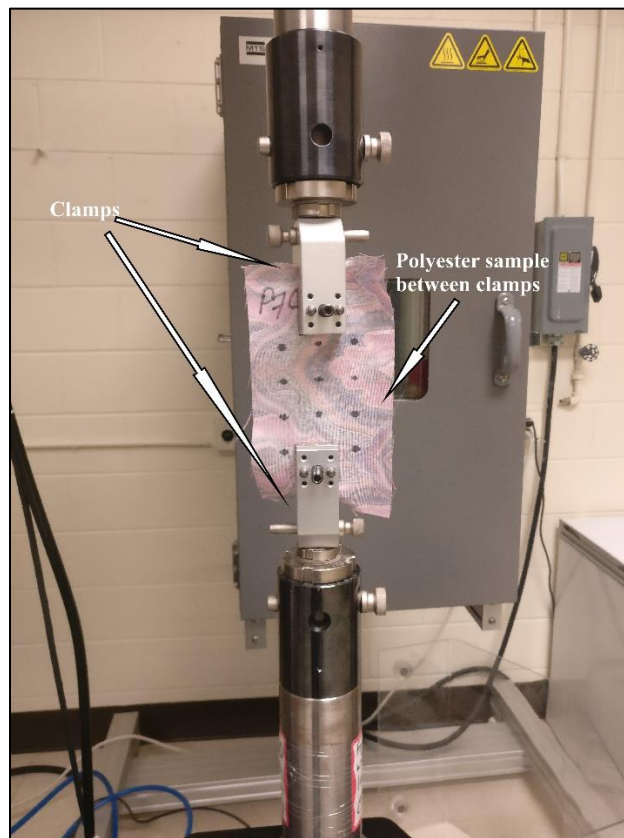


Figure 17 Polyester Sample Setup Between Clamps

As the standard grips were on order but not available at the time of testing due to longer lead times from the manufacturer, the ASTM standard was followed with one exception i.e. the grip size was 30mm x 30mm. Note that before testing the fabric samples on an MTS tester machine, they were put in a humidifier for conditioning them for a minimum of four hours at a set temperature and relative humidity of 21 degree Celsius and 65% relative humidity as per ASTM standard D1776. The samples in the humidifier are shown below in Figure 18.



Figure 18 Samples in Humidifier

The results of the tensile tests are shown in the results section 4.3.2 for machine direction and 4.3.3 for cross direction.

4.3 Results

The results of permittivity and tensile strength tests conducted on used cotton, polyester and 50/50 cotton-polyester samples are discussed and presented in this section.

Permittivity results for all three categories of used textiles are presented in section 4.3.1 and tensile testing results in the machine and cross directions are presented in sections 4.3.2 and 4.3.3 respectively. Orange line in all of the figures represent the average value of data with respect to the figure. Force-Displacement plots examples for used cotton, polyester and mixed cotton-polyester in machine and cross directions are shown in Appendices A-F at the end of this study. For tensile test and permittivity, the google drive links for data calculations are pasted in Appendix G and H respectively. The raw data for these tests is also available and can be presented upon request as well.

4.3.1 Permittivity Results

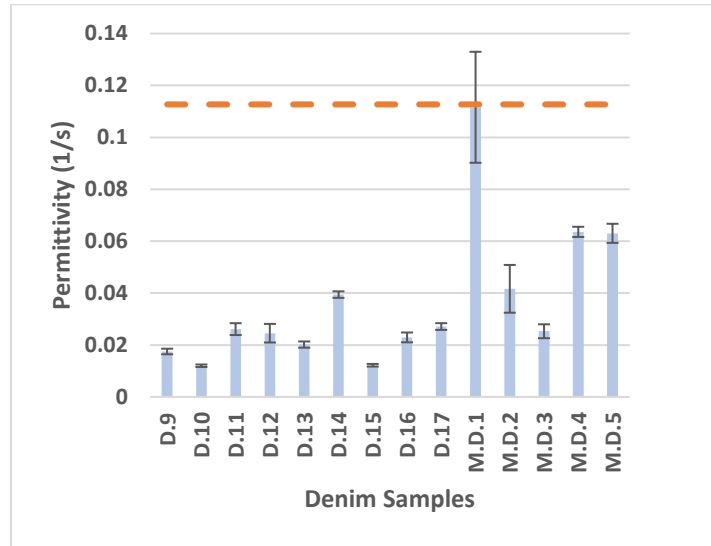


Figure 19 Denim Samples Permittivity

Figure 19 shows the permittivity from 14 different denim garments made of 100% cotton denim of unknown wear. Nine of these samples are from the Goodwill of Delaware bale while five of the samples are from Goodwill of Duluth-Minnesota bale. The average permittivity for all 14 samples was 0.04 1/s and standard deviation for all samples was calculated to be 0.03 1/s. The orange line in the figure represents the average and overall the standard deviation value shows less variance in permittivity among all denim samples. Also, the standard deviation for nine Goodwill-DE samples and five Duluth-MN samples is 0.008 1/s and 0.03 1/s respectively. This means that Goodwill of Delaware samples didn't vary much from each other in their permittivity while Duluth-MN samples did have slight variance in their values. An outlier was observed for Duluth-MN samples M.D.1 with a value of 0.11 1/s. M.D.1 denim sample was thinner as compared to other samples hence it had more permittivity than other samples and impacted the average value and therefore, none of the sample value was above average. Without the outlier, the average mean permittivity and standard deviation of 13 samples decreases to 0.03 1/s and 0.02 1/s respectively.

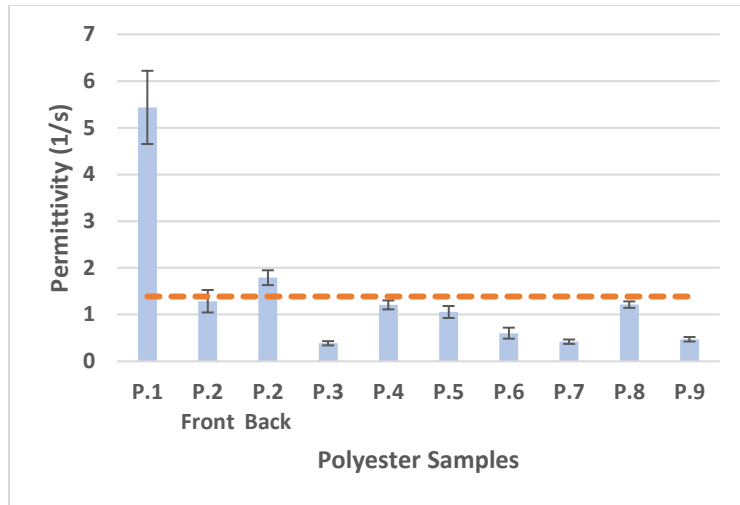


Figure 20 Polyester Samples Permittivity

Figure 20 shows the permittivity values from nine different polyester garments, all from Goodwill of Duluth-MN. The average permittivity for all these samples is 1.39 1/s and standard deviation for all samples is 1.45 1/s. This standard deviation value shows that there is significant variance in the permittivity values of these fabrics. An outlier was observed for P.1 sample with values at 5.44 1/s. P.1 sample had a thin feeling to the garment as well thereby increasing its permittivity more than other samples. This outlier affected the average value and standard deviation of all samples. Without the outlier, the average permittivity and standard deviation is calculated to be 0.94 1/s and 0.48 1/s meaning less variance among the data.

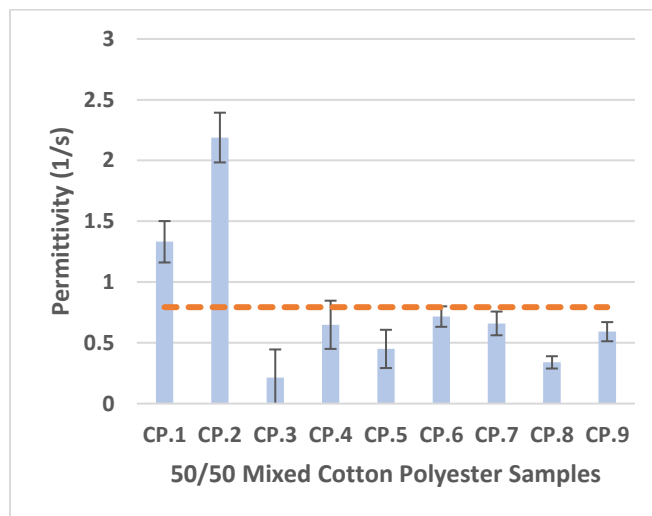


Figure 21 50/50 Cotton-Polyester Samples Permittivity

Figure 21 shows the permittivity values from nine different mixed cotton polyester garment blends, all from Goodwill of Duluth-MN. Cotton-polyester blend combines the properties of both cotton and polyester to give the textile unique properties. Garments made from this blend doesn't shrink and are more comfortable as compared to pure polyester garments. The average permittivity for all these samples is 0.79 1/s and standard deviation for all samples is 0.60 1/s. This standard deviation value shows that there is considerable variance in the permittivity values of these fabrics. A couple of outliers were observed for CP.1 and CP.2 samples with values at 1.33 1/s and 2.19 1/s. These outliers also affected the average value and standard deviation of all samples, hence the permittivity values of only CP.1 and CP.2 were below average. Without outliers, the average permittivity and standard deviation of other samples decreases to 0.51 1/s and 0.22 1/s respectively showing less variance.

4.3.2 Tensile Testing Machine Direction Results

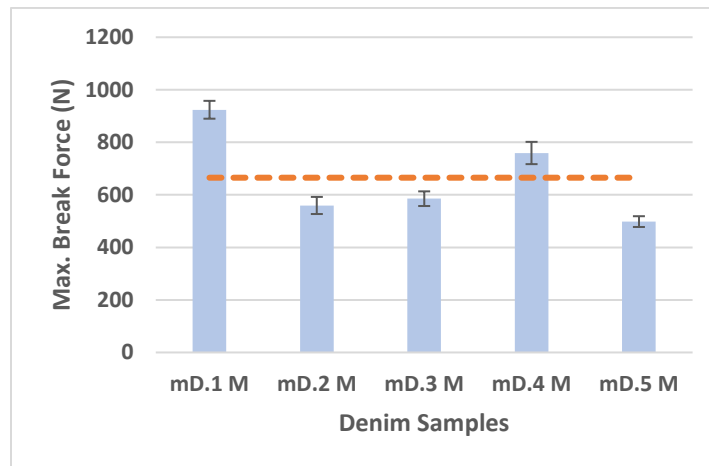


Figure 22 Denim Samples Break Force in Machine Direction

Figure 22 shows the maximum break force of five denim samples from Goodwill of Duluth-MN in machine direction. The average break force for these samples in machine direction is 665.30 N and standard deviation is 174.01 N. The standard deviation value shows that there is considerable variance in the break force values of these samples in machine direction. An outlier is observed for mD.1 M sample at 924 N. Without the

outlier the average break force and standard deviation is 600.6 N and 112 N respectively showing less variance in data.

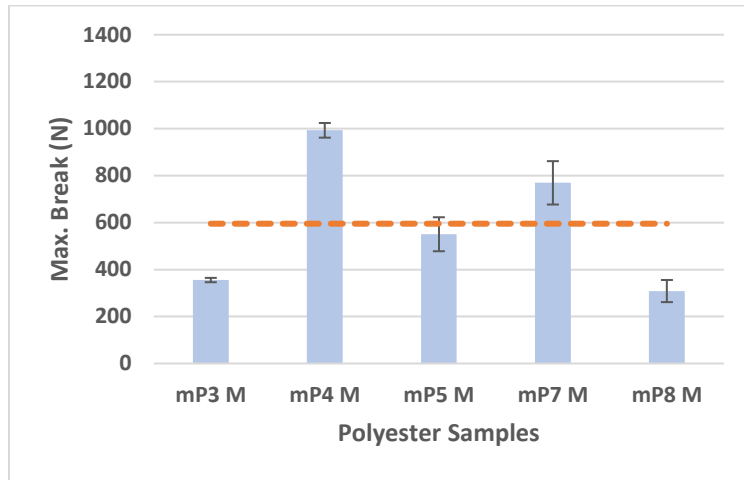


Figure 23 Polyester Samples Break Force in Machine Direction

Figure 23 shows the maximum break force of five polyester samples from Goodwill of Duluth-MN in the machine direction. The average break force for these samples in machine direction is 595.31 N and standard deviation is 287.33 N. The standard deviation value shows that there is significant variance in the break force values of these samples in machine direction. An outlier is observed for mP4 M sample at 992.92 N. Without the outlier, average break force and standard deviation is 495.90 N and 210.25 N respectively showing less variance in data.

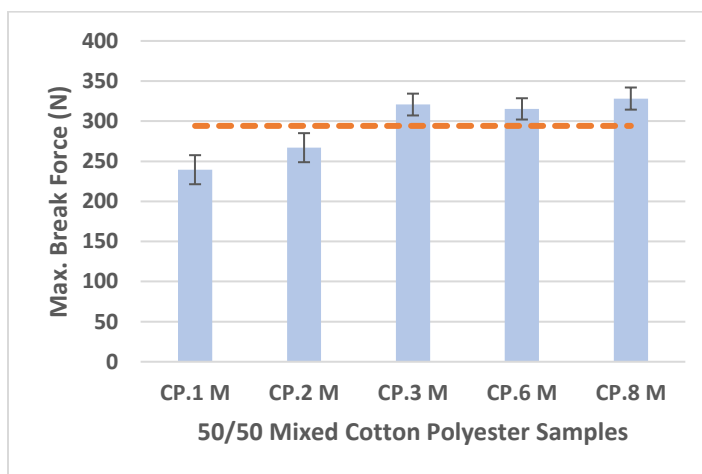


Figure 24 50/50 Cotton-Polyester Break Force in Machine Direction

Figure 24 shows the maximum break force of five 50/50 cotton-polyester samples from Goodwill of Duluth-MN in machine direction. The average break force for these samples in machine direction is 294.10 N and standard deviation is 38.87 N. The standard deviation value shows that there is less variance in the break force values of these samples in machine direction.

4.3.3 Tensile Testing Cross Direction Results

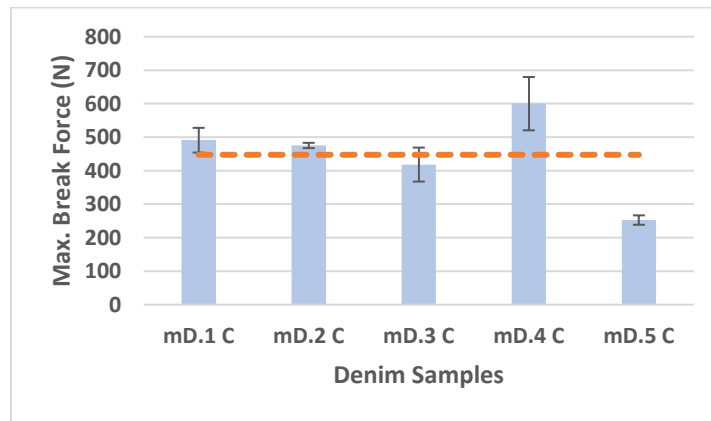


Figure 25 Denim Samples Break Force in Cross Direction

Figure 25 shows the maximum break force of five denim samples from Goodwill of Duluth-MN in the cross direction. The average break force for these samples in the cross direction is 447.47 N and the standard deviation is 127.30 N. The standard deviation value shows that there is considerable variance in the break force values of these samples in the cross direction. An outlier is observed for mD.4 C sample at 600.19 N. Without the outlier, average break force and standard deviation is 409.28N and 109.04N respectively showing less variance in data.

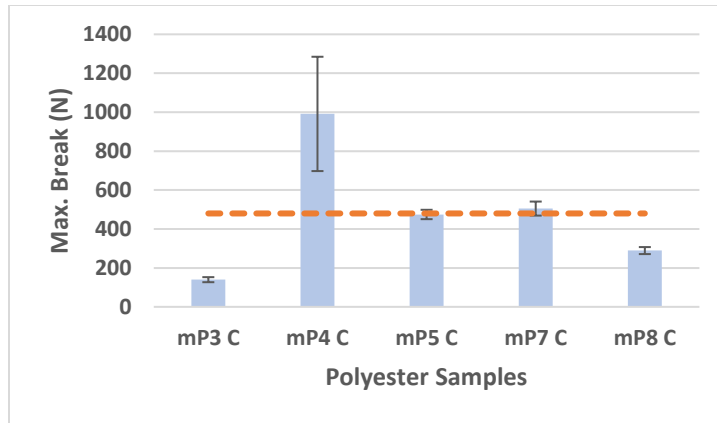


Figure 26 Polyester Samples Break Force in Cross Direction

Figure 26 shows the maximum break force of five polyester samples from Goodwill of Duluth-MN in the cross direction. The average break force for these samples in the cross direction is 479.86 N and standard deviation is 321.78 N. The standard deviation value shows that there is some variance in the break force values of these samples in the cross direction as well. An outlier is observed for mP4 C sample at 991.10 N. Three samples are above average break force value. Without the outlier, average break force and standard deviation is 352.05N and 170.75N respectively showing considerably less variance in data.

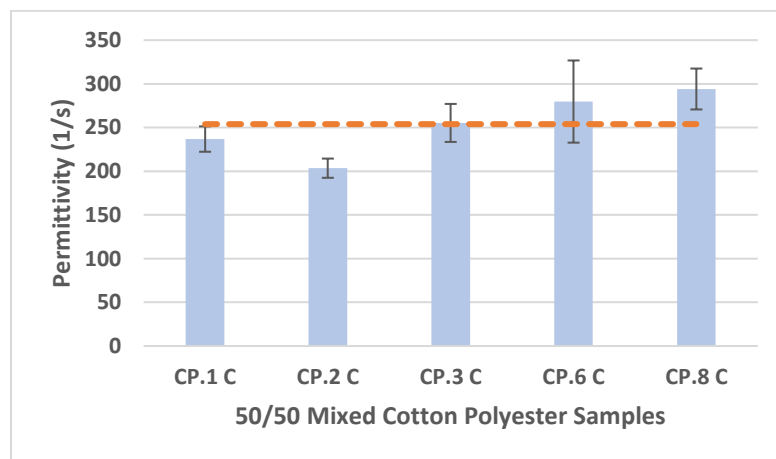


Figure 27 Cotton-Polyester Break Force in Cross Direction

Figure 27 shows the maximum break force for five 50/50 cotton-polyester samples from Goodwill of Duluth-MN in the cross direction. The average break force for these samples in cross direction is 253.87 N and standard deviation is 35.77 N. The standard deviation value shows that there is less variance in the break force values of these samples in the cross direction. No outlier is observed for these samples in the cross direction.

4.4 Discussion

The average permittivity and average break force in the machine and cross directions for cotton, polyester and 50/50 cotton-polyester were compared with the lowest standard values available from several state Department of Transportations (DOTs) across the U.S. and AASHTO to better assess the reuse potential of used woven textiles. Comparison of average permittivity values of used woven textiles with standard values is shown in Figure 28.

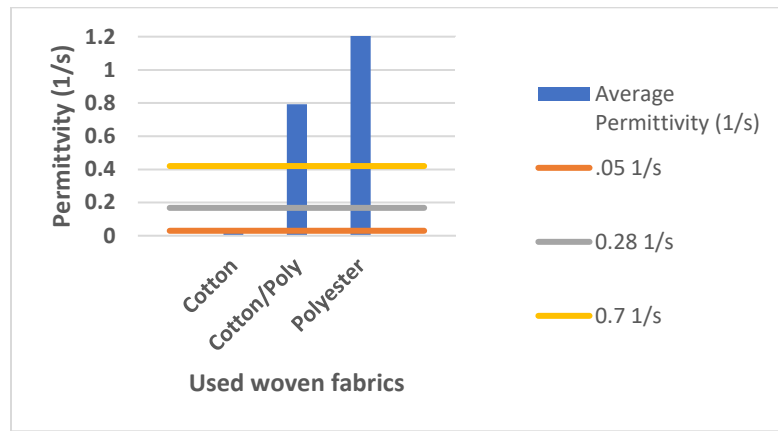


Figure 28 Comparison of Average Permittivity Values with Standard Values

Figure 28 shows the comparison of average permittivity values of cotton, cotton/polyester and polyester with lowest standard permittivity values of AASHTO and DOTs. As the average permittivity values of cotton/polyester and polyester are above the AASHTO and DOTs values of 0.05 1/s, 0.281/s and 0.7 1/s, these fabrics have the reuse potential as woven geotextiles for in stabilization, separation, filtration/drainage, reinforcement, temporary cover and erosion control applications. All other standard values from DOTs

were above the average values of used woven textiles, thus those applications are an inappropriate use for used woven textiles.

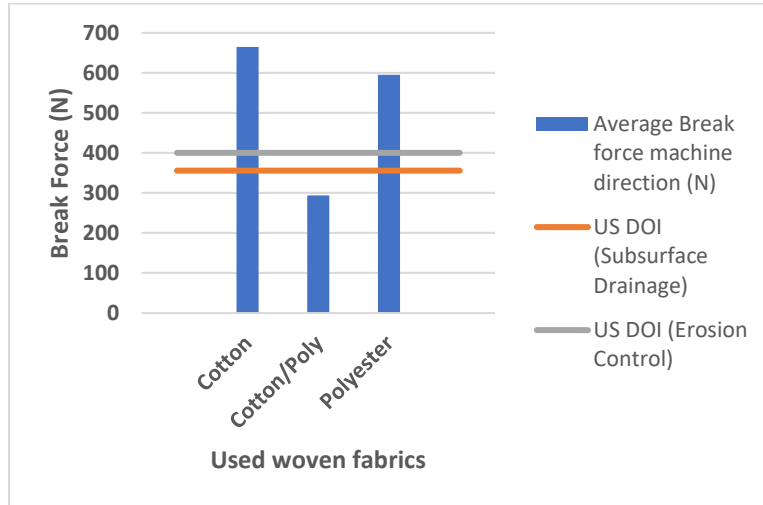


Figure 29 Comparison of Average Break Force (Machine Direction) with Standard Values

Figure 29 shows the comparison of the average break force values of cotton, cotton/polyester and polyester in the machine direction with the lowest standard break force values of US DOI. As the average values of cotton and polyester for breaking force in the machine direction are above the US DOI standards, this implies that clothing made from these materials have the potential for reuse as woven geotextiles for drainage and erosion control.

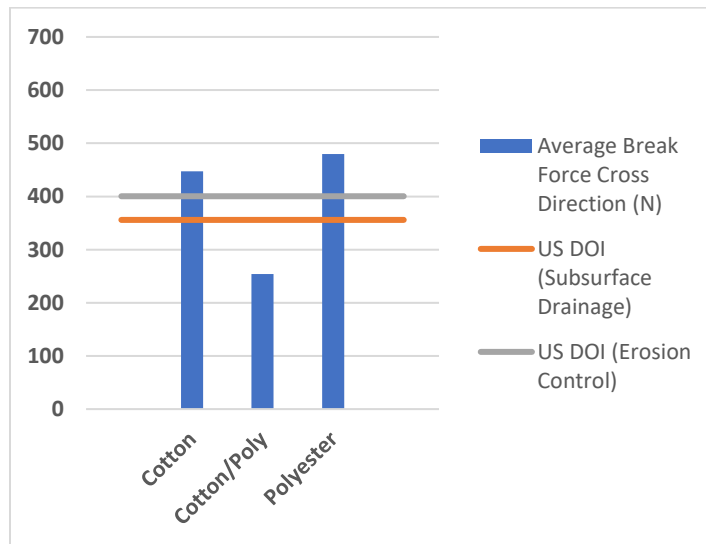


Figure 30 Comparison of Average Break Force (Cross Direction) with Standard Values

Figure 30 shows the comparison of the average break force values of cotton, polyester and cotton/polyester in the cross direction with the lowest standard break force values from the US DOI. As the average values of cotton and polyester are above the US DOI values, these used clothing material types have the potential for reuse as geotextiles for drainage and erosion control.

Polyester is seen to be consistent in all Figures 28, 29 and 30, with average permittivity and breaking force values above lowest standard values available for DOTs standard values. Cotton has the breaking force values above the lowest standard values from DOTs in both the machine and cross directions and cotton-polyester blends have the average permittivity values above the lowest DOTs permittivity standard values.

The materials tested cannot be used directly in their current state as geotextiles. The available width and length of individual secondhand garments is much too small to meet the needs for geotextile application that have to fit under roads and alongside hill slopes continuously. Estimating the square area availability of used textiles is necessary to suggest that there is enough used woven textile available to be reused as geotextiles. The estimates for square area are discussed in chapter 5. These used textiles cannot be used in their current form so solving the problem for joining these smaller pieces of used textiles available and testing the material properties of these joined secondhand textiles would test the feasibility of reuse of these discarded textiles as geotextiles in a more realistic manner.

4.5 Conclusions

In order to determine the material composition and properties of woven textiles, bales from Goodwill of Delaware and Goodwill of Duluth-MN were sorted out. Since cotton polyester and blends had the largest percentages in donated bales of used clothing, denim samples from both locations, and woven polyester and 50/50 cotton-polyester textile samples from Goodwill of Duluth-MN were selected for material testing. As used cotton and polyester had single material composition, 50/50 cotton-polyester blends were chosen because they have the properties of both 100% cotton and 100% polyester. Permittivity and tensile material properties of these textiles were determined, and these

permittivity values were compared with the standard values from AASHTO and DOTs and the tensile values were compared with USDOJ, AASHTO and DOTs standard values. The permittivity comparison showed that used polyester and 50/50 cotton-polyester have the potential of reuse as these garments have the reuse potential as woven geotextiles for in stabilization, separation, filtration/drainage, reinforcement, temporary cover and erosion control applications. The tensile comparison showed that used cotton and polyester can be used for drainage and erosion control applications. Further research of the material properties of shredding and joining the used cotton and polyester pieces from used clothing is needed. Also, research is needed on annual availability of used clothing and how it compares with the market for geotextiles.

5 Reuse Applications of Used Clothing as Geotextiles (Paper in Preparation for IDETC-CIE 2020 Conference)

5.1 Introduction

In order to assess the reuse potential of used textiles, it is imperative to determine the material composition of discarded textiles by sorting them and calculating their annual weight and square area. It is also crucial to determine the material properties of used textiles for determining their reuse potential. Determining the material properties of used textiles allows the comparison of these properties with the industry specifications of geotextiles. This chapter provides an overview of extrapolating the textile data available from a Goodwill-DE thrift store, to determine the nationwide used textiles availability in square area and relate it to the monetary value. The chapter also assess the market of used textiles available as opposed to what is projected for 2020 woven geotextiles market.

5.2 Materials and Methods

5.2.1 Bale Sorting Methodology

For the purpose of determining the material properties, collaboration with Goodwill of Delaware in 2016 and Goodwill of Duluth-Minnesota in 2017 was pursued. Both thrift stores donated a bale of used clothing, which were sorted manually to determine the material composition as discussed in section 3.2.2.

5.2.2 Permittivity Testing

After the selection of 14 denim used textiles from both locations and nine polyester and nine mixed cotton-polyester used textiles from Duluth-MN bale, these were tested according to ASTM D4491 as explained in section 4.2.5 and the permittivity values measured were shown in section 4.3.1. These values are also compared with their average values as well.

5.2.3 Tensile Testing

The selected used woven textiles were subjected to tensile testing according to ASTM D5034 as explained in section 4.2.6. The tensile test values were measured in the

machine and cross directions and plotted against their average values as shown in section 4.3.2 for machine and 4.3.3 for cross directions respectively.

5.2.4 Relating Monetary Values for Geotextile Sales to Square Area

The consumption of woven geotextiles is projected to grow slightly rapidly at a growth rate of 2.6% between 2015 and 2020 than that of nonwoven geotextiles at 2.1%.

Therefore, in order to assess the reuse potential of used woven textiles as geotextiles, it is necessary to estimate: 1) the square area availability of discarded woven textiles; 2) and also relate it to the monetary value of the discarded textile [28]. In 2020, annual sales of woven geotextiles in million square yardage are expected to be 653.01 square kilometers at a monetary value of \$704 million USD [28]. Due to the projected increase in the consumption of woven geotextiles, the availability of annual square area of discarded woven textiles was assessed to consider the feasibility of the reuse potential of discarded textiles as geotextiles. Market share of used textiles that is feasible for recycling is discussed in section 5.3.4.

5.3 Results

5.3.1 Annual Textile Bale Weights and Cost

As discussed in section 3.2.2, bales from Goodwill of Delaware and Goodwill of Duluth-MN were sorted manually to determine the material composition of discarded textiles by percentage weight. The annual bale data for this study came from Goodwill-DE and represented an average from 2012 to 2014. From Goodwill-DE, the annual weight in metric tons for discarded cotton was determined to be 1010 metric tons. An average weight per area value for used clothing by material types was used to calculate the annual weight of Goodwill-DE used cotton. Annual area for discarded cotton was estimated to be 2.2 square kilometers. The annual weight of used polyester from Goodwill-DE was reported to be 482 metric tons which make up 1.3 square kilometers in annual area. Based on the Goodwill of Delaware bale price data averaged from 2012-2014, the cost of bale was reported by thrift store at \$416/ton (\$459.69/ metric ton) [114]. This price data was collected by thrift store themselves and provided to researchers with the donation of the bale. Also, this bale price did not include the manual labor of sorting as no reliable

sorting costs were available in literature, therefore, these costs are not included in the bale price. Adding the manual sorting labor costs would drive up the price of used cotton and polyester textiles. An assumption that used cotton and polyester textiles bales of one metric ton each could replace new cotton and polyester inputs priced at \$416/ton (\$459.69/metric ton), was used. Utilizing this assumption of price per a ton of bale allowed the calculation of the total annual economic value of Goodwill-DE's used cotton and polyester textiles. The calculated annual economic values did not account for the sorting labor costs and processing costs including material and transportation costs for recycling these used textiles.

5.3.2 Annual Textile U.S. Weight Estimates

The number of recyclable material merchant wholesalers (NAICS code 423930) is 7088 [115]. With the assumption that each thrift store would have the same annual weight in metric tons as that of Goodwill-DE, a rough estimate of used annual cotton and polyester could be made for the whole U.S. This assumption is reasonable as Goodwill-DE is one of many Goodwill franchises and it is a medium sized industry. In this context, the annual weight of discarded cotton and polyester in U.S. is given respectively by Equations 4 and 5 in Appendix I. From equation 4, the annual weight of discarded cotton textiles in the U.S is calculated to be 7,158,880 metric tons. From equation 5, the annual weight of discarded polyester textiles in the U.S. is calculated to be 3,416,416 metric tons.

Equations 4 and 5 are also given below:

$$\text{Annual discarded cotton weight in U.S.} = (\text{Average discarded cotton weight/wholesale establishment}) \times \text{total number of wholesale establishments} \quad (4)$$

$$\text{Annual discarded polyester weight in U.S.} = (\text{Average discarded polyester weight/wholesale establishment}) \times \text{total number of wholesale establishments} \quad (5)$$

5.3.3 Material Properties of Used Textiles Compared to Geotextile Standards

The average permittivity and tensile strength values in the machine and cross directions were determined for different used cotton, polyester and mixed cotton-polyester textile samples as detailed in sections 4.3.1-4.3.3. These values were then compared with DOTs standards to assess their reuse as woven geotextiles for different applications as discussed in detail in section 4.4.

5.3.4 Percentage Market Share and Square Kilometers Feasible for Used Textiles

In 2020, annual sales of woven geotextiles by square area are expected to be 653 square kilometers at a monetary value of \$704 million USD [28]. Therefore, authors of this study have attempted to give a percentage market share of used cotton and polyester, in \$mil and square kilometers, that can replace newly manufactured woven geotextiles. Annual \$mil value and square kilometers value for used cotton and polyester for whole U.S. is given by Equations 6 and 7 respectively in Appendix J. From equation 6, annual \$mil value for used cotton and polyester is calculated to be 3290.9 \$mil and 1570.5 \$mil respectively. The \$mil value for used cotton and polyester suggests that an opportunity is being discarded in landfills. This monetary value is indicative of the unprocessed baled used cotton and polyester. Wholesale establishments would incur sorting labor costs and processing costs including material and transportation costs for recycling these used textiles. And the \$mil value for the recycled bale of annual cotton and polyester would be increased by all the processing costs. Annual square area of used cotton and polyester is calculated by equation 7 as shown in Appendix J. From equation 7 annual square kilometers of used cotton and polyester textiles is calculated to be 15594 km² and 9214 km² respectively.

Calculations of the annual \$mil/km² of used cotton and polyester textiles and using 2020 woven geotextiles data [29] is given by Equations 8 and 9 respectively in Appendix J. From Equation 8, the annual \$mil/km² of used cotton and polyester is estimated to be 0.21 \$mil/km² and 0.17 \$mil/km² respectively. From Equation 9, the annual \$mil/km² of using woven geotextiles data in 2020 [28] is calculated to be 1.08 \$mil/km². Since the annual \$mil/km² of used cotton and polyester textiles is less as compared to 2020 woven geotextiles annual \$mil/km², the reuse of used textiles as input materials replacing newly synthetic geotextiles is economically feasible. Given that manual sorting labor costs of used textiles are significantly less than the difference between the annual \$mil/km² of used textiles and annual \$mil/km² of used woven geotextiles, replacing woven geotextiles with these used textiles inputs would be economically feasible.

5.4 Discussion

5.4.1 Material Availability

Annually, approximately 24 times more used cotton textile is available than what is predicted for 2020 woven geotextiles market in annual square area and 14 times more used polyester is available than what is projected in 2020 for woven geotextiles in annual square area, given by Equation 10 in Appendix J. Therefore, if recycling efforts are ramped up it, enough used woven textile is available to replace the newly made woven geotextiles and can be used specifically for applications like filtration/drainage, stabilization and separation, reinforcement, subsurface drainage and erosion control, due to the material properties these used textile materials possess. These used textile materials were tested for tensile strength and permittivity. Tensile strength correlates to all geotextile functions and permittivity primarily applies to filtration and drainage functions, but since geotextiles are permeable fabrics, determining permittivity is essential for assessing performance of geotextiles.

5.4.2 Market for Geotextiles

Increasing the recycling efforts of used textiles nationwide and solving the problem of joining used woven textiles together would make it feasible to use used textiles as geotextiles for different industries in the applications of filtration/drainage and erosion control. Used cotton and/or used polyester textiles can be used in drainage/filtration and erosion control applications in construction, transportation, coastal protection and environmental industries. The geotextile end market would open a lot of venues for different used textiles markets.

5.4.3 Conclusions

After bale sorting of Goodwill-DE, the weight in metric tons and annual area in square kilometers of used cotton and polyester was determined. Material testing experiments were conducted to collect permittivity and tensile test data of used cotton, 50/50 cotton-polyester and polyester fabrics. The permittivity data was compared with standard values of AASHTO and several DOTs and tensile data was compared with US DOI, AASHTO and DOTs. It was found that used polyester and 50/50 cotton-polyester have potential

reuse in filtration/drainage, stabilization and separation, reinforcement, subsurface drainage and erosion control applications based on the permittivity data comparison with industry specified values. With the comparison of tensile data with industry specified values it was found that used cotton and polyester has the potential for subsurface drainage and erosion control applications. Based on the bale data and market projection of woven geotextiles, a nationwide annual \$mil/km² was estimated for used cotton and polyester and compared with 2020 woven geotextiles annual \$mil/km². Annual \$mil/km² of used cotton and polyester was estimated to be 0.21 \$mil/km² and 0.17 \$mil/km² respectively, less than 1.08 \$mil/km² of woven geotextiles in 2020. It was concluded that replacing woven geotextiles with used textiles inputs is economically feasible, given that the manual sorting labor cost of used textiles is less than the difference of annual \$mil/km² of used textiles and woven geotextiles. Based on annual square area comparison of used textiles with woven geotextiles, it was determined that more than enough of used textiles are available to meet the needs of market and used textiles are feasible for their reuse as woven geotextiles for various applications. The \$mil value calculated for used textiles shows that an economic opportunity is being discarded annually in landfills. This monetary value is solely of unprocessed used textiles and is based on the bale price averaged from Goodwill of Delaware bale sales data from 2012-2014 [114]. Once the used textile is processed for recycling its cost will increase due to sorting labor, transportation and other miscellaneous costs. Significant work is still needed to ensure feasibility of reusing the used textiles for various geotextile applications.

6 Conclusions and Future Work

6.1 Impact of Research

Used textiles were donated by Goodwill of Delaware and Goodwill of Duluth and a hybrid EIO-LCA hybrid model was developed using total volume of discarded used clothing by the bale from 2012-2014 available from Goodwill of Delaware. Cotton had the greatest percentage of material available by weight from both thrift store chains. A hybrid EIO-LCA model was developed to assess the combined environmental and economic impact of reusing cotton into seven American industrial sectors. Of these seven industrial sectors, the U.S. apparel industry was found to be the most promising sector for reuse of discarded cotton textiles. Furthermore, reusing woven textiles for woven geotextiles applications was also assessed by measuring the remaining material properties and the total square area available of woven used textiles by material type. In that regard textile samples from used woven denim (100% cotton), polyester and blends of 50% cotton and 50% polyester were tested for the material properties of permittivity and tensile strength. These material properties relate to all the functions of geotextiles, which is why these two material properties were tested for. The permittivity and tensile strength of the samples was compared with standards from state DOTs and the U.S. Department of the Interior. Polyester exceed the lowest standard values of permittivity and tensile strength for some filtration/drainage and erosion control applications while cotton exceeds the lowest standard values of tensile strength for some drainage and erosion control applications. Cotton denim and polyester were estimated to be 24 and 14 times, respectively, more likely to be available throughout the U.S. than the square area of woven geotextiles projected to be sold in 2020. Based on the more than sufficient annual square area availability of used cotton and polyester calculated from Goodwill of Delaware's 2012-2014 bale data, these used textile material types have the potential to be used as woven geotextiles for the identified filtration/drainage and erosion control applications.

This research added to the literature on the combined environmental and economic impact of recycling used textiles by showing with a hybrid EIO-LCA model that the apparel industry has the best potential for reuse of used textiles in the U.S. This research

also contributed new knowledge on the recycling of post-consumer used woven textiles by assessing their permittivity and tensile strength material properties and assessing their reuse potential as geotextiles. Overall, this research contributed to previous work in the following ways:

1. Bales from Goodwill of Delaware (Sorting done by Isabella Aswad and Eric Johnson) and Goodwill of Duluth (Sorting done by Ben Zbornik) were sorted for determining material type composition for post-consumer used textiles and Goodwill of Delaware bale data from 2012-2014 was analyzed for estimating annual availability of used cotton and polyester. Cotton was found to have the highest percentage by weight from both locations' bales.
2. A hybrid EIO-LCA model was developed using the bale data available from Goodwill of Delaware to assess the environmental and economic impact of replacing virgin materials with recycled textile inputs for American industries. The apparel industry was found to be the most promising market for reusing the discarded cotton.
3. Material properties testing was conducted to determine permittivity and tensile strength of used woven textiles as these two properties correlate to all major functions of geotextiles. The data determined from these experiments was compared with industry specified values to assess the feasibility of reuse potential of used cotton, polyester and 50/50 cotton-polyester. Based on permittivity data comparison, polyester and 50-50 cotton-polyester had the potential for reuse as for filtration/drainage, stabilization and separation, reinforcement, subsurface drainage and erosion control applications. Cotton and polyester based on the comparison of breaking load in machine and cross direction had the potential for subsurface drainage and erosion control applications.
4. The annual \$mil/km² nationwide values of used woven cotton and polyester were estimated using Goodwill-DE bale data calculated by Eric Johnson, Isabella Aswad and Dr. Abigail Clarke-Sather and these values were compared with the annual \$mil/km² value of woven geotextiles projected in 2020 market. It was established that annual \$mil/km² of used textiles is less than annual \$mil/km² of woven geotextiles 2020 market which makes the replacement of woven

geotextiles with these used textiles inputs economically feasible. Also, the comparison of annual square areas of used textiles with 2020 woven geotextiles showed that these post-consumer used textile types are available in far excess of the projected market demand in 2020 for woven geotextiles. The \$mil value of discarded used textile shows that economic opportunity is being discarded into landfills.

6.2 Future Work

Further research involving collecting used textiles from a greater variety of thrift store locations across America and sorting them for material composition would give a more realistic idea of which used textile material is most available nationwide. A hybrid EIO-LCA model developed from nationwide used textile availability data by material type would give a more accurate estimate of the environmental and economic impacts of recycling textile material into different American industrial sectors and into different product streams. The toxicity impacts and the environmental effects of degrading used textiles, associated with the direct applications of used textiles either above or below ground are not known and need further research before pursuing the direct reuse of used textiles for various applications. Also, addressing the issue of joining used woven textiles and material testing these textile joins for permittivity and tensile strength would also provide a more accurate feasibility of using these textiles for woven geotextile applications directly.

7 References

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Appendix A

Denim Samples Force-Displacement Plot Examples in Machine Direction (Raw data can be provided upon request)

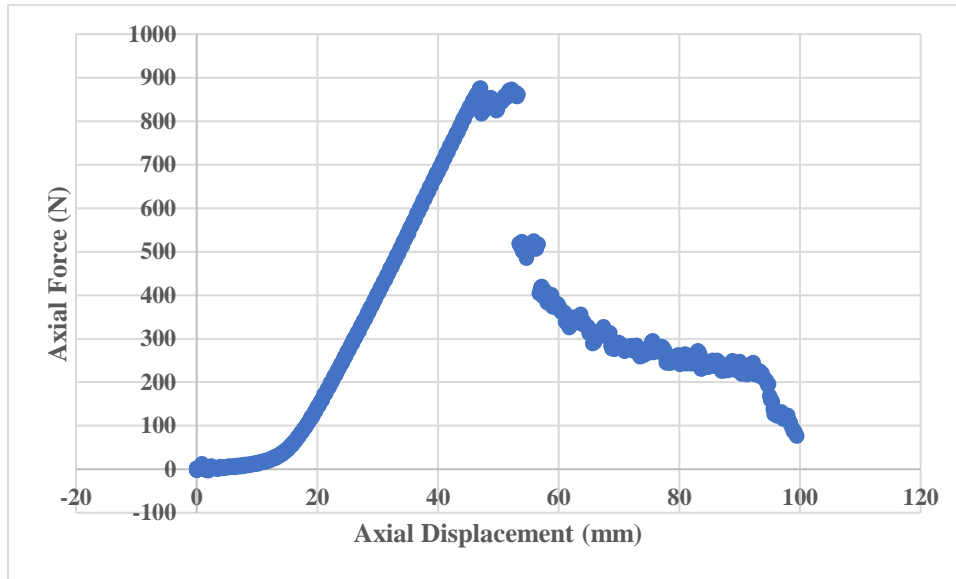


Figure 31 mD.1 M1 Force-Displacement Plot in Machine Direction

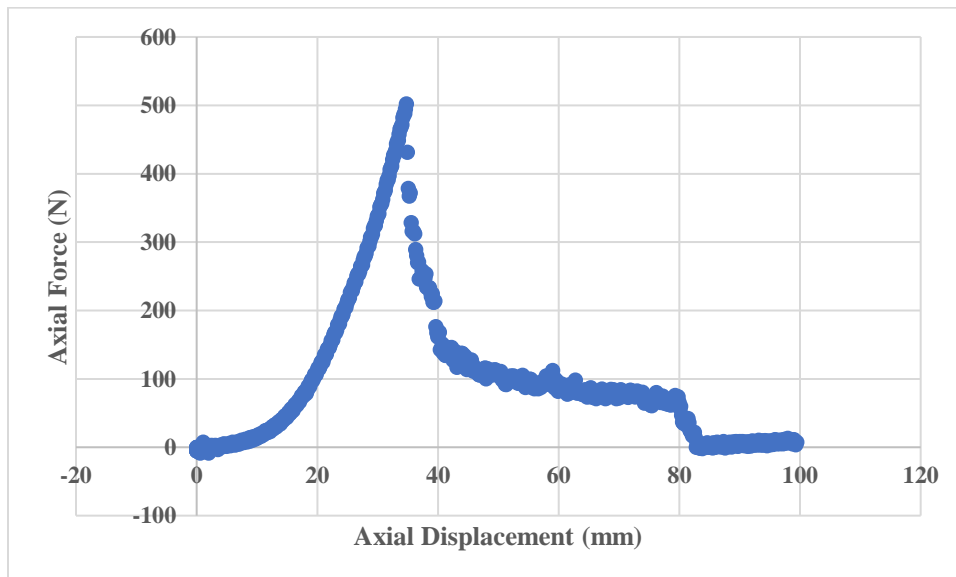


Figure 32 mD.5 M1 Force-Displacement Plot in Machine Direction

Appendix B

Denim Samples Force-Displacement Plot Examples in Cross Direction (Raw data can be provided upon request)

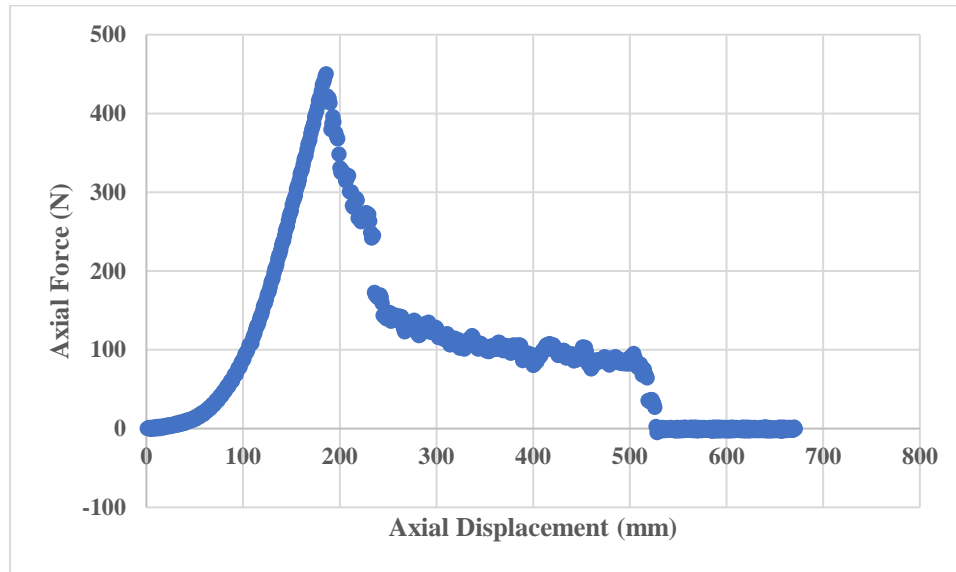


Figure 33 mD.1 C1 Force-Displacement Plot in Cross Direction

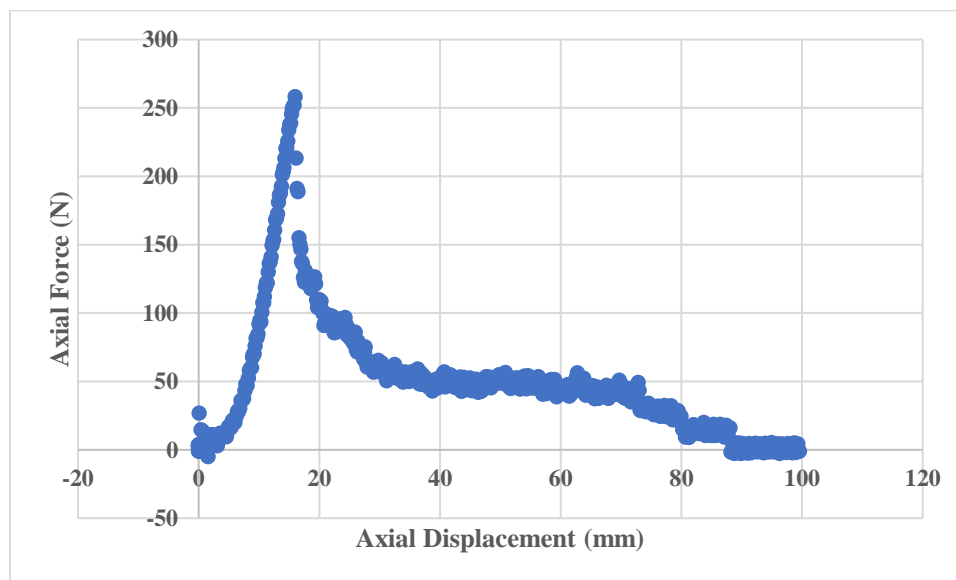


Figure 34 mD.5 C1 Force-Displacement Plot in Cross Direction

Appendix C

Polyester Samples Force-Displacement Plot Examples in Machine Direction (Raw data can be provided upon request)

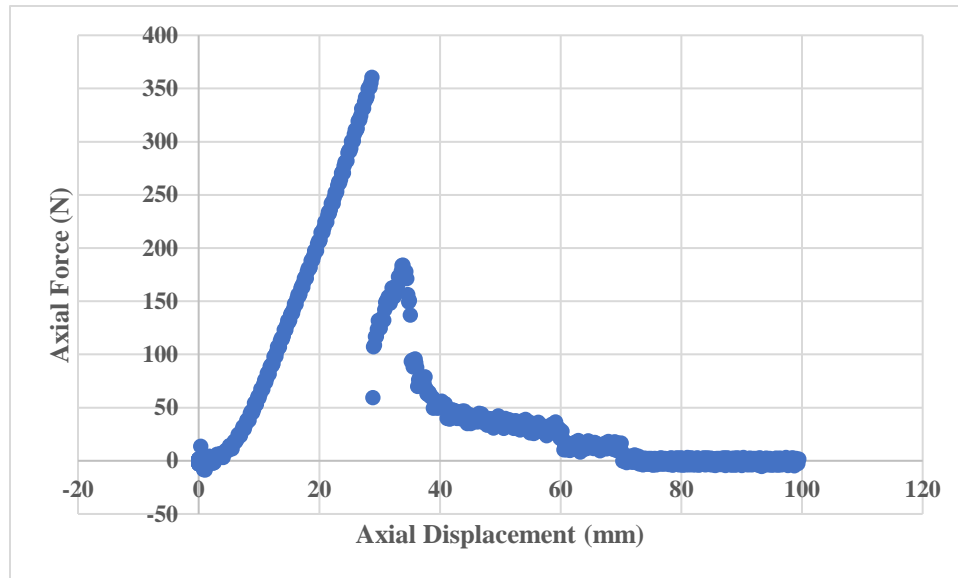


Figure 35 mP.3 M1 Force-Displacement Plot in Machine Direction

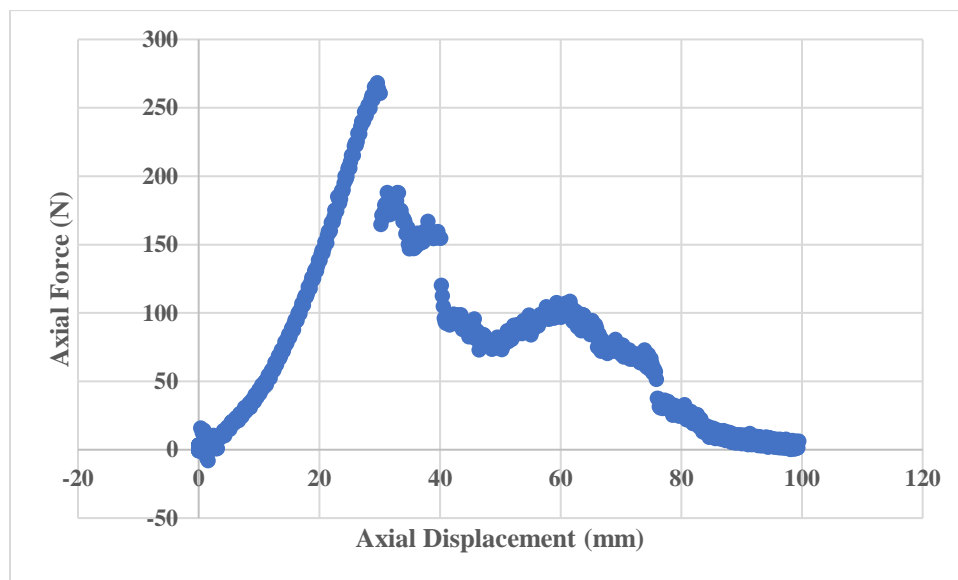


Figure 36 mP.8 M1 Force-Displacement Plot in Machine Direction

Appendix D

Polyester Samples Force-Displacement Plot Examples in Cross Direction (Raw data can be provided upon request)

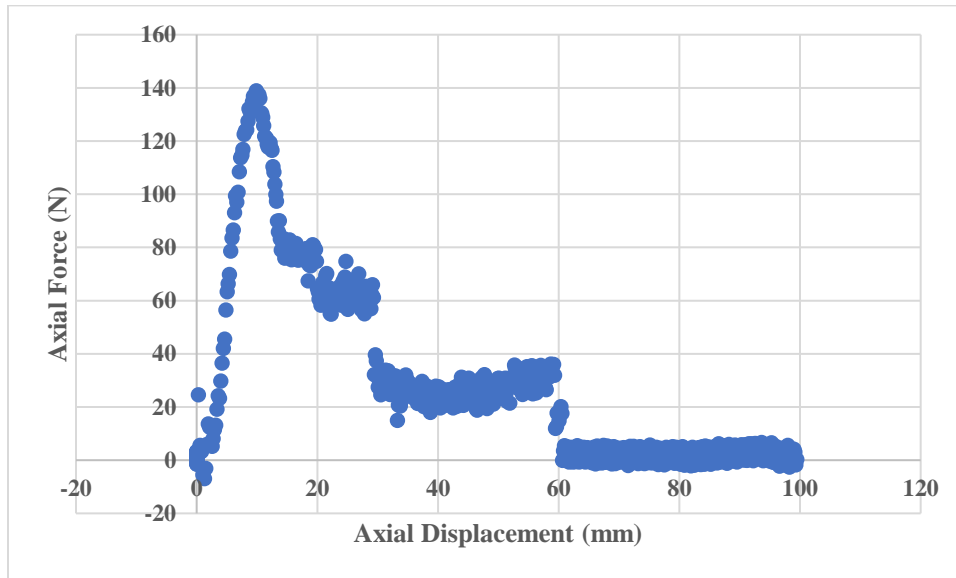


Figure 37 mP.3 C1 Force-Displacement plot in Cross Direction

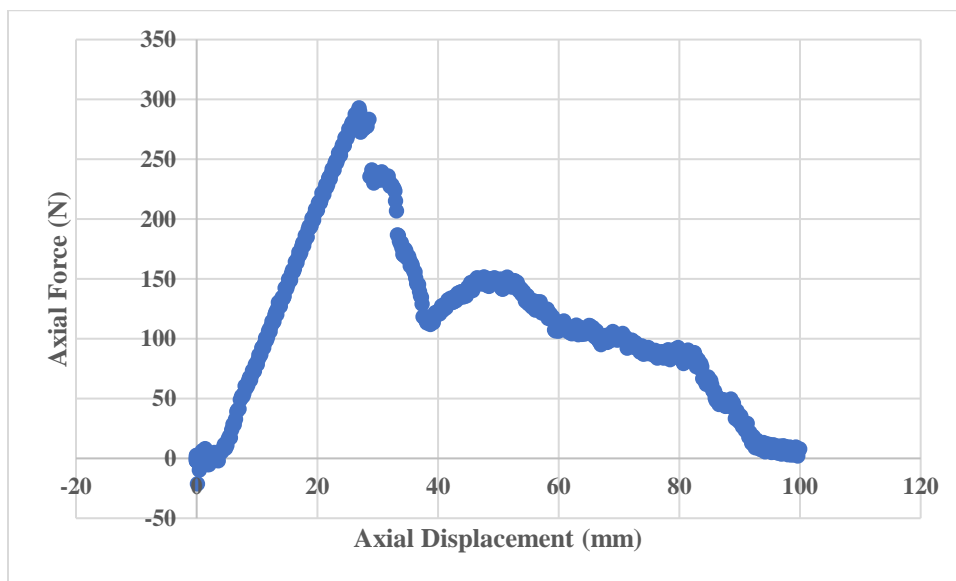


Figure 38 mP.8 C1 Force-Displacement Plot in Cross Direction

Appendix E

Mixed Cotton-Polyester Samples Force-Displacement Plot Examples in Machine Direction (Raw data can be provided upon request)

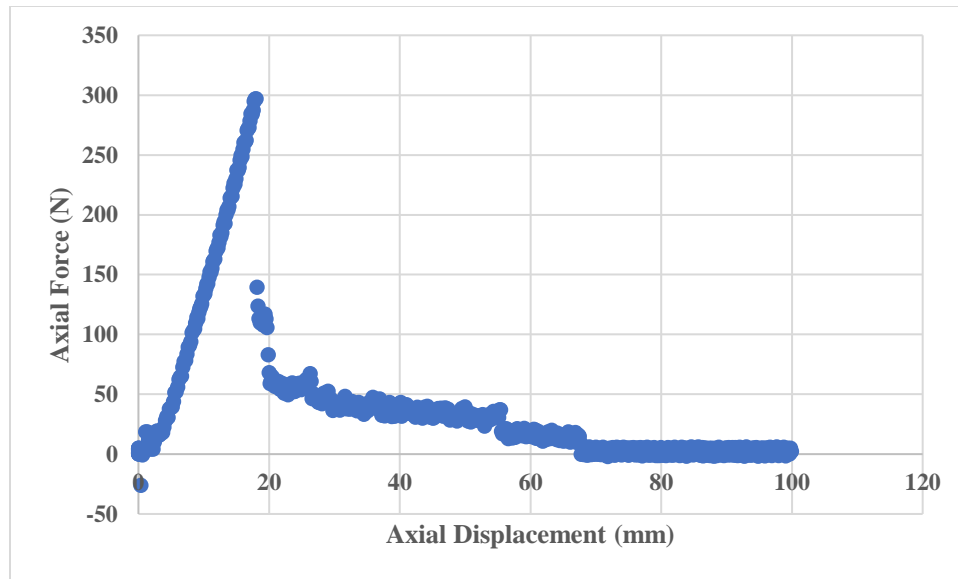


Figure 39 CP.6 M1 Force-Displacement Plot in Machine Direction

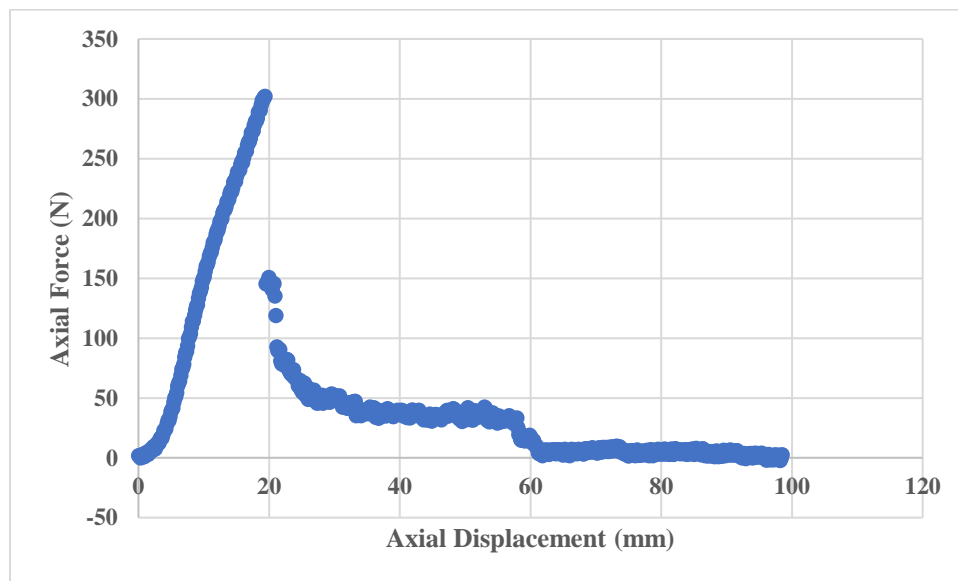


Figure 40 CP.8 M1 Force-Displacement Plot in Machine Direction

Appendix F

Mixed Cotton-Polyester Samples Force-Displacement Plot Examples in Cross Direction (Raw data can be provided upon request)

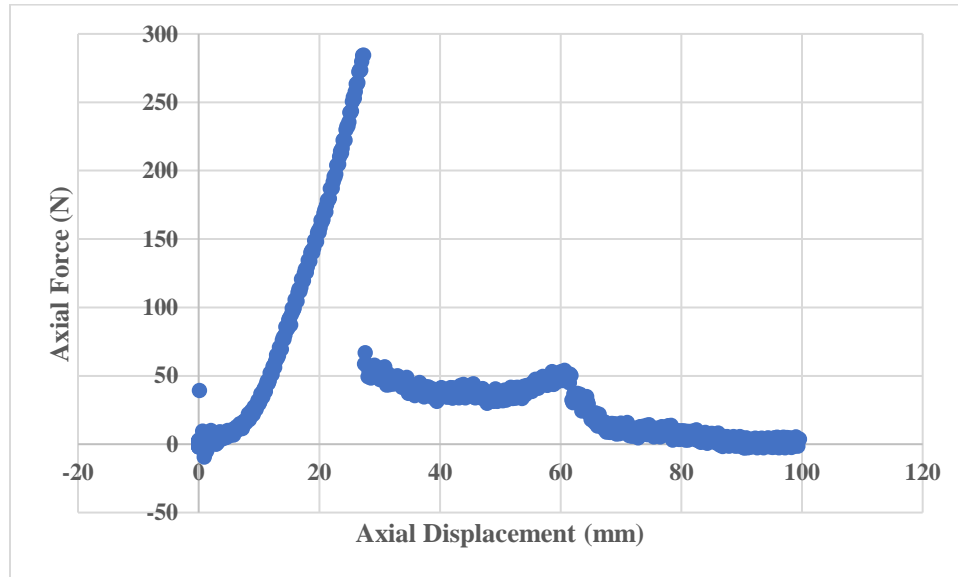


Figure 41 CP.6 C1 Force-Displacement Plot in Cross Direction

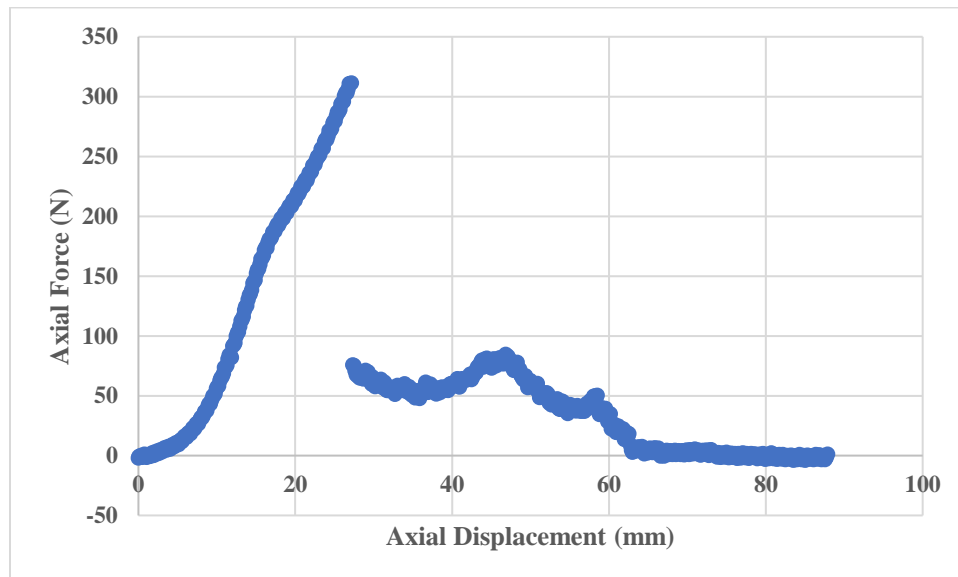


Figure 42 CP.8 C1 Force-Displacement Plot in Cross Direction

Appendix G

Raw Tensile Test Data Google Drive Links of Used Cotton, Polyester and 50/50 Cotton Polyester (Raw data can also be provided upon request)

The google drive link for excel file for used cotton tensile data in machine direction is pasted below:

<https://drive.google.com/file/d/12EWtrFShRrVPCG7z19xZr71XE1tuQOmi/view?usp=sharing>

The google drive link for excel file for used cotton tensile data in cross direction is pasted below:

<https://drive.google.com/file/d/1DC7349vV-qAA6UVjQe5JQKjqQWcezw3f/view?usp=sharing>

The google drive link for excel file for used polyester tensile data in machine direction is pasted below:

<https://drive.google.com/file/d/1LQ1MHOGb8RFu90AHNXo731vMUzCQpp0l/view?usp=sharing>

The google drive link for excel file for used polyester tensile data in cross direction is pasted below:

<https://drive.google.com/file/d/1kbT0DJqL7ktsrPrt1zTRR4d5m0VCw1wI/view?usp=sharing>

The google drive link for excel file for 50-50 used cotton-polyester tensile data in machine direction is pasted below:

https://drive.google.com/file/d/1Ai7XunGKEwR3NbP9rElpD_5Oiy8K2OFv/view?usp=sharing

The google drive link for excel file for 50-50 used cotton-polyester tensile data in cross direction is pasted below:

<https://drive.google.com/file/d/1ITGn0amHh1FqvV8IYov5z0MgCaJ0xQla/view?usp=sharing>

Appendix H

Raw Permittivity Data Google Drive Links of Used Cotton, Polyester and 50/50 Cotton Polyester (Raw data can also be provided upon request)

The google drive link for excel file for used cotton permittivity data is pasted below:

For Duluth, Minnesota used cotton:

https://docs.google.com/spreadsheets/d/1ZKyRTFn1h9ENridd0ZFit4Yf3liFC0sT_15f8ca_LsQ/edit?usp=sharing

For Delaware used cotton:

https://docs.google.com/spreadsheets/d/1ea4pSKxQaYPzk7d8FJLQcBtxh9_BIx--laXWszKsS-s/edit?usp=sharing

The google drive link for excel file for used polyester permittivity data is pasted below:

https://docs.google.com/spreadsheets/d/1IXmJ2o6fo05m37BnQeZCtP_-9C4-MNBS4XB-Rcl3dW4/edit?usp=sharing

The google drive link for excel file for used 50/50 cotton-polyester is pasted below:

https://docs.google.com/spreadsheets/d/1qVnWaTCJHC1LkLVXEt4Na8WW3L2Xa_nwdm0CmqdHE/edit?usp=sharing

Appendix I

Formulas for Annual Textile U.S. Weight of Used Textiles

The number of recyclable material merchant wholesalers (NAICS code 423930) is 7088 [115].

Annual discarded cotton weight in U.S. = (Average discarded cotton weight/wholesale establishment) x total number of wholesale establishments)
(4)

Annual discarded cotton weight in U.S. = 1010 metric tons x 7088

Annual discarded polyester weight in U.S. = (Average discarded polyester weight/wholesale establishment) x total number of wholesale establishments)
(5)

Annual discarded polyester weight in U.S. = 482 metric tons x 7088

Appendix J

Formulae for Annual \$mil/km² of Used Textiles and Woven Geotextiles (2020 Market) and Annual Square Area of Used Textiles Compared with 2020 Woven Geotextiles Market

The number of recyclable material merchant wholesalers (NAICS code 423930) is 7088 [115].

Annual \$mil value for used textile material (\$mil) = (price of used material/metric ton) x (total number of wholesale establishments) x (\$mil/10⁶ USD) (6)

Annual \$mil value for used cotton = \$459.69/metric ton x 7,158,880 metric tons x \$mil/10⁶ USD

Annual \$mil value for used polyester = \$459.69/metric ton x 3,416,416 metric tons x \$mil/10⁶

Annual square area of used textile material = (used material square area/wholesale establishment) x total number of wholesale establishments (7)

Annual square area of used cotton = 2.2 km² x 7088

Annual square area of used polyester = 1.3 km² x 7088

Annual cost of used textiles/ Annual square area of used textiles = Annual cost of used textiles (\$mil) / Annual square area of used textiles (km²) (8)

Annual cost of used cotton/ Annual square area of used cotton = (3290.9 \$mil/15594 km²) = 0.21 \$mil/km²

Annual cost of used polyester/ Annual square area of used polyester = (1570.5 \$mil/9214 km²) = 0.17 \$mil/km²

Annual cost of woven geotextiles in 2020 (\$mil) / Annual square area of woven geotextiles in 2020 (km²) = 704 \$mil/653.01 km² = 1.08 \$mil/km² (9)

Market share of used textile in square area compared to 2020 woven geotextiles data = ((annual square area value of used textile)/2020 square area value) (10)

Market share of used cotton in km² compared to 2020 data = 15594/653.01 = 23.8 = ~ 24

Market share of used polyester in km² compared to 2020 data = $9214/653.01 = 14.11 = \sim 14$