A Multi-Attribute Utility Theory Analysis of Alternative Erosion Control Materials to Class 2 Riprap in Alabama

By

Christopher Joseph Gerber

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Approved by

Dr. Jorge Rueda-Benavides, Chair, Assistant Professor of Civil Engineering
Dr. Michael Perez, Assistant Professor of Civil Engineering
Dr. Wesley Donald, Research Fellow of Civil Engineering

ABSTRACT

Riprap is an extremely common material for construction projects and often assumed to be the most cost-effective option for channel armoring. However, a study done by Auburn University found that in the state of Alabama riprap's unit cost can fluctuate drastically based on the location of a given project. In the northern regions of the state riprap's unit cost can be as low as 73% of the state average, whereas in the south near Mobile the rate can be increased as much as 160% that of the state average. This research study aimed to facilitate a more cost-effective and efficient decision process for material selection for channel armoring by focusing on materials available in Alabama. Historic bid data and unit price trends of riprap were compared to those of alternatives such as tied concrete block mats, turf reinforcement mats, and cellular confinement systems to compare the construction costs of all materials. These were coupled with geographic price variations, such as shipping costs, the life expectancy, projected maintenance, and flow resistance for each product. It was found that for initial construction turf reinforcement mats were universally more cost-effective than riprap with tied concrete block mats and cellular confinement systems being comparable in price in southern regions. Furthermore, a multi-attribute utility theory (MAUT) analysis was conducted for six different aspects of the material analyzed. This analysis method was then used to create a spreadsheet-based design tool called Channel Armoring Material Selector, which could be used for future project planning. The results of this study could prompt the Alabama Department of Transportation to revisit their approved channel erosion prevention techniques to allow for more cost-effective practices. This could lead to increased competition in the bidding of projects for ALDOT and an overall cost savings to taxpayers if implemented.

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"It is impossible to clap with only one hand."

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To my friends, new and old. What makes the trying days of work and study the most bearable are the shining moments of kindness and love from those who know you best. Thanks for the healthy distractions and laughs had.

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LIST OF ABBREVIATIONS

ADEM	Alabama Department of Environmental Management
ALDOT	Alabama Department of Transportation
C/E	Cost-Effectiveness
CAMS	Channel Armoring Material Selector
CBA	Cost-Benefit Analysis
CCS	Cellular Confinement System
CGP	Construction General Permit
DOT	Department of Transportation
E&SC	Erosion and Sediment Control
FHWA	Federal Highway Administration
MAUT	Multi-Attribute Utility Theory
NPDES	National Pollutant Discharge Elimination System
NPV	Net Present Value
RECP	Rolled Erosion Control Practice
SWPPP	Stormwater Pollution Prevention Plan
TCBM	Tied Concrete Block Mat
TRM	Turf Reinforcement Mat

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Erosion and sediment control is the practice of preventing the erosion of soils and the transportation of said soils away from their origin and into waterways. This is a common consideration for design criteria for any construction project. In fact, these practices are required for any such work to prevent the pollution of America's waterways (Clean Water Act). However, even with these requirements, it is estimated that as much as 3.9 billion tons of sediment are discharged from US worksites every year (Schussler, Mitchell). In 2019, the state of Alabama was on record as having experienced the third highest rainfall amount in a 24-hour period of 32.5" in the United States (State Climate Extremes, 2022). Alabama's combination of high frequency and intensity of storm events means that the potential for rainfall caused erosion is incredibly high. It is therefore important for the state to implement effective erosion control practices.

1.2 EROSION CONTROL IN ALABAMA

Erosion control is the practice of preventing the breaking up of soil and sediment particles in an area. The main objective is to stop or minimize the erosion of soils so that sediment controls, which are meant to prevent eroded soils from leaving an area, will have a much lighter load imposed on them. Currently, the state of Alabama has many different practices for erosion and sediment control. The Alabama Department of Transportation (ALDOT) has 2 approved material lists for just erosion control practices (II-11, II-24) with over 140 items combined. These range from concrete-lined mats, to ditch checks used to slow water flow, to simple vegetation practices to stabilize an area with grasses. Notably however, one material is missing in this list, riprap. Riprap is defined by section 814 of the ALDOT Specifications for Highway Construction as being, "field stone or rough unhewn quarry stone as nearly rectangular as is practicable." Large stones have been used for the stabilization of slopes and channels for centuries such as the ancient, 426km long aqueduct of Constantinople, which used stone-lined channels throughout its network (Johannes Gutenberg Universitaet). Today, while it may be missing from ALDOT's erosion and sediment control materials list, riprap continues to armor channels and slopes and has two primary applications in civil construction. First, it can be used to structurally stabilize steep slopes and embankments, and second, it protects these areas from the erosive forces caused by water.

1.3 MOTIVATION

Today, riprap has become an industry standard and is used throughout Alabama and the greater United States. The main motivating factors behind this wide acceptance of riprap are twofold. One, riprap is very effective at stabilizing an area structurally, and it is incredibly resilient to weathering and deterioration over time. Two, riprap is incredibly common throughout the world and is, therefore, very easy for universal adoption. However, riprap's availability is not uniform geographically throughout the state of Alabama. A 2020 study conducted by Auburn University analyzed ALDOT project bids from 2006 to 2016 that used class 2 riprap. The results showed that due to the geographic concentration of riprap quarries in the northern part of the state, the unit price of riprap could vary from the state average at 73% in the north and 160% at the Gulf (Arevalo, 2020). However, it is not just riprap sources that are geographically linked. Precipitation rates are statistically higher in the Gulf Region of Alabama, with a recorded average rainfall of 67.6 in, as compared to 56.5in, 57.5in, and 56.0in for the southern, central, and northern regions respectively. This shows that while the Gulf Region of Alabama has the most rainfall, and subsequent potential for rainfall caused erosion, it also has to pay the most per ton of riprap to protect its shores and landmasses.

1.4 RESEARCH OBJECTIVES

The main objective of this investigation was to facilitate a more cost-effective and efficient decision process for material selection for channel armoring. This paper will show the process and results of an investigation conducted on the effectiveness of alternative erosion control techniques in comparison to riprap throughout the state of Alabama. This looked at identifying all possible approved alternatives that had comparable performance criteria to riprap. Once these materials were found, a price per unit of each commodity, including riprap, was created. These combined the principle of economies of scale (Stigler, 1958) and the geographic cost index previously developed by Arevalo, and were based on current market price values at the time of publication. Along with cost of each material, the investigation also looked at the installation process itself. This yielded a productivity rate along with an hourly cost of installation for each material. The overall shear strength of each material was also assessed to ensure it met ALDOT's 10 psf strength requirement. Each material's associated Manning's Roughness Coefficient was also included to reflect the flow conditions that each lining would experience. All of these criteria were combined into a Multi-Attribute Utility Theory analysis to assess the overall effectiveness of each material. This investigation then made general suggestions for each region of the Alabama Regional Riprap Cost Index and created an excel program that could be used by Alabama contractors when deciding on materials for their own projects in the future.

1.5 ORGANIZATION OF PAPER

This paper will provide an overview of the process followed in the investigation. First, a background into the practice of erosion control, the process of unit pricing, nonlinear regression analysis, as well as post-construction considerations for infrastructure will be covered in ***Chapter 2: Background and Literature***

Review. Next, a description of the process that was used in the investigation will be given in *Chapter 3: Methodologies*. *Chapter 4: Analysis and Results* will show the main takeaways of the investigation, including trends and statistically significant correlations found in the data. Finally, *Chapter 5: Conclusions and Recommendations* gives insight into the results of chapter 4 and discusses the implications of these findings for the state of Alabama's construction industry. As well as future research suggestions related to this topic.

CHAPTER 2: BACKGROUND AND LITERATUTRE REVIEW

2.1 INTRODUCTION

This chapter seeks to summarize the literature reviewed for a comparative cost and performance analysis of different erosion control materials for use by the Alabama Department of Transportation (ALDOT). The first section covers the general practice of erosion control in construction as it pertains to permanent infrastructure. The second section deals with the assessment of riprap and its equivalent alternatives. Followed by a comprehensive look at how to evaluate the effectiveness of a piece of infrastructure is needed. The overall cost of installation, while important, is not the only factor for consideration. Other factors include routine maintenance as well as the resilience of a piece of infrastructure. Finally, this literature review will look at evaluation scoring matrices and how to compare proposed projects in a cumulative manner. Multi-Attribute Utility Theory (MAUT) was used to create a model that combines all of the previously-mentioned factors into a comprehensive score-based decision-making tool that operates based on the user's input.

2.2 SOIL EROSION

Soil erosion is the natural process by which sediment is broken up and transported away from its original location by natural forces such as wind, water, and in some cases the movement of ice (National Geographic, 2018); (Earth Eclipse, 2022). These erosive forces, while naturally occurring, can cause severe damage to the engineered and natural world. In July of 2019, the Los Angeles Times published an article reporting on the disappearance of California's coastline (Xia, 2019). Entire communities are debating between relocation or shoreline armoring to combat water erosion. Multi-million-dollar mansions in Malibu and the iconic Pacific Highway are in danger of sinking into the ocean.

Figure 1: Seashore Erosion is Threatening Homes in California (Xia, 2019)

The erosion of California's shoreline is sadly only one of many examples of the destructive power of natural erosion. Just in the United States, wind is transporting nutrients away from farmland in the Midwest, and glacial retreat in the Rocky Mountains is leading to an increase in soil content in the mountainous streams and rivers (Nelson, 2002). While wind and ice are certainly a concern when it comes to erosion, it is water that has state and federal transportation agencies the most concerned (Adams, 1978). California is facing rampant bank erosion, but there are five main types of soil erosion due to water: splash, sheet, rill, gully, and bank (Ricks, 2019). Splash erosion is when a raindrop first impacts the earth and dislodges sediment. Sheet is the uniform flow of water off of a surface, most closely associated with roadways during a rain event. Rill and gully go hand-in-hand. Rill is when sheet flow becomes concentrated on a slope and begins to cut a small channel, usually an inch or two wide at most, into the soil. Gully is the result of unchecked rilling and is when the rills have expanded into larger gullies. Bank erosion is where a body of water slowly eats away at its own shoreline. (Earth Eclipse, 2022).

Rainfall and storm surges can have a profound, lasting effect on our infrastructure. If left unchecked, they can destroy roadways and lead to structural collapses of buildings and bridges. Similar to other Departments of Transportation (DOTs) across the U.S., ALDOT has several practices in place to help reduce the effect of erosion due to water. The most common of which is armoring shorelines, slopes, and channels with large stones called riprap.

2.3 RIPRAP AND EROSION CONTROL

The Alabama Department of Transportation's Standard Specifications for Highway Construction outlines how to install riprap systems for Alabama roadways (Alabama Department of Transportation, 2020). These guidelines say that riprap installations, "shall consist of a protective course of stone or other approved materials on embankment slopes, in channels and ditches, wave protection for causeways and shoreline roadway embankments, bridge piers and abutments, or other work as shown on the plans or directed" (Alabama Department of Transportation, 2020). The design idea is simple but effective. To prevent erosion of soils, simply line the area with large stones to help reduce the effect of flowing water and rainfall. This armoring technique is not unique to Alabama's roadways. Riprap appears as an accepted erosion control practice or slope stabilization material in all 50 states.

Erosion control is not a "new science" by any means and has been around for centuries. However, in 1972, with the passing of the Clean Water Act, the United States began to take an acute interest in reducing erosion of soils to prevent their deposition in America's waterways. The National Pollutant Discharge Elimination System (NPDES) was created just for this purpose and required all general contractors for construction projects to submit a Construction General Permit (CGP) that included Stormwater Pollution Prevention Plans (SWPPP) (Schussler & Perez, 2022). This required all construction projects in the United States to have plans in place to prevent the erosion and transportation of sediments off their sites during construction. It also meant that any new construction would have to have proper permanent erosion and sediment controls (E&SC) in place to mitigate the impact of the land use change on the environment. In both temporary and permanent applications riprap has become a default alternative for contractors. Riprap has proven to be a resilient alternative not only as an erosion control tool to protect existing infrastructure, but also as part of the new effort to reduce soil runoff into rivers and streams. In today's design world that role continues to thrive and expand.

The National Cooperative Highway Research Program, an organization founded by the Transportation Research Board, published their 568th research report in 2006 (National Cooperative Highway Research Program , 2006) This document outlined the design criteria, recommended specifications and quality control for riprap installations on US highways and has become a staple design reference for many DOTs, including ALDOT. This report gave greater insight into the construction applications of riprap that had been learned in the 34 years since the passing of the Clean Water Act and subsequent research into erosion control practices. That report adopted ASCE's definition of riprap, which states that riprap is "broken stone or boulders place compactly or irregularly on dams, levees, dikes, etc. for protection of earth surfaces against the action of waves or currents…" (National Cooperative Highway Research Program , 2006)

2.3.1 ALDOT's Use and Classification of Riprap

ALDOT classifies riprap by the weight of the stones used. Typically, a given classification must have at least 50% of its stones weigh a given amount and a maximum of the top 10% weighing over a certain threshold. Likewise, a certain bottom percent of a given class must not be below a certain weight on average. For example, class 1 riprap must have at least 50% of the stones over 50lb in weight, with the top 10% not weighing more than 100lb per stone on average and no more than 10% of stones weighing 10lb or less.

Table 1:Weight Requirements for ALDOT Riprap Classifications

Riprap Classification	Percent Weight					
	W_{10}	W_{15}	W_{25}	W_{50}	W_{75}	W_{90}
Class 1	10 lb.	-	-	50 lb	-	100 lb
Class 2	10 lb	-	-	80 lb	-	200 lb
Class 3	-	25 lb	-	200 lb	-	500 lb
Class 4	-	-	50 lb	500 lb	1,000 lb	-
Class 5	-	-	200 lb	1,000 lb	-	2,000 lb

(Alabama Department of Transportation, 2018)

Asphalt, concrete, and steel are some of the most popular materials usually associated with highway construction activities, while the influence of other incidental materials like riprap, which are not directly used in road structures, are usually disregarded. However, Arevalo (2020) found that projects awarded by ALDOT between 2006 and 2016 included the purchase of more than 2.2 million tons of riprap, which represents a total cost of $74 million. About $6.7 million of taxpayers' money per year. That study allowed Arevalo (2020) to conclude that "riprap has a considerable impact on ALDOT's construction program," which is probably something that could be said about most transportation agencies. However, Arevalo (2020) also questioned the cost-effectiveness of riprap applications in some parts of the state, as explained in the next section.

2.3.2 Geography's Role in Pricing

Riprap has many desirable characteristics for a building material and is quite commonly used throughout Alabama, the United States, and the greater world at large. The main motivating factors behind this wide acceptance of riprap is a twofold alternative. One, riprap has proven to be effective at stabilizing an area structurally, and it is resilient to weathering and deterioration over time. Two, riprap is worldwide accepted and used making it easy for universal adoption without the need of further justification. Afterall, the use of large loose stones for construction purposes has been a standard in construction for millennia (Johannes Gutenberg Universitaet Mainz, 2021). However, riprap availability is not uniform geographically throughout the world or across the state of Alabama.

A review of ALDOT project bids from 2006 to 2016 conducted by Arevalo (2020) found that the non-uniform distribution of quarries across the state could be responsible for the great variability of Class 2 riprap unit prices in Alabama, with significantly higher unit prices being paid in the south of the state. It should be noted that Class 2 is one of the more common classifications of riprap used by ALDOT. According to Arevalo (2020), on average, ALDOT is paying about 140% more for Class 2 riprap installed in Baldwin

County (southern region) than for the same type of riprap used in Lawrence County (northern region). Figure 2 shows the average difference between unit prices in each county and the state average level of pricing for Class 2 riprap in Alabama. The darker color indicates prices higher than the state average, whereas the lighter colors show counties with a lower unit price. As one can see this gradient is tied closely to the relative position of any hypothetical project in question. Thus, Lawrence County Class 2 riprap prices in Lawrence County tend to be 35% lower than the state average, while ALDOT is paying about 56% more for the supply and installation of that material in Baldwin County

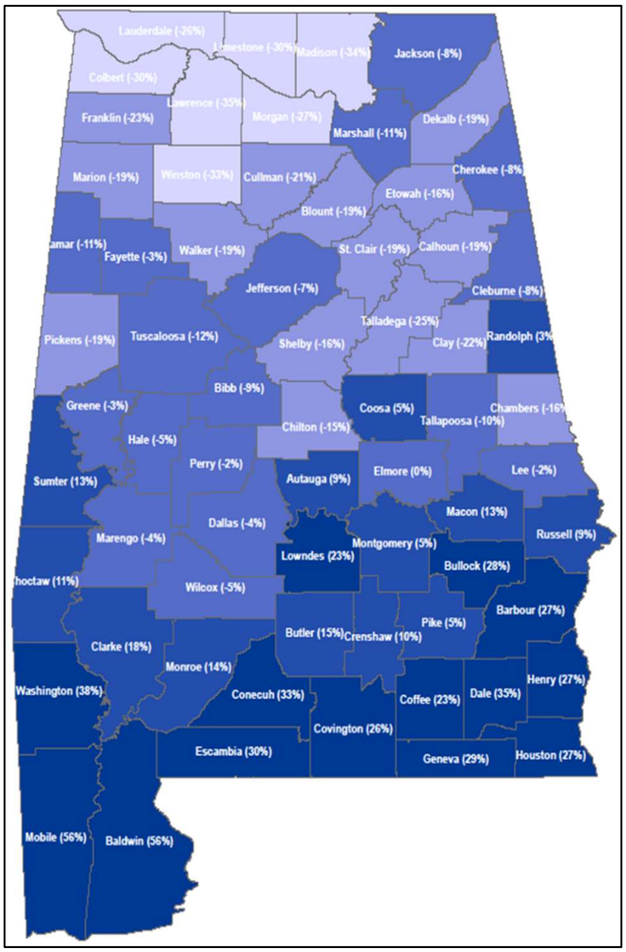


Figure 2:County Map with Relative Difference in Riprap Prices to State Average (Arevalo, 2020)

Arevalo (2020) could also find some level of correlation between the variability of Class 2 riprap prices and the location of quarries that produce that type of material in Alabama, which is shown in Figure 3. This explains the higher riprap unit prices paid by ALDOT in the southern counties. The more distant one is from a resource, the more effort one will need to exert to retrieve said resource and implement it. The inverse is also true, if a resource like riprap is relatively close and in high supply, then the cost to acquire it will be relatively low. It was found that a portion of the price paid in the southern counties corresponds to higher transportation costs to deliver the material at the jobsite. Those findings have prompted the investigation presented in this thesis, which is aimed to facilitate a more cost-effective and efficient decision process for material selection for channel armoring.

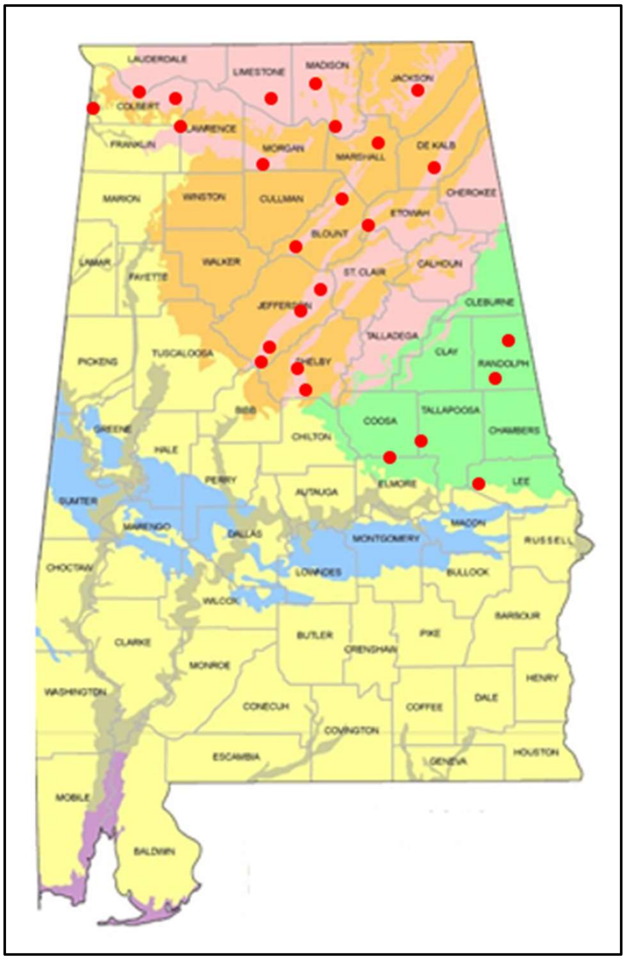


Figure 3: Map of Quarries Producing Class 2 Riprap in Alabama (Arevalo, 2020)

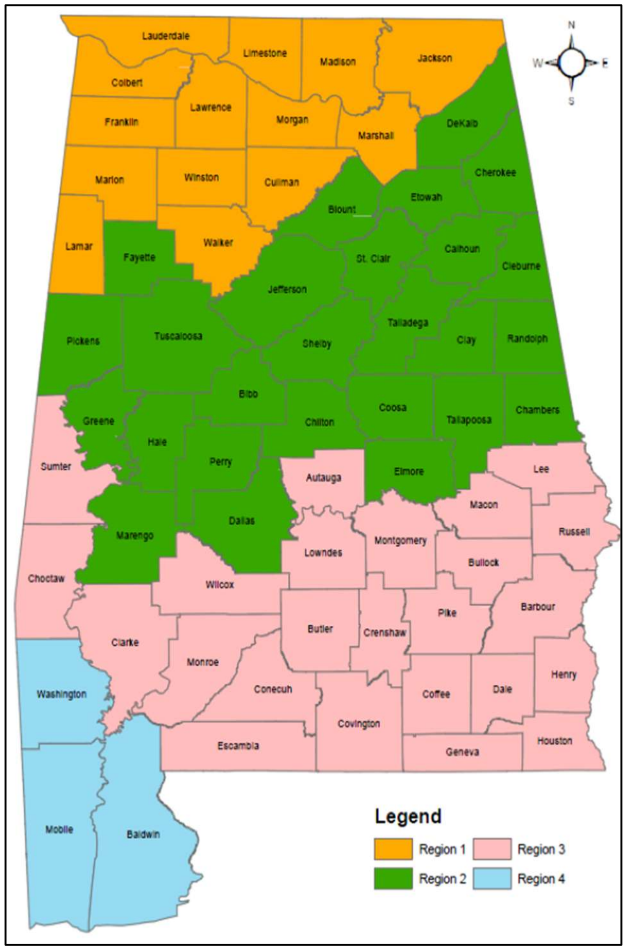


Figure 4: Map of Cost Regions for Class 2 Riprap in Alabama (Arevalo, 2020)

2.4 ALTERNATIVES TO RIPRAP

Riprap is typically meant to protect areas of high intensity flow rates of water. This is referenced by both NCHRP and ALDOT by defining it as a suitable lining for bridge piers and coastal roadways (National Cooperative Highway Research Program, 2016) (Alabama Department of Transportation, 2018). For instances of low flow or simple rainwater erosion prevention, there are other less intensive practices available. The most common of these is simply planting vegetation (Wang, 2000). The effectiveness of vegetative cover varies depending on the amount of coverage itself but also by the vegetation type. For example, natural grasses are typically more effective than planted grasses due to their stratified structure (B., 2010). What creates this gap in performance is simply a factor of time. Plant life that has existed in an area for years has had time to cover an area uniformly. This can be seen in the USDA's TR-55 runoff coefficient values for grassy areas (Natural Resources Conservation Service, 1986). For these values, the lower the number, the less runoff that occurs. For example, a grassy lawn will receive a rating between 39 and 89. The 39 shows a very low amount of rainfall runoff occurring while an 89 reflects the opposite.

The number can fluctuate based on the type of soil (i.e., Clay, sand, and loam content) or by the percent area covered with vegetation. Clay soils have very low infiltration as compared to sand and loams. Likewise, the less vegetation coverage an area has, the higher the erosion and runoff from it. However, if vegetation has time to establish coverage, an area can see a large reduction in runoff. Time also allows grasses to grow extensive root systems. Complex root systems and extensive ground level vegetative cover have considerable influence in the erosion resistant qualities of soils (Wang, 2000). These roots act as anchors for topsoil and create a structural web that resists erosive forces.

Time is not always on the side of engineers at the end of a construction project and this means that uniform coverage can be hard to achieve. For example, the Alabama Department of Environmental Management (ADEM) requires that construction jobsites achieve 95% coverage before the project can be officially closed, but this benchmark can be hard to achieve. To combat this reality, several materials have been created that provide the necessary ground coverage and flow resistance for an area, while encouraging the long-term growth of natural plant life. These materials are defined by ALDOT Section 659 as Rolled Erosion Control Products (RECPs). RECPs can be categorized as either permanent, providing effective strengthen and coverage permanently, or degradable, which help protect vegetation as it becomes established but eventually degrade.

RECPs are rated by their designed application of either slope or channel protection. These are broken down by the maximum slope and shear stress they can resist, as shown in Table 2.

Table 2: ALDOT Erosion Control Products, Types and Applications

Erosion Control Products			
Product Application	**ECP Type***	**Maximum Slope (H:V)**	**Maximum Anticipated Channel Shear Stress (Pounds per Square Foot)**
Slope	S4	4:1	-
	S3	3:1	-
	S2	2:1	-
	S1	1:1	-
Channel	C2	-	2.0
	C4	-	4.0
	C6	-	6.0
	C8	-	8.0
	C10	-	10.0

*ECP Type refers to the application (channel or slope, S or C) and its performance rating

(Ex. An S2 ECP Type is meant for slope installations with steepness of 2:1 or lower. Likewise, a C4 rated material is meant for channels that will experience a maximum shear stress of 4psf)

Examples of RECPs include turf reinforcement mats (TRM) and tied concrete block mats. Both of these are ALDOT approved erosion control practices (Alabama Department of Transportation, 2022) and are within the Standard Specifications for Highway Construction criteria for riprap replacement, which states that, “a traversable tied concrete block mat may be used in lieu of riprap… or shall be a similar product that has a minimum shear stress capacity of 10 pounds per square foot” (Alabama Department of Transportation, 2018). Another alternative considered in this study, but not currently included in the list of ALDOT’s RECPs, is the use of cellular confinement systems (CCS). Each of these three alternatives to riprap were assessed in this thesis and are described in the following sections.

2.4.1 Tied Concrete Block Mats (TCBM)

Tied concrete block mats (TCBMs) are specifically cited in the ALDOT standard specification manual as an acceptable alternative to riprap. TCBMs are a network of 6.5” x 6.5” x 2.25” blocks tied together with a high strength polyester geogrid at 1.5” spacing between blocks (see Figure 5 & Figure 6 (Motz Enterprises, Inc.)). Similar to TRMs, TCBMs are a rolled material that provides instant coverage to an aerial. Unlike TRMs, however, TCBMs have a much higher shear force strength and are designed for shoreline and channel flow (Motz Enterprises, Inc., n.d.). They do encourage the growth of natural plant life, but because the majority of their coverage is concrete blocks (See Figure 6), they do not promote nearly as much germination as a TRM. It may be helpful to consider TCBMs to be a type of hybrid of riprap and TRMs, they provide the high strength of loose stone but also a RECP that encourages plant growth.

Figure 5: Example of Field Installation of Block Mats (Motz Enterprises, Inc., 2021)

Figure 6: Concrete Block Mat with Initial Plant Growth (Motz Enterprises, Inc., 2021)

TCBMs offer an easier installation process than riprap and could be/are classified as green soil stabilization techniques. They are faster to install without compromising the shear stress offered by riprap. They are promising alternatives to riprap but extensive cost and performance analyses must be done to assess their viability.

2.4.2 Turf Reinforcement Mats (TRM)

While not specifically cited as an alternative to riprap in ALDOT's Standard Specifications for Highway Construction, TRM do fall under the category of "similar products, with 10psf minimum shear strength" (Alabama Department of Transportation, 2018). Only the highest rated TRM product sold by American Excelsior achieves this threshold, and it is rated for exactly 10psf. Turf reinforcement mats are a simple rolled erosion control practice, designed to provide immediate cover for an area while seeds take time to germinate and grow (see Figure 7 and Figure 8). The mats provide the mechanical stabilization that is typically provided by the roots of natural grasses. This solves the issue of time that usually plagues contractors when trying to achieve a certain land coverage percentage to finish a project. They are made of polypropylene fibers and are a common practice to protect large, exposed areas of soil (American Excelsior, n.d.).

Figure 7: Example of TRM (Tenax US, 2021)

Figure 8: TRM Installed in Practice (Tenax US, 2021)

A typical cross section of TRMs is loosely compacted soil, followed by the anchored mat and a layer of grass seed. The mat can then be buried under a layer of topsoil in order for the seeds to have room to grow through and provide permanent stability to a slope.

2.4.3 Cellular Confinement Systems (CCS)

CCS is another alternative considered in this study as a substitute to riprap. CCS is similar to turf reinforcement as both are fabricated mats used in the stabilization of channels, but they differ in their configuration and stabilization approach. CCS is a geosynthetic material that expands out like an accordion into a honeycomb structure, as shown in Figure 9. These honeycombs are laid out in the bed of a stream or slope and then filled in with soil. The result is a mechanically stabilized earth layer that is more resistant to shear and compressive forces, as well as erosion. The honeycombs are then able to grow vegetation that further stabilize the surface.

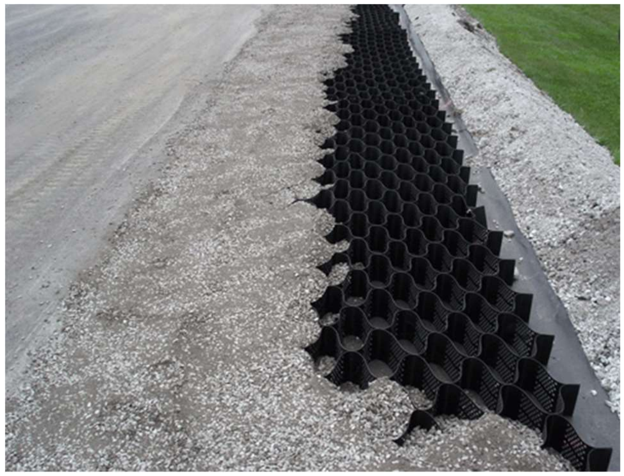


Figure 9: Example of Cellular Confinement System in Practice (Presto Geosystems, 2022)

While it is still not listed by ALDOT as an approved erosion control material, it has been extensively researched by Vasconcelos (Simpson, 2018); (Vasconcelos, 2019). Vasconcelos has found CCS to be a suitable erosion control practice in real world installations in Alabama, as well as a potential sediment trap similar in application to a channel waddle. His work prompted investigators to include the material in this analysis for potential adoption into ALDOT's approved materials list.

2.5 UNIT PRICE CALCULATION

Unit pricing is a basic function in economics. The unit price or "going rate" of an item is simply the market or estimated price for one unit of a given commodity, activity, or service (Russo, 1977). Being able to accurately estimate the unit cost of items in a project bid is always a challenge for general contractors, due to their tight profit margins, and for project owners, such as state DOTs. Pre-award planning activities for construction projects, regardless of their nature, require cost estimating efforts by the DOT in an attempt to predict final project costs. That estimate is then used to determine if the project is economically feasible, if the required level of funding is reasonable given the intended project outcomes/benefits, and to make sure that the agency has the financial capacity to undertake the project (Molenaar, 2011). This practice helps agencies ensure that they are accepting projects that are low in cost but do not dip so low as to sacrifice quality (Kermanshachi, 2018). Those estimates are usually broken down into a list of cost/bid items represented in the form of unit prices with their respective estimated quantities of work.

Estimating unit prices is not a simple endeavor and many factors must be taken into consideration. According to Pakalapati and Rueda (2020), there are five main cost-influencing factors for construction contracts: (Pakalapati & Rueda-Benavides, 2020)

1. Time
2. Scale
3. Geographic Influence
4. Market Competition
5. Uncertainty

2.5.1 Unit Price Modeling - Nonlinear Regression

Previous studies have used historical bid data and regression analysis as the foundation for unit price modeling (Arevalo, 2020) by creating regression equations that define the relationship between unit prices and estimated quantities of work. While the scale factor would be directly considered by these models, other factors such as time, geographic influence, and market competition could be considered by an appropriate selection of the input data. For example, the use of recent bid data is expected to represent recent pricing trends (time factor), while models created with regional data would incorporate geographic considerations and local market conditions into the unit price estimating process. According to the Federal Highway Administration (FHWA), the most accurate means of predicting unit rates of a given infrastructure installation are those utilizing bid data no more than 24 months prior to the estimating period (American Association of State Highway and Transportation Officials, 2013). Karthik Pakalapati (2018) developed a methodology to determine the optimal look-back period for data-driven construction cost estimating on a case-by-case basis (Pakalapati & Rueda-Benavides, 2020).

Pricing uncertainty, on the other hand, can be considered via data-driven probabilistic analyses of regression models. Previous studies have also shown that construction unit prices tend to have a nonlinear relationship with quantities of work. This is due to the concept of economies of scale, which was first introduced by George Stigler in 1958. Stigler proposed that as production of a commodity scales up, the unit price to produce it drops precipitously at first and then plateaus before rising again (see Figure 10). This pattern can be seen with most modern commodities and extends beyond production to the consumer. However, the point where prices start increasing again is usually reached at the industry- or market-level due to saturation (O'sullivan & Sheffrin, 2003). At a project-level, unit prices usually keep decreasing as delivered quantities of work increase, as shown in Figure 11.

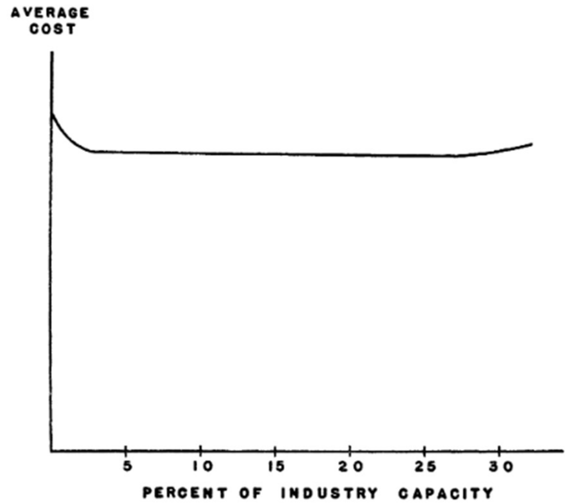


Figure 10: Average Cost as a Function of Production (Stigler, 1958)

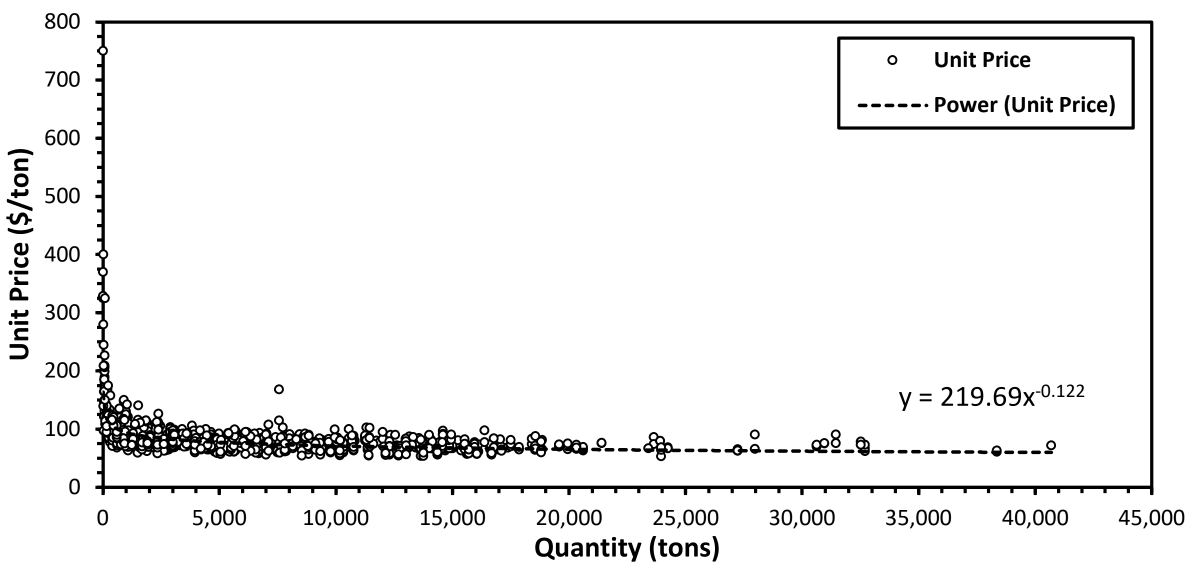


Figure 11: Hot Mix Asphalt Non-Linear Regression Model – ALDOT (Xu 2018)

As found by Rueda (Rueda-Benavides, 2016), when unit prices paid by DOTs for most construction materials and activities are modeled as a function of quantity, they tend to follow a nonlinear, inverse power model, as the one shown in Figure 11. Rather than the function increasing exponentially, it tappers out and becomes almost flat. Understanding this concept, one can simply use previous bid data for unit price and quantity to create a power function that models the unit cost to produce or deliver a given material or commodity such as riprap. When ALDOT's bid, data is used to develop a unit price model, it includes the unit cost for raw materials, the cost of transportation to the jobsite, and labor and installation costs. This is shown in ALDOT bid items tab that claims that bid item pricing shall reflect the cost of materials and installation on all projects (Alabama Department of Transportation, 2022)

2.6 POST CONSTRUCTION CONSIDERATIONS

While the logistics of sourcing, moving, and installing materials, along with labor, are the primary concerns on the front end of projects there are other aspects to consider. Most materials that are installed in the field require some amount of inspection and maintenance by ALDOT personnel over the course of their lifespans. These inspections look to ensure that a piece of infrastructure is operating in a state of good repair throughout its life and to correct any problems that may occur. Selecting a material that is not maintenance intensive and is resilient to changing conditions can ensure a longer period of effectiveness and reduce the likelihood of complete rehabilitation of the asset in the future.

2.6.1 Maintenance

Riprap, tied concrete block mats, turf reinforcement mats, and cellular confinement systems are all classified as permanent erosion controls measures. Therefore, long-term maintenance costs of these assets should be carefully considered during material selection.

2.6.1.1 Riprap Maintenance

Riprap installations are required by the Alabama Soil and Water Conservation Committee to be inspected "regularly and follow significant storm events." (ASWCC, 2018) As most channels must be built for a 10-year, 24-hour storm event (Pitt, 2007), the channel should be inspected after every such event or every 10 years . These inspections are meant to ensure that the system has not become compromised and to schedule regular clearing of the channel or slope. The Massachusetts Dept. of Environmental Protection recommends removal of any "woody" vegetation to prevent the large root systems from dislodging stones (Massachusetts Department of Environmental Protection, 2022). All obstructions should be removed so as to prevent a change in flow characteristics. A discussion of this matter with ALDOT's maintenance engineers confirmed that riprap is considered by this agency as a low-maintenance alternative with intervention from ALDOT's staff rarely required during the lifespan of the asset. Maintenance is mainly limited to vegetation removal, as needed.

2.6.1.2 Rolled Erosion Control Measures Maintenance

In contrast, tied concrete block mats, turf reinforcement mats, and cellular confinement systems encourage plant growth. The idea of these rolled erosion control measures is to provide structural relief for plant life to take root and grow without soil loss in the meantime. However, ALDOT does perform regular mowing of these areas to make the right-of-way accessible for crews and inspectors.

2.6.2 Cost Estimates

For either spraying or mowing, the cost of maintenance can be calculated as the unit cost per length of channel multiplied by the total length to be treated. The agency incurs in these costs a number of times during the lifespan of the asset. Taking into consideration the concept of time value of money (Gallo, 2014), it is not appropriate to simply add up all maintenance expenses from different years, comparing maintenance costs among erosion and sedimental alternatives. That type of comparison requires the calculation of the present value of all maintenance expenses as shown in Equations (1) & (2). Following FHWA's guidance on the calculation of lifecycle costs for transportation assets, Equations 1 & 2 do not consider inflation. Likewise, FHWA recommends the use of a 7% annual discount rate (FHWA 2020). All erosion control methods considered in this study were assumed to be inspected and maintain every two years. Thus Equation 2, which is typically used to calculate the present value of an annuity, is applied with the biennial discount rate (r) calculated with Equation 1. Equation 2 must be used to recalculate a biennial discount rate if the FHWA changes its recommendation on the annual rate or if the agency decides to use a different rate.

$$\boldsymbol{r = 2 \times i + i^2 = 2 \times 0.7 + 0.07^2 = 0.1449} \quad (1)$$

$$\boldsymbol{PV = C_m \times \frac{1 - \frac{1}{(1+r)^n}}{r}} \quad (2)$$

Where,

PV = present value

C_m = current cost of maintenance run

i = annual discount rate

(Gallo, 2014).

Tied concrete block mats are meant for both channel and general slope protection and will likely be subject to higher shear forces than turf reinforcement mats. Because of this, care should be taken during inspections to ensure that the mats have not become compromised since the previous inspection. For both TRMs and TCBMs the main cause for compromised mats, beyond large events like hurricanes and severe storms, is due to installation errors. If not properly secured, the mats can be uplifted by wind or water flows and expose loose topsoil. The initial inspection at the conclusion of a construction project is the crucial step to ensure the long-term performance of both of these products. Uniform coverage of the protected area and proper anchoring at the ends of the mats must be ensured with these inspections.

2.6.3 Runoff and Water Infiltration

When discussing soil erosion prevention practices, it is important to review the Natural Resource Conservation Service Technical Report – 55 (TR-55) (Natural Resources Conservation Service, 1986). This report outlines the process by which engineers can estimate rainwater runoff for small urban watersheds. Rainfall data has been regularly collected and recorded since the late 19th century, and such information allows scientists to create regression models for stormwater events, similar to that of the unit cost models using bid tabs (Hernantes, 2013). These estimated frequency and intensity charts make it easy for engineers to then design systems that are built to the personalized profile of a given region.

The TR-55 estimates runoff as a function of precipitation amounts, soil type, and ground surface coverage. The soil type and ground coverage work together to affect the total amount of runoff to be expected from a given area. Runoff is simply the amount of precipitation that leaves a site during and after a rainfall event (Zhang, 2012). Certain soils and surfaces are able to absorb a high amount of water, while some barely see an abstraction. These different rates are given as scores, called curve numbers, as they are calculated based on regression model curves from measuring surface runoff for different materials. These curve numbers (CN) are used in equations (3), (4), and (**5**) to calculate the estimated runoff for a given storm event.

$$\boldsymbol{Q = \frac{(P - I_a)^2}{(P - I_a) + S}} \tag{3}$$

$$\boldsymbol{I_a = 0.2S} \tag{4}$$

$$\boldsymbol{S = \frac{1000}{CN} - 10} \tag{5}$$

Where,

P	=	Precipitation amount (in)
I_a	=	Initial Abstraction (in)
S	=	Potential maximum retention after runoff begins (in)

(Natural Resources Conservation Service, 1986)

Ideally the total runoff should be minimized for an area to reduce potential erosion and storm surge to downstream waterways. While the precipitation and soil of a given region cannot be changed, one thing can be, surface coverage. The better the coverage is for an area in reducing runoff, the better it is for the environment from a structural and ecological standpoint.

2.7 SCORING MATRIX

To properly assess the effectiveness of riprap and its selected alternatives, a comprehensive evaluation integrating all the attributes for each alternative was needed. Cost-benefit analyses are typically used to conduct this type of comparative evaluations. Cost-benefit analysis (CBA) is an evaluation of different alternatives that relates all aspects in question to the equivalent monetary value of each (Pearce, 1971, 1983). The concept is simple. All aspects, such as materials, delivery, and installation have an associated monetary cost, which could be easily estimated. It might not be that easy for other aspects such as time or environmental impact, but similar types of non-monetary factors must be usually monetized in CBA procedures. All factors can then be tallied as an overall cost of the alternative under consideration, covering not only the inherent costs, but also other effects that are not economic in nature.

In 1971 and again in 1983, D.W. Pearce wrote about CBA, its origins, and the subsequent theories that have emerged from it. The concept of monetarily assessing all aspects of projects gave way to the idea of cost effectiveness ratios (C/E). This ratio took the ideas of full project costs from CBA and directly compared them to the estimated monetary effectiveness of its implementation. The lower the ratio, the better the project was on a per dollar basis (high effectiveness, low cost). However, some critics of CBA quickly pointed out its main drawback, the quantification of intangibles (Hamburg University of Technology, 2022). Equating the value of materials and labor is very easy to quantify. Yet, concepts such as environmental impact, deterioration over time, and personal preference are much more difficult (Robinson, 1993). Bearing this in mind, a system that considers multiple aspects and values of a given project is needed.

Multi-Attribute Utility Theory (MAUT), as the name suggests, is an analysis method that accounts for multiple aspects of a given topic. Rather than deciding purely based on the equivalent monetary values of the alternatives, it uses a weighted scale based on the desired outcomes of the evaluating party (Khalafalla, 2019). These scales are usually adjusted around utility values assigned by the interested party. For example, when deciding to purchase a home, several factors must be considered, such as the price, the location, and size. However, these are 3 distinctly different categories and are all measured differently by dollar amounts, distance, and area, respectively. The theory of MAUT is to utilize an analysis approach that is more nuanced and connects all of these factors together. A single adult may not want a large home, whereas a couple with children would. A single adult may want to live close to a downtown area to enjoy the nightlife, while a family would want to live close to the children's schools (Winterfeldt, 1973); (Gercek, 2004).

MAUT weighs the importance of each aspect with a given utility rating and scores each aspect of a potential solution on each metric. These weights are tallied together to give an overall ranking of each candidate and a final decision can be adjusted based on the user's personal preference rather than pure monetary values. Equation (6) shows this process.

$$\boldsymbol{U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} u_i(x_i) w_i(x_i)} \quad (6)$$

Where,

$\boldsymbol{u_i(x_i)}$ = Utility Score of given characteristic

$\boldsymbol{w_i(x_i)}$ = Weight of importance of given characteristic

The utility of each material's characteristics can be determined by set parameters or arbitrary conditions based on opinion. The usefulness of this analysis is that it takes all aspects, regardless of the units of measurement each uses, and normalizes them into a comprehensive score. This method would be implemented for this investigation.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

This chapter describes the processes performed throughout the duration of the comparative analysis of riprap and its alternatives. It includes examples and figures that should help the reader to understand how the investigation was conducted, as well as how to repeat this process for future analysis. First, the classification of riprap and the appropriate alternatives were selected. Investigators then gathered the appropriate data for modeling the unit price of each material. For riprap, 2 years of ALDOT bid data was extracted to be used in a regression model of current prices in the state. Because there were very little projects in the same 2-year period that used the selected alternatives, manufacturers and distributors in the state were solicited for this information. These prices were then used to create a similar function to that of riprap for the unit price of each alternative. These unit prices were, in turn, used to determine the cost of installation for a given project on a cost-per-square foot basis. The timeline for installation was also determined to account for differing project timelines. Next, the maintenance cost of each material was calculated based on the desired lifespan of the product. This consisted of inspections and vegetation control measures. When designing a channel, it is important to understand the flow characteristics of the material lining. For these purposes each material's Manning Roughness Coefficient was programmed in to account for the changes to flow that may occur. Finally, a scoring matrix for each aspect described was assigned, based on the minimum requirements set by ALDOT and the USEPA. These scores were compiled into an overall ranking that showed which material was ideal for each region by size of area and application. All of this was combined into an excel program called Channel Armoring Material Selector which could then take user input to alter the results, based on the weight of importance for each project aspect. For example, a project user could emphasize the importance of a fast installation to get a hypothetical project completed as quickly as possible regardless of cost, as well the reverse. Figure 12 shows the full sequence of events for this analysis as a flow chart.

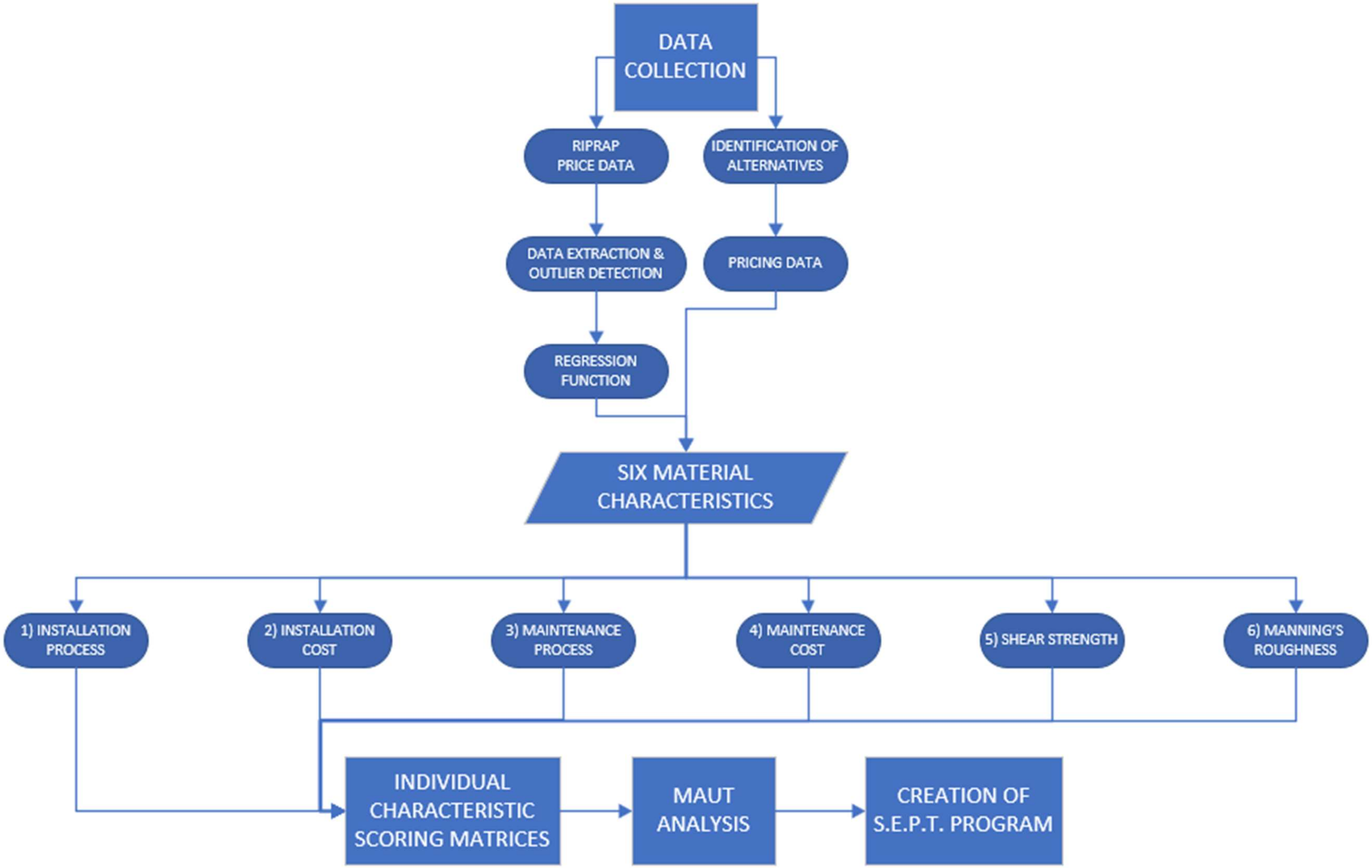


Figure 12: Logic Flow of Analysis Methodology

3.2 DATA COLLECTION AND COST ESTIMATES

The purpose of this investigation was to compare the overall cost and performance of riprap for a channel stabilization in comparison to approved alternative materials. This required the procurement of cost data for all materials in question, based on the quantity needed and the project's location. Each material was analyzed separately with the objective of creating a function to show the unit price of each as a function of project size.

3.2.1 Riprap Price Data

To properly compare riprap to alternative materials for the same installation area a baseline unit price had to be established. This comparative baseline is based on previous bid data from ALDOT projects. The FHWA suggests utilizing an analysis period of no more than 2 years (FHWA, 2006). This allows an adequate sample size to be collected but does not extend back so far as to make the data considered "not current." Anything further back than 2 years from the period of estimate is considered susceptible to inflation and must have this accounted for in the cost comparison. Bid data of 23 months from January 2020 to November 2021 was retrieved from ALDOT letting data. Along with this being the most current data at time of analysis, this timeframe was selected because it included the onset of Covid-19 and the subsequent effect it has had on the market as of the writing of this analysis.

The letting data was retrieved from ALDOT's bid tabulation selection page on July 15, 2021 and again on January 10, 2022. The following is the cleaning and usage process of this data. For future uses of this methodology, a similar 18–24-month sample should be retrieved for the current analysis period to ensure accuracy. The raw data was provided in PDF letting sheets that included full information on projects granted by the Alabama Department of Transportation in the time period. This information included contractor names, project description and location, all proposed bids (accepted and not), start/end dates, contract ID numbers, and a full list of materials bid for the project among other items. This data needed to be converted to a user-friendly format for analysis and so were converted to Microsoft Excel files.

3.2.1.1 Data Extraction

The PDFs were converted to a spreadsheet format for easier extraction and manipulation of data values (pdftoexcelconverter.net, 2022). The resulting values were in broken cells of text and numeric values that were then converted to string cells. Finally, these strings were filtered using callout commands to retrieve the following information: Letting Date, County of Project, Contract ID, Contract Item ID, ALDOT Product ID number, Unit Cost, Unit Quantity, Item Standard Units, and Item descriptions. All ALDOT items that corresponded to virgin class 2 riprap installations were then extracted for analysis. See Table 3. One project from each month was selected at random from this and compared to the PDF file visually to ensure that the data had been extracted correctly.

Table 3:ALDOT Contract Material Items Used in Analysis

ITEM	UNIT	ITEM DESCRIPTION
610A002	Square Yard	Loose Riprap,Class 2,12" Thick
610A003	Square Yard	Loose Riprap,Class 2,18" Thick
610A004	Square Yard	Loose Riprap,Class 2,24" Thick
610A010	Square Yard	Loose Riprap,Class 2,48" Thick
610A012	Square Yard	Loose Riprap,Class 2,30" Thick
610C001	Ton	Loose Riprap, Class 2
665I000	Ton	Temporary Riprap, Class 2

All values were converted to equivalent weight units to directly compare unit prices over projects and because the industry standard for suppliers is to sell riprap by the ton. For example, item 610A00: Loose Riprap Class 2, 12” thick, refers to spreading class 2 riprap over a one square yard area at a thickness of 12 inches. This was converted to the equivalent price per ton of class 2 riprap using the following equation:

$$\$\,\boldsymbol{per\ ton} = \frac{\$}{\boldsymbol{sq.yd}} \times \frac{\frac{\boldsymbol{36in}}{\boldsymbol{yd}}}{\boldsymbol{\rho_{stone}} \times \boldsymbol{A} \times \boldsymbol{t} \times \boldsymbol{p_{voids}}} \tag{7}$$

Where,

ρ_{stone} = density of stone (lb/cf)

A = area (sq. yd)

t = thickness (in)

p_{voids} = percent voids

After extraction of all projects with these given products and subsequent conversion to the price per ton, the data was plotted so that a regression analysis could be performed. Figure 13 shows all data points extracted.

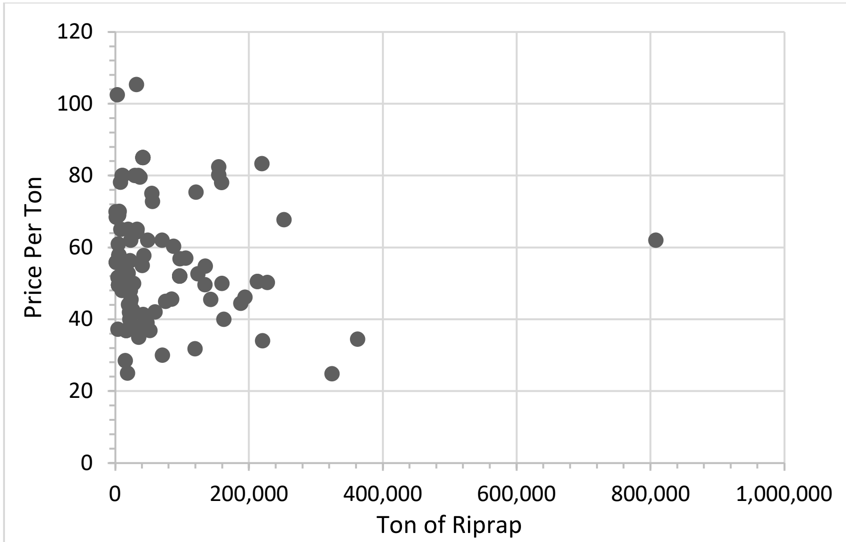


Figure 13: Plot of all data points in sample, n=112

3.2.1.2 Outlier Detection and Removal

Before a representative function for riprap unit prices could be created for the state and each region, any outliers had to be removed from the dataset. Outliers are, in the words of Merriam-Webster, "a statistical observation that is markedly different in value from the others in the sample." If these outliers are allowed to remain within a given sample for analysis, then that "marked difference" can cause the data to be skewed. This can delegitimize conclusions made from that data set, meaning detection and removal of these outliers is of the utmost importance.

The modified z-score method was selected as the primary detection identifier for the dataset. This method is, as the name suggests, a modified version of the typical z-score method. Rather than mean-based comparison, this method analyzes a sample in relation to the median of the set. The advantage is that, while the mean can be skewed due to an extreme outlier or set of outliers, the median of a dataset is far less likely to be affected in this way. This helps to eliminate extreme values that may otherwise be left in using a standard z-score and likewise save values that may be accidentally removed (Zach, 2021). For this dataset, any values that were more than 2.325 standard deviations from the median were removed as 2.325 correlates to the 99th percentile range for a distribution. See Equations (8) (9) & (10).

$$Z_{Score} = \frac{x - \mu}{\sigma} \quad \textbf{(8)}$$

$$Modified\ Z_{Score} = 0.6745 \frac{x_i - \tilde{x}}{MAD} \quad \textbf{(9)}$$

$$MAD = median\ absolute\ deviation\ of\ sample = \tilde{x}(|x_{i-n} - \tilde{x}|) \quad \textbf{(10)}$$

Where,

x_i = Single value from sample

$\tilde{x}$ = Median of sample

3.2.1.3 Regression Analysis

Five nonlinear regression models were generated from the project data. The first model included all of the data points for the entire state of Alabama in order to create an average unit price function for the entire state. Then four additional models were created to show the unit price by region, based on Arevalo's location cost indices. These accounted for the regional disparities in riprap unit price that exist due to the associated geographic correlation between the locations of the material source and of a given project. This was further supported as the R-squared values for each data set's regression model increased by at least eight percent when this was done. For the purposes of this investigation, these same regions would be assumed to be unchanged. This assumption could be made for two reasons: 1) no new sources of riprap production have been introduced since the writing of Arevalo's work, and 2) no new major arterial roadways have been built to improve travel efficiency. To check the current suppliers of riprap the Mineral Resources Data System was used to identify all riprap producing quarries in and around Alabama (USGS, 2022). All of the sites were identical to that of Arevalo's and still in operation at the time of this analysis. It was therefore concluded that the regional locations previously used for the cost indices were still valid and the regional boundaries remained the same. The regression functions were generated using Microsoft Excel Version 2202 and are shown in Figure 14. Table 4 shows the corresponding equations for each function as they were used in the analysis.

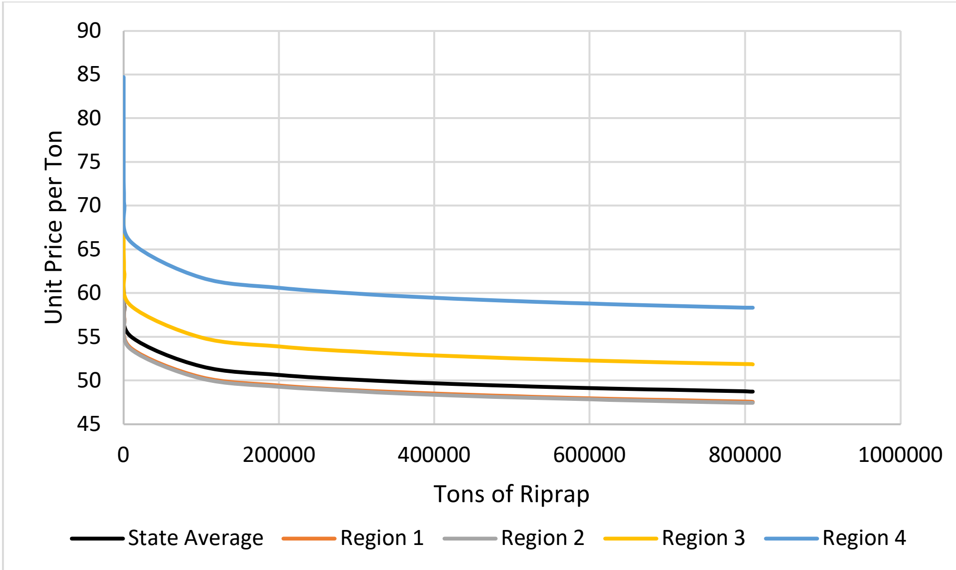


Figure 14:Riprap Regression Functions by Region and State Average

Table 4:Regression Function Equation Values

Riprap Price as Function of Quantity		
Region	**C**	**E**
State	70.79	
One	69.10	
Two	68.91	-0.0274
Three	75.33	
Four	84.71	

$$Price = Cx^E \qquad \textbf{(11)}$$

3.2.2 Alternatives to Riprap

This section shows the selection process for alternative erosion control materials to be used in place of class 2 riprap for ALDOT installations. First, an analysis was done of the market supply of class 2 riprap outside of Alabama in neighboring states. This was to identify any potential quarry sites that were located closer to the southern counties of the state. One such location was found and the cost of using that stone was calculated but given that it is a valid option for contractors it was assumed to have been considered for bids in Alabama. For this analysis it was not included as potential alternative given its availability and assumed participation in the Alabama market. Next a selection was done based on ALDOT's minimum design criteria for a stormwater channel conveyance system for products other than riprap. Unit prices were determined based on solicitations to suppliers based on the maximum and minimum riprap coverages approved for construction in the January 2020 to November 2021 project bid data. This ensured that the prices reflected current market conditions and were based on the same constraints as the riprap unit price function. These costs were combined to create a unit price per square foot of installation for direct comparison to riprap.

3.2.2.1 Identification of Alternatives

While confirming the continued operation of all quarries from Arevalo's work, investigators identified several sites outside of Alabama that also produced class 2 riprap. These were mostly concentrated in the area bordering the northern half of the state and so were assumed to not be of significance. One site was identified south of the previously southernmost site and were considered as additional potential sources. However, given that this site does produce stone within Alabama's requirements for class 2 riprap, it is already likely being used or at least considered for use by contractors in Alabama. Therefore, it was assumed that this source is already accounted for in previous bid tabulations and no further investigation would need to be performed.

Given the geographic correlation between riprap's unit price and the location of a project utilizing the material, it was decided to identify alternative stabilization materials from stone that could be used in place of it. Section 610.02 of the ALDOT Standard Specifications for Highway Construction states that a tied concrete block mat from the Department's Misc. Approved Products List or a similar product with a minimum shear stress capacity of 10 pounds per square foot can be used in lieu of riprap. From this approved list there were two products known as tied concrete block mats (TCBMs). Flexamat of Motz Enterprises, Inc. and Shoreflex of Premier Concrete Products would be analyzed for pricing data.

Along with TCBMs, this investigation also looked at turf reinforcement mats. This product has one ALDOT approved design for 10 psf of shear force that is sold in Alabama. This was the Recyclex TRM from American Excelsior, produced in Texas and distributed locally in Florence, Alabama. Cellular confinement systems were also selected as they are alternative stabilization materials designed to provide reinforcement to soil while also allowing for the growth of vegetation. There are no approved vendors for these products for ALDOT, but there is a distribution warehouse for Presto Geosystems Geoweb in Montgomery, AL.

3.2.2.2 Alternative Products Unit Prices

After identifying and assessing the vitality of possible alternatives, a unit price function, similar to that of riprap, was needed. However, no ALDOT project within the January 2020 to November 2021 list utilized these products. As a result, a new price collection method was used to find the appropriate information. The total coverage area for each class 2 riprap project in the sample was calculated and the minimum and maximum values were selected. All projects were assumed to be two feet depth of class 2 riprap with 33%

void space and rock density of 150 lb/cf. This was used to calculate the extreme quantities of 629.73 tons and 807,785.34 tons equated to coverages of 6,266 sq ft and 8,037,665 sq ft respectively. These areas were then used as the margins for pricing collection from manufacturers and suppliers of these materials in Alabama.

To obtain the corresponding unit prices, investigators solicited quotes from Alabama based distributors of the alternative products. The suppliers were not told the intended use of the products and were only asked to supply a price for a specified quantity. As expected, the higher quantity orders were lower unit prices than the lower quantity bids. These unit prices were then used as points to calculate a power regression function to be used as a model of the unit prices for each product. However, this data only showed the cost of the TRM and CCS materials themselves and did not cover the installation in field. Labor and delivery would need to be calculated for this material.

3.3 INSTALLATION

Given that the riprap regression model accounted for delivery and installation of the product in the field, the equivalent unit price model for TCBMs, TRMs and CCS would have to reflect this as well. To calculate the unit price of installation investigators consulted the RSMeans data catalog. RSMeans is an industry standard for labor bid estimates for different construction processes. While no productivity rates were available for TCBM installation the suppliers that were interviewed claimed that the material's installation rate was comparable to TRM and geotextile deployments. This was the assumption made for this analysis. RSMeans also includes the pay rate and number of workers required so that the cost of installation could be calculated based on the productivity rate given.

After collecting the unit price of each material and the associated delivery and installation costs, a unit cost of installation could be calculated. Per ALDOT, all bid item prices include the cost of materials and installation on site, and the bid data-based regression model already accounted for this. Using this cost per ton, a given installation of riprap's construction unit cost could be calculated as the unit cost per ton of riprap multiplied by the amount required. This would give the total cost of installation, which when divided by the area it covered produced a cost per unit area. This process could then be performed for all identified alternatives. The total cost of materials, delivery, and labor to install over a given area divided by said area would yield a cost per unit area price. These values could then be used for direct comparison. See Table 9.

In addition to the installation productivity rates and costs there was also the additional materials and products needed for each alternative. For example, class 2 riprap is not simply installing the stones themselves into a channel by themselves. The channel must first be lined with a geotextile and then lined with No. 4 stone to protect the lining from the riprap being dumped from an excavator bucket. Likewise, TRM requires anchors to secure the mat, then a layer of topsoil (Table 8) with seeds (Table 5 and Table 6) and fertilizer (Table 7) on top of the TRM. This is usually followed by an erosion control blanket to protect the topsoil from rainfall as the seeds germinate. TCBM also require seeding and fertilizer and CCS require geotextile lining before the honeycombs are deployed. All material requirements for this were retrieved from the ALDOT Construction Best Management Practice Plan Handbook (ALDOT, 2018)

Table 5: Region 1 and Region 2 Seed Mix

Seed	lb/acre
Bermudagrass	33
Annual Rye	20
Lespedeza	38
White Dutch Clover	6

Table 6: Region 3 and Region 4 Seed Mix

Seed	lb/acre
Bermudagrass	30
Annual Rye	18
Lespedeza	31
Crimson Clove	5
Pensacola Bahia	47

Table 7: Fertilizer Requirements

Chemical	lb/acre
Nitrogen	120
P_2O_5	120
K_2O	120

Table 8: Topsoil Requirements

Seed	lb/acre
Deleterious Materials (rock, gravel, slag, cinder, roots, sod)in the Total Sample	7 % maximum by weight
Organic Material in Portion of Sample Passing the No. 10 {2 mm} Sieve	2 % to 20 % by weight
Sand Content in Portion of Sample Passing the No. 10 {2mm} Sieve	10 % to 90 % by weight
Silt and Clay Content in Portion of Sample Passing the No. 10 {2 mm} Sieve	10 % to 90 % by weight
pH	5 to 7

Table 9: Productivity and Installation Rates of Different Materials

Material	Productivity Rates	Unit	Daily Output	Crew Description
Riprap	#4 Stone Fill	Ton	700	Crew B-11A + individual Pricing 1 Equip Op. - $42.85/hr 1 Laborer - $31.90/hr 1 Excavator, over 200HP - $90.84/day + $2.50/hr Op
	Geotextile Lining	SY	2,500	Crew B-1 1 Labor Foreman - $33.90/hr 2 Laborers - $31.90/hr (each)
TCBM	TCBM	SY	2,500	Crew B-11A + individual Pricing 1 Equip Op. - $42.85/hr 1 Laborer - $31.90/hr 1 Excavator, 90HP - $57.94/day + $2.14/hr Op
	Seeding: Field seed and fertilizer only	Acre	1.5	Crew B66 1 Equip Op (light) - $43.60/hr 1 Loader-Backhoe - $223.60/day
TRM	TRM: Synthetic erosion control, polypropylene mesh, stapled, 6.5 oz. / SY	SY	2,500	Crew B-1 1 Labor Foreman - $33.90/hr 2 Laborers - $31.90/hr (each)
	ECB	SY	2,500	Crew B-1 1 Labor Foreman - $33.90/hr 2 Laborers - $31.90/hr (each)
	Geotextile Lining	SY	2,500	Crew B-1 1 Labor Foreman - $33.90/hr 2 Laborers - $31.90/hr (each)
	Seeding: Topsoil placement and grading, loam or topsoil, fine grading and seeding, with equipment	SY	1,000	Crew B14 1 Labor Foreman - $36.35 4 Laborers - $34.35 1 Equip Op (light) - $43.60 1 Backhoe Loader, 48HP - $320.40/day
CCS	Cellular Confinement System	SY	1,600	Crew B-6 2 Laborers - $34.35 1 Equip Op (light) - $43.60 1 Backhoe Loader, 48HP - $320.40/day
	Geotextile Lining	SY	2,500	Crew B-1 1 Labor Foreman - $33.90/hr 2 Laborers - $31.90/hr (each)
	Seeding: Topsoil placement and grading, loam or topsoil, fine grading and seeding, with equipment	SY	1,000	Crew B14 1 Labor Foreman - $36.35 4 Laborers - $34.35 1 Equip Op (light) - $43.60 1 Backhoe Loader, 48HP - $320.40/day
	Backfill (by hand, no compaction)	LCY	14	Crew 1 Clab - $24.43 *Assume same crew ($97.70)
	Backfill (dozer, no compact)	LCY	1,200	Crew B-10B 1 Equip Op - $42.85/hr 1 Dozer, 105HP - $594.11/day + $34.02/hr Op

3.4 MAINTENANCE OF THE SYSTEM

Unfortunately, no system performs ideally and maintenance must be considered for any infrastructure installation. For riprap, ALDOT typically has an inspection rate of once every two years. These inspections are meant to simply check for loss of stone coverage and to ensure that there is no vegetation growing in the area. If there is vegetation, it is sprayed with herbicide to remove it. All other products in question should also be inspected once every two years, but rather than spraying for vegetation, these areas are allowed to grow. However, they do need to be mowed in order to ensure that crews can access the area if need be, for maintenance. The cost of these maintenance practices was calculated based on the NPV of these future expenses. See Equation (12)

$$\mathbf{NPV = P/A = A\frac{(1+i)^n - 1}{i(1+i)^n}} \qquad \textbf{(12)}$$

Where,

I	=	average rate of inflation
n	=	number of inspections or maintenance operations over 50 years
A	=	cost of maintenance operation

The cost of each operation was retrieved using RSMeans, the same database that was used for the installation cost and productivity rates.

3.5 MANNING'S EQUATION AND CHANNEL LINING ROUGHNESS

Controlling channel flow and velocity is important for conveyance systems. One of the most common equations used to calculate the flow of an open channel is Manning's Equation. This equation relates the geometry of a channel's cross section, the slope of the section, and even the roughness of the lining of the channel. See Equation (13).

$$\boldsymbol{Q = \frac{1.49}{n} AR^{2/3}\sqrt{S}} \qquad \textbf{(13)}$$

Where,

Q	=	Flow Rate (cf/s)
n	=	Manning's Roughness Coefficient (unitless)
S	=	Slope of Channel (ft/ft)
A	=	Flow Area (sf)
R	=	Hydraulic Radius (ft)

Manning's Roughness Coefficient, n, represents the friction or impedance of flow imposed by a lining material. In the case of most channels a high coefficient is desirable as it leads to slower flow velocity and therefore less stress imposed by the moving water. For this investigation the roughness coefficient for each material was determined in order to account for the anticipated friction and lower velocity of flow in a channel lined with each material.

3.6 RESILIENCY OF THE SYSTEM: SHEAR FORCE STRENGTH

ALDOT gives a standard detail for all classes of roadways within its network. With each of said cross sections, it includes the standard ditch dimensions running parallel to the roadway as follows ("Roadway Typical Section ALDOT"):

- Slope from roadway 6:1 (H:V)
- Slope from surrounding area 3:1 (H:V)
- Minimum Bottom Width of 4 ft
- Minimum Depth of 3.5 ft

These dimensions were used as the standard channel dimensions for analysis. Once these basic dimensions are known the shear exerted on a channel can be expressed by equation (14):

$$\boldsymbol{\tau_{max} = \gamma \times RH \times S} \qquad \textbf{(14)}$$

Where,

γ = unit weight of water (62.43 lb/cf)

RH = hydraulic radius = $\frac{cross\ sectional\ area}{wetted\ perimeter}$

S = Channel Slope

τ_{max} = 6.41 lb/ ft^2

All products in question were ranked higher than the given max shear for the channel, leaving riprap as the only material left to ensure that the shear could be matched or exceeded. The formula for permissible shear exerted on rock on diameter D50 is given by equation (15):

$$\boldsymbol{\tau_{permissible} = F^{*}(\gamma_s - \gamma)D_{50}} \quad \textbf{(15)}$$

Where,

F*	=	0.15
γ_s	=	density of stone (165 lb/cf)
γ	=	density of water (62.4 lb/cf)
D_{50}	=	Average Stone Diameter (1 ft)

$$\tau_{permissible\ class\ 2\ riprap} = \frac{15.39lb}{ft^2}$$

The following table shows all the permissible shear forces for the materials that were analyzed:

Table 10: Maximum Design Shear Force

Material	Shear (lb/sf)
Class 2 Riprap	15
Tied Concrete Block Mats	24
Turf Reinforcement Mats	10
Cellular Confinement System	18

3.7 SCORING MATRIX

Knowing the cost and timeline of installation, along with the projected maintenance costs of a system, is beneficial for project managers to know when estimating the total cost of an asset over its lifetime rather than just upfront costs. This can result in savings for their clients and for taxpayers who typically the primary source of funding for municipality infrastructure projects. The same goes for Manning's Roughness Coefficients and subsequent design flow of a channel for hydrologic engineers. These are characteristics that they base their system designs around and dictate how well an area will do during a storm event with regards to flooding. However, it is rare for these two disciplines to interact with each other when it comes to deciding what should be installed in the field. Typically, a water resource engineer designs a system for a given load and the contractor installs that system in the field while trying to minimize the overhead cost of the operation.

What this project aimed to do was implement a scoring matrix for these aspects of stormwater materials. Each aspect of the design of a stormwater system was given a score between 0 and 1.0. For example, for the Manning's Roughness Coefficients the lowest possible coefficient value was 0.01 and the highest was 0.15 for lined channels. These were given MAUT scores of 0 and 1.0 respectively and all other values were calculated based on the linear scale between these two extremes. This calculation can also be applied to speed of installation, cost of materials, runoff rates, and overall capacity rating. For characteristics such as construction cost, the scale was applied in a similar fashion, but the maximum and minimum values were set differently. The cheapest material was given the most desirable ranking of 1 and the least desirable was anything 15% more expensive than the riprap option, as this was a comparative analysis for alternatives to riprap. These scores were then weighted by importance depending on the desired traits for a given project. Figure 15 through Figure 18 show these utility functions as they were used in the analysis. Note that Figure 15 and Figure 16 show the relative relationship used for productivity and cost. These values change for each scenario and therefore varied by inputs.

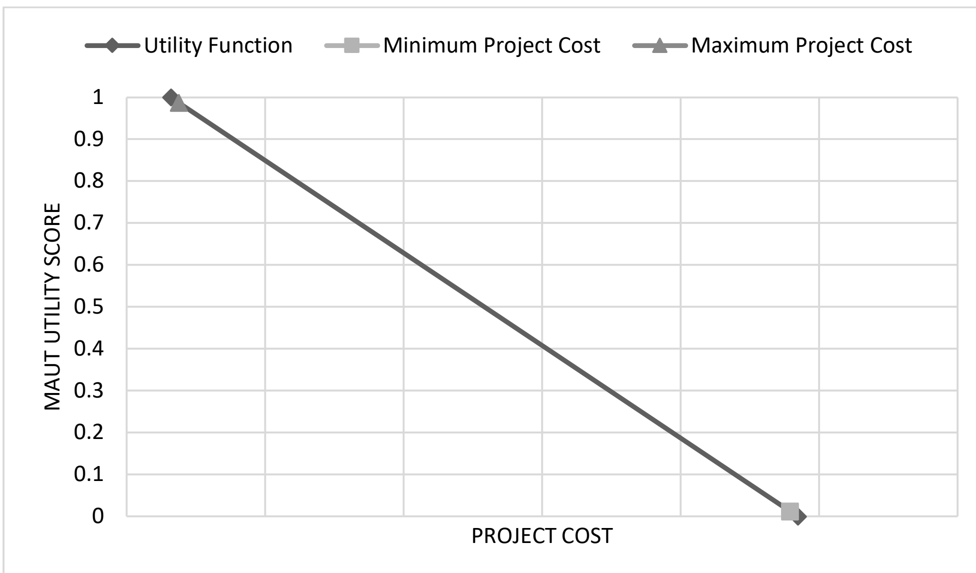


Figure 15: Example Utility Function of Project Cost

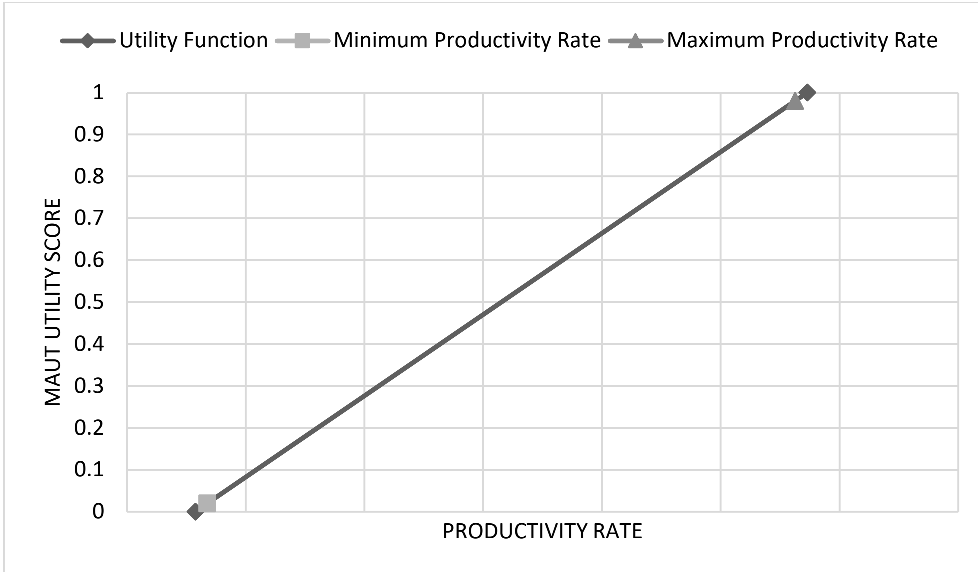


Figure 16: Example Utility Function of Productivity Rates for Installation

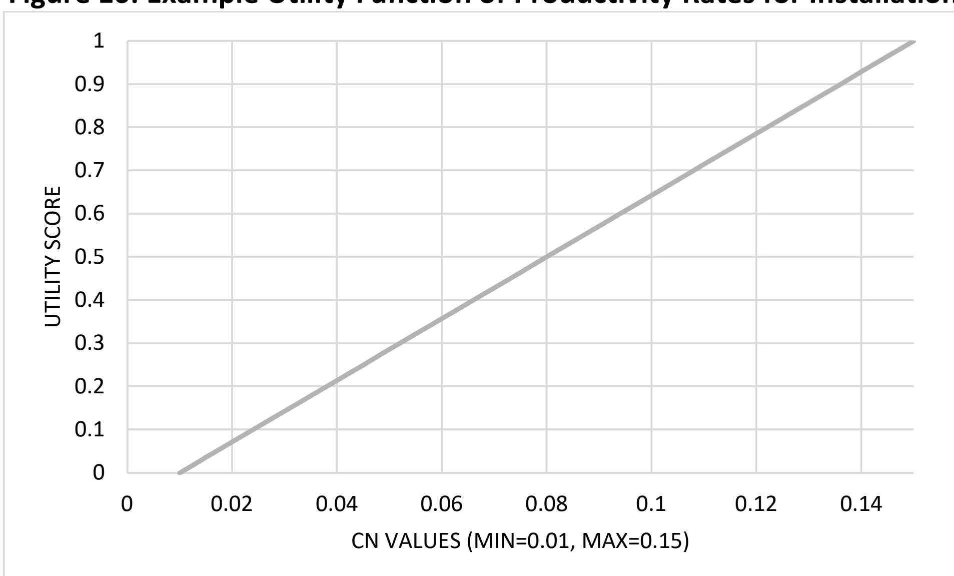


Figure 17: Manning' Roughness Coefficient Utility Function

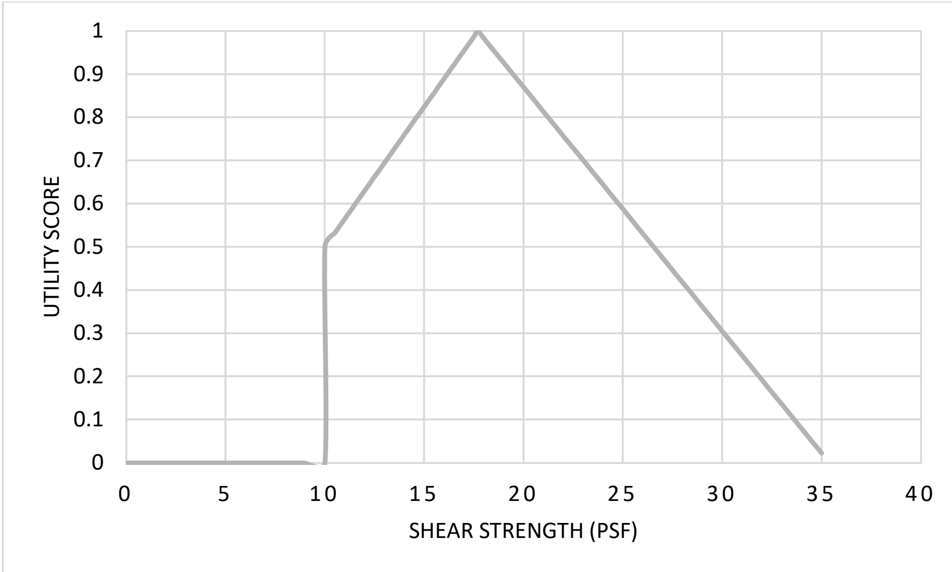


Figure 18: Shear Strength Utility Function

Figure 18 shows the only nonlinear utility function used in this analysis. The reason for its odd shape was due to the constraints placed on the shear strength requirements. All shear values under the 10psf minimum were given a score of 0. Meeting the minimum was a score of 0.5 with a perfect 1.0 being given to a strength of 15% greater than riprap's 15psf or 17.25psf. This shear value represented an ideal substitute with any over that being a "diminishing returns" scenario. More strength is always appreciated but over designing a system can result in overextended budgets for projects.

3.8 TWO ANALYSIS TECHNIQUES: SINGLE AND MULTI-ATTRIBUTE TESTING

To properly assess the four materials, it was determined that there would be two distinct analysis methods. The first of these would be direct, one-to-one comparisons of each characteristic of the materials. This would mean directly comparing the unit cost per square foot of each product as well as the maintenance, Manning's Roughness Coefficients, strength ratings, etc. However, some of these characteristics were varied geographically and/or by scale of the project. For example, the economies of scale for each product mean that the unit price would decrease as quantity increased. Therefore, each material would be assessed based on scale of the project and the geographic regions previously established by Arevalo. Next, because many of the individual characteristics of the materials did not share common units and each has a different potential importance level for a project, a MAUT analysis would be performed to evaluate the products on overall performance for all material characteristics.

Each material would be assessed for single and multi-attribute models. Each would look at the three project sizes based off of the ALDOT bid data for riprap projects. The formula for mean diameter of riprap to line a channel is shown in Equation (16):

$$\boldsymbol{t = 2 \times d_{50}} \qquad \textbf{(16)}$$

*thickness of rock mantle, 0.02 < S < 0.4 (Pitt, 2007)

Understanding that Class 2 riprap has an average diameter of 12" the design thickness of a riprap channel lined with class 2 stones would be 24". This was applied to all ALDOT bid project data to get equivalent areas that could be covered by the amount of stone purchased using Equation (17).

$$\boldsymbol{Area = \frac{ton \times \frac{2,000lb}{ton}}{\rho\,(1 - \%_{voids}) \times 2ft}} \qquad \textbf{(17)}$$

Where,

ρ = density of class 2 riprap (150 lb/cf)

$\%_{voids}$ = percent voids between stones (0.33)

Once the areas were retrieved, three values were extracted that were meant to represent projects of varying sizes. These values were the 1, 50, and 90 percentile values from the ALDOT bid data and were equal to approximately 10,000sf, 280,000sf, and 1,600,000sf respectively. These areas were then applied to the standard channel dimensions covered by the ALDOT standard cross section details. The dimensions of these six analysis projects can be seen in Table 11.

Table 11: Dimensions of Channels for Analysis

Project Area	10,000sf	280,000sf	1,600,000sf
Width	35.5'	35.5'	35.5'
Left Side Slope	3:1	3:1	3:1
Right Side Slope	6:1	6:1	6:1
Length	275'	7,701'	44,007'
Bottom Width	4'	4'	4'

After the sizing parameters were set, the regional geographic differences were accounted for by the regions created in Arevalo's analysis. Once again, due to the unchanged supply chain of materials and no new major arterial roadways being built since that analysis this was assumed to be an ideal group to account for geographic variance in riprap and its alternatives. These locations were represented by finding the county that occupied the approximate center of each region. See Table 12 and Figure 19.

Table 12: Counties Selected as Representative Samples for Regions

Region	County
1	Lawrence
2	Shelby
3	Butler
4	Mobile

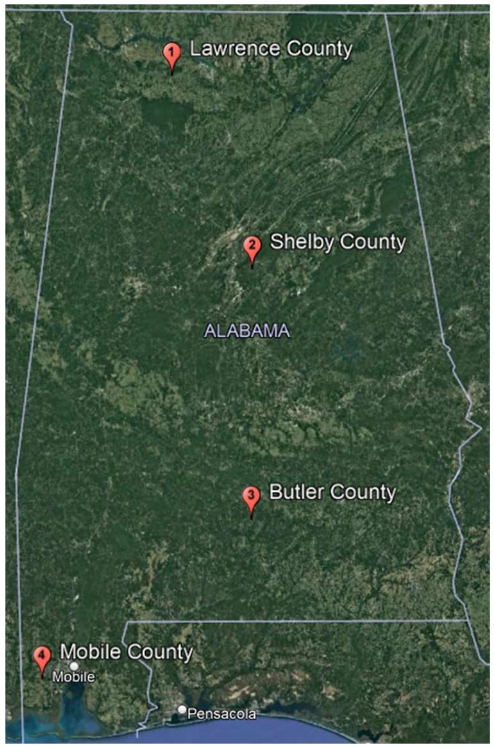


Figure 19: Map of Hypothetical Project Locations

An analysis of each material characteristic and was run for the three project sizes in each region and then two MAUT tests were run. The first was set so that each characteristic was of equal weight of importance and the other was meant to simulate the priorities of a DOT when considering a project. Table 13 shows the weights used for that evaluation.

Table 13: Realistic Priority List

Metric	Priority (0-10)
Construction Cost $	10
Installation Time (hr)	4
Maintenance Cost (NPV over 50 years)	6
Maintenance Time	1
Shear Strength (psf)	10
Flow Impedance (Manning's Coefficient)	3

These MAUT evaluations were meant to create a cumulative analysis of all the characteristics of each material. Riprap provides a high roughness coefficient and shear strength but may not be cost effective in all aspects. Likewise, materials such as CCS and TRMs may not provide the strength required but are much more easily installed and cheaper than riprap. These MAUT evaluations would account for these differences and rank the materials based on the desired qualities from the priority list.

3.9 CHANNEL ARMORING MATERIAL SELECTOR TOOL

The value of this analysis and the MAUT scoring system developed for it cannot be understated. The balance between performance and cost has always been the guiding task of engineers. While most would like to build water resources to rival the Roman aqueducts of antiquity, it is unlikely for a given municipal government of today to possess the capital to do so. In light of this, the evaluation and scoring system created is invaluable to meeting departmental budget requirements. However, if this paper does not cover a particular material or condition that a municipality is or is not concerned about, then what? Furthermore, the individual evaluations show the overall differences in each category by project scale and location, but the weights given in the MAUT analysis can vary by interested party. It is important that a different analysis be performed on a case-by-case basis. To help mitigate this problem a comprehensive program was written to aid engineers and contractors to implement the systems from these previous chapters.

3.9.1 Channel Armoring Material Selector: A Comprehensive Design Aid

Channel Armoring Material Selector (CAMS) is a spreadsheet-based program that utilizes the processes covered previously and combines them into a user-friendly design tool for stormwater systems. The user simply enters the parameters of a project, such as dimensions of the channel in need of erosion control, the size of the watershed, what county it is located in within AL, along with importance ratings for different aspects such as cost and time. The system will then use the catalog of processes outlined previously to make a suggestion of which material should be used for that project. Furthermore, CAMS has a “Custom Material” function that allows the user to enter in the general characteristics and dimensions of a new material to compare it to the existing catalog of materials already in the system. This allows users to make use of CAMS even as the market changes in the future.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 INTRODUCTION

This section looks at the results of the comparative analysis conducted to facilitate a more cost-effective and efficient decision process for material selection for channel armoring along ALDOT roadways. A total of 12 hypothetical projects were created. These projects were for channel protection, that covered three project sizes for areas of 10,000sf, 280,000sf, and 1,600,000sf for each of the four analysis regions. The following six characteristics were evaluated for these projects: construction cost, construction time, maintenance cost (calculated as Net Present Value over a 50-year period), maintenance time (how long each inspection and vegetation control practices will take), shear strength of material, and Manning's Roughness Coefficient of each material. These were evaluated both individually and as part of a Multi-Attribute Utility Theory analysis or MAUT. The MAUT analysis looked at two scenarios. One where all material characteristics were weighed equally in importance and the second as a simulated rank of importance to that of a typical DOT when deciding on a project. This gave investigators the ability to analyze how each characteristic was affected by project scale and geography and then how all of these characteristics contributed to each material's overall desirability in different scenarios. This MAUT systems was then developed into a spreadsheet-based program called the Channel Armoring Material Selector (CAMS) so that practitioners can utilize and expand on the work conducted here.

4.2 RESULTS OF SINGLE ATTRIBUTE ANALYSIS

All six attributes of the materials were analyzed on an individual basis to see which material performed best in each category. After analyzing the results, it was discovered that installation time, maintenance time and cost, shear strength and Manning' Roughness Coefficients were not affected by project size. This intuitively makes sense because all of these characteristics are dependent on crew efficiency and material properties.

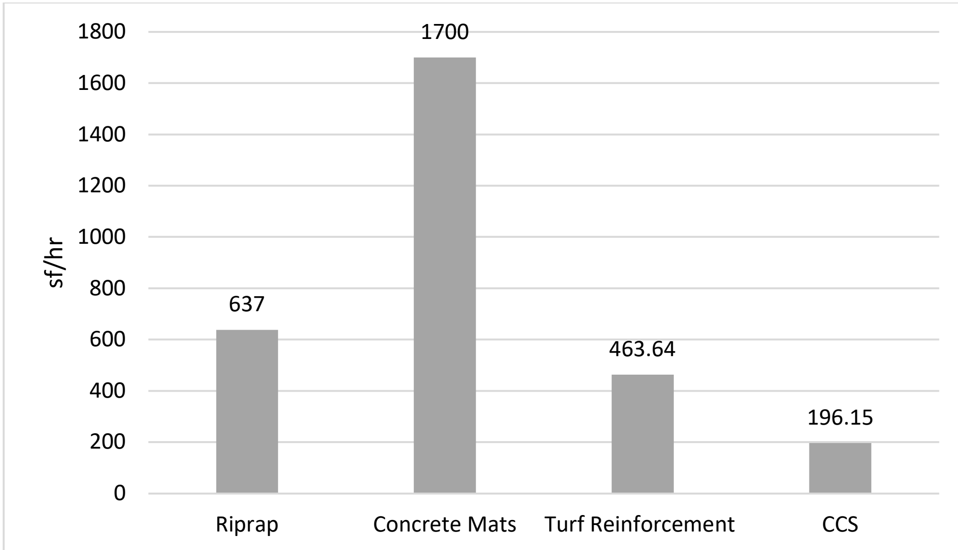
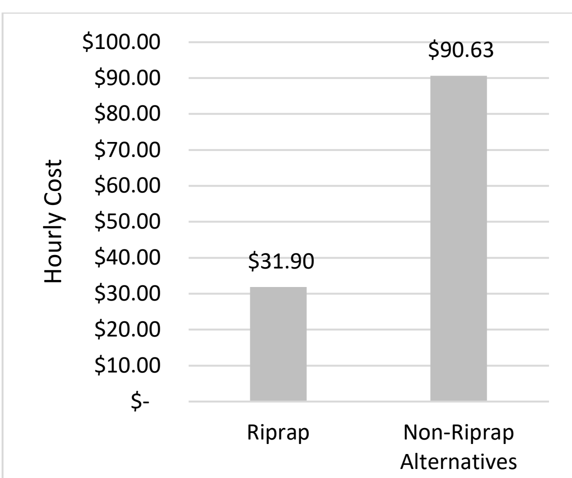
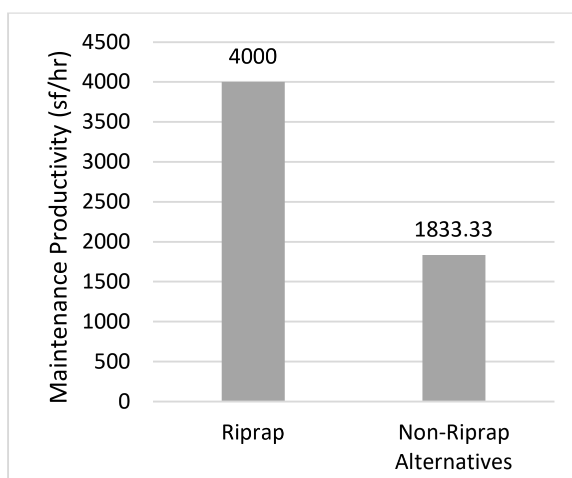


Figure 20: Installation Productivity Rates of Each Material

The installation productivity rates seen in Figure 20 show the coverage that can be installed of each material per hour of installation. Riprap involves the installation of a geotextile and base layer of No. 4 ALDOT stone and then the placing of the riprap itself. The entire operation is limited by the rate at which class 2 riprap can be placed by an excavator operator. This value is reflected in Figure 20. Likewise, cellular confinement systems are also limited by the slowest process of installation, which is backfilling the cells with a bulldozer. Tied concrete block mats and turf reinforcement mats are both rolled out over an area and either trenched or staked down. However, the anchoring process is much more intensive for the lightweight TRMs and very limited for the heavier TCBM. TRMs also include topsoil and seeding in their installation process which severely slows the overall production.



a) Hourly Rate for Maintenance of System



b) Productivity Rate for Maintenance

Figure 21: Results of Maintenance Single Attribute Analysis

Figure 21 shows the associated maintenance characteristics of the four materials in this investigation. Riprap requires vegetation controls such as spraying herbicides, while all of the other practices (labeled "Rolled Erosion Control Practices" Figure 21) encourage plant growth but do require mowing to ensure the areas in question do not become overgrown. Figure 21 shows the hourly cost of inspecting and maintaining each system. Mowing is more labor and equipment intensive than spraying herbicides and is reflected in the costs shown. It also shows the productivity rates of the maintenance practices. This is shown as the hourly rate for spraying herbicide or mowing. These two characteristics play into each other as the cheaper rate and faster application of spraying vegetation compounds into a much cheaper cost per square foot to maintain. Table 14 shows these relationships:

Table 14: Maintenance Costs and Productivity Rates

Material	Hourly Cost	Coverage Rate (sf/hr)	Cost per Acre
Riprap	$31.90	4,000	$347.39
Alternatives	$90.63	1833.34	$2,153.36

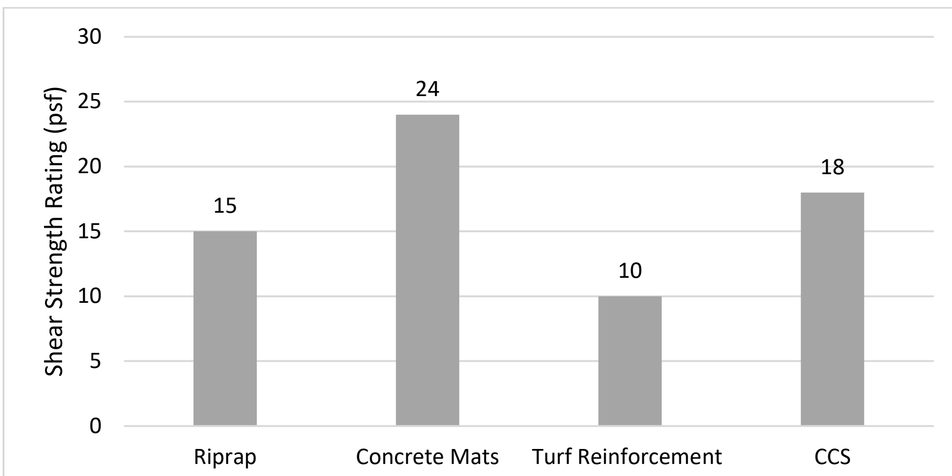


Figure 22: Shear Strength of Each Material

Figure 22 shows the rated shear strength of each material. ALDOT requires that any substitute for riprap be able to handle at least 10psf of shear. The Recyclex TRM from American Excelsior meets this minimum requirement with all other products rated for higher than this mark. Class 2 riprap shear strength was determined using the standards from two different sources (FHWA, 2005) (Pitt, 2007). Given that this was a constant value regardless of geography or scale of a project these values could be directly compared to one another. When entered into the MAUT analysis, this value was altered slightly to reflect the idea that more strength is desirable until a threshold of 15% increase to riprap's shear strength is met. After that point increasing strength is subject to diminishing returns. See Figure 18.

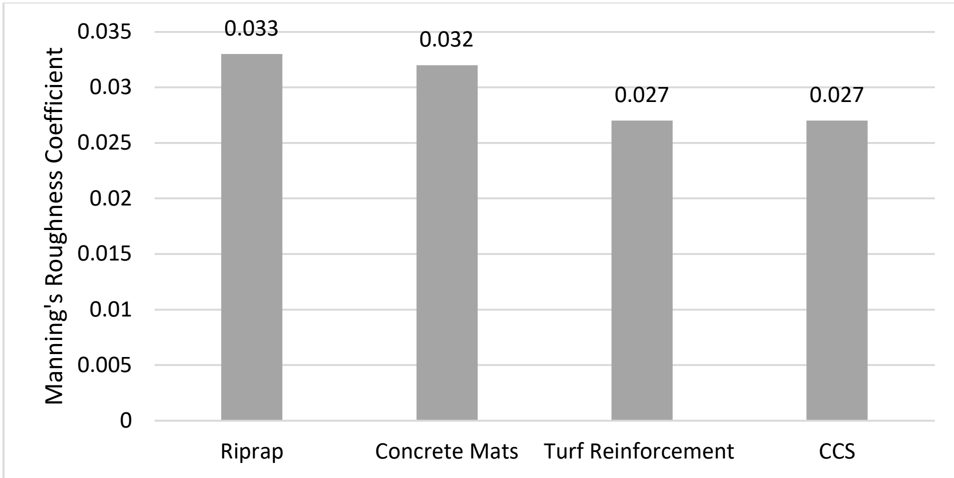


Figure 23: Manning's Roughness Coefficient by Material

Figure 23 shows the Manning's Roughness Coefficients for each material analyzed. The Manning's Coefficient values show the relative roughness of a given channel lining, which in turn can be used to calculate the flow in that channel. A higher value represents a rougher material and therefore a lower flow rate. These values are constant for a given material and therefore are not dependent on scale or location of the project in question. Of the four materials analyzed riprap had the highest Manning's Coefficient meaning it has the slowest flow rate (Manning's n for Channels, 2006). This was followed by turf reinforcement mats and cellular confinement systems which line a channel with natural vegetation. Finally, tied concrete block mats had the lowest roughness coefficient given the smoothness of the blocks and relatively low amount of vegetation. These values can inform a designer that may wish to slow flow for a given channel by reducing the velocity of the water.

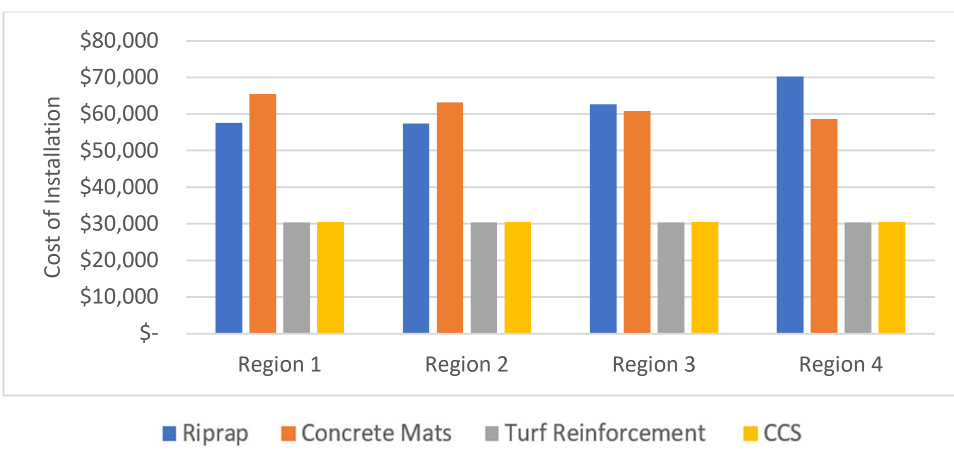


Figure 24: Cost of Installation by Region (10,000 sf Project)

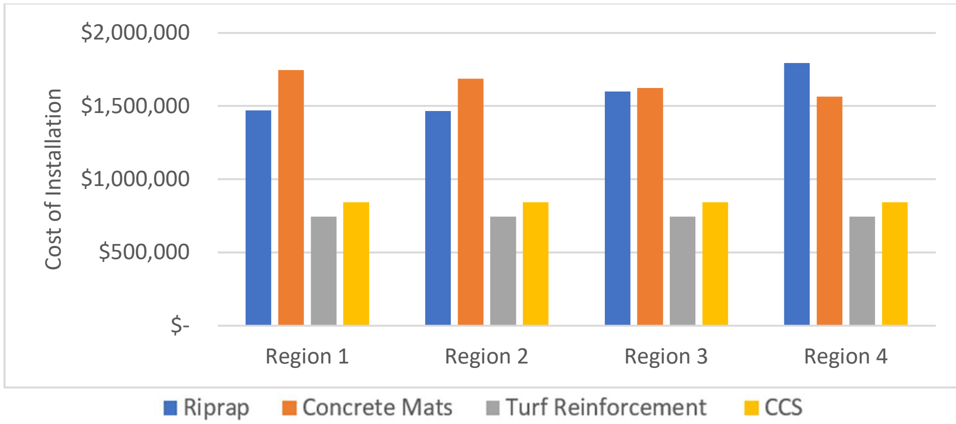


Figure 25: Cost of Installation by Region (280,000 sf Project)

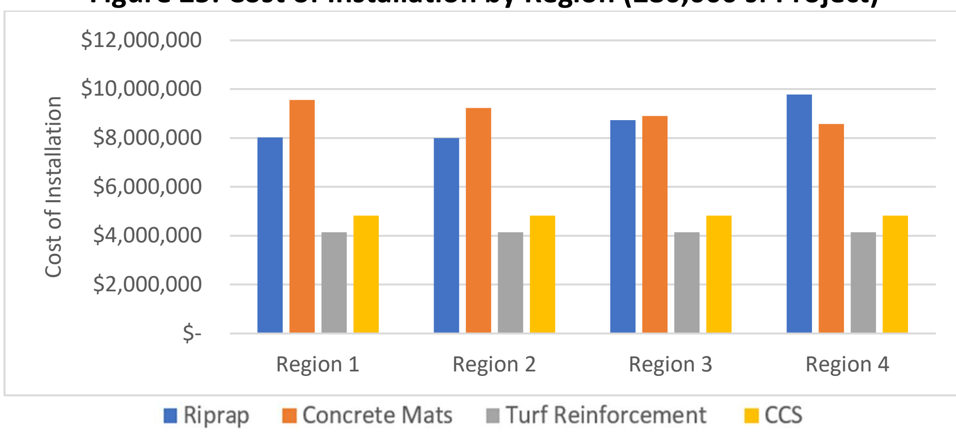


Figure 26: Cost of Installation by Region (1,600,000 sf Project)

Figure 24, Figure 25, and Figure 26 shows the trends of project installation costs across the four regions of the study, along with changing project sizes. The figures show that turf reinforcement mats are, across the board, the most cost-effective material to install on a cost-per-square-foot basis. However, at small scale projects it becomes even with CCS. The figures also show that the geographic link between riprap unit price has an effect on its overall cost by region. In every case shown in Figures 24, 25, and 26, riprap is cheaper than tied concrete block mats in the northernmost region of the state, Region 1. However, as the projects move further south (ascending order of regions) riprap becomes more expensive and less cost-effective. This gap in prices only becomes more pronounced as project scale increases.

The results of this individual characteristic analysis show that each material has its own advantages and disadvantages. Riprap is incredibly easy to maintain, has a relatively high installation productivity rate, and offers approximately 15 psf shear strength. However, it is one of the more expensive materials when it comes to initial installation. Tied concrete block mats have incredibly high shear strength and can be installed quickly in the field, but do not allow for high water infiltration and are more expensive to maintain than riprap. Turf reinforcement mats are cheaper to purchase. However, their low shear strength and maintenance cost, along with extensive installation process may not make them applicable for all scenarios. Finally, cellular confinement systems are slow to install and relatively expensive to maintain in comparison to riprap, but they do offer the second-best shear strength rating and high infiltration rates. The variability of these different characteristics prompted investigators to conduct a Multi-Attribute Utility Theory analysis for the different materials to assess their overall effectiveness.

4.3 RESULTS OF MULTI-ATTRIBUTE UTILITY THEORY ANALYSIS: M.A.U.T.

To properly account for all six characteristics of each material being assessed, investigators conducted a Multi-Attribute Utility Theory analysis, known as MAUT. A MAUT analysis is useful because it takes multiple inputs with different units of measurement and simplifies these into a comprehensive score for each material. These scores are then based on individual importance rankings of each characteristic and benchmark performance criteria set by the available range of the materials. The MAUT system for this investigation ranked each individual characteristic on a zero to one scale then applied an importance weight to each before summing the total of all attributes to produce an overall score for each material on the same zero to one scale.

Two scenarios were calculated for the materials. The first was an "all things equal" scenario, in which all attributes of the material were weighed equally in importance. The result of this would be a ranking of each material by its overall performance for all characteristics in question.

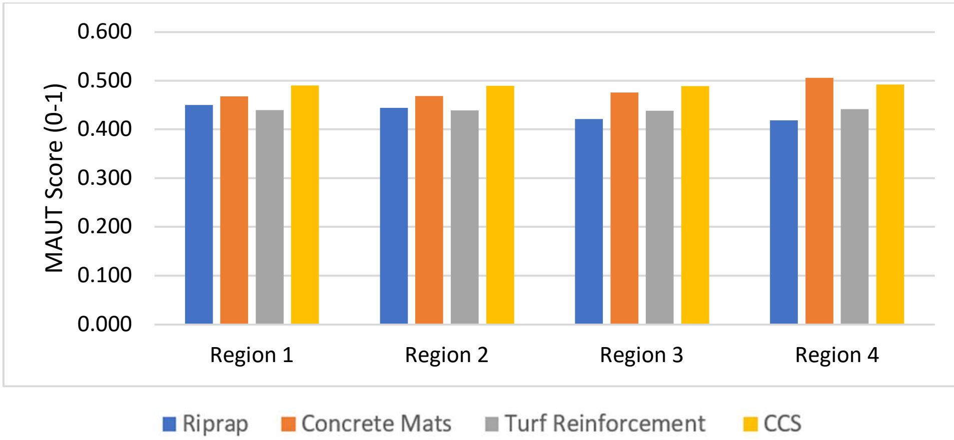


Figure 27: MAUT Scores of Materials with Equal Importance Weights (10,000sf)

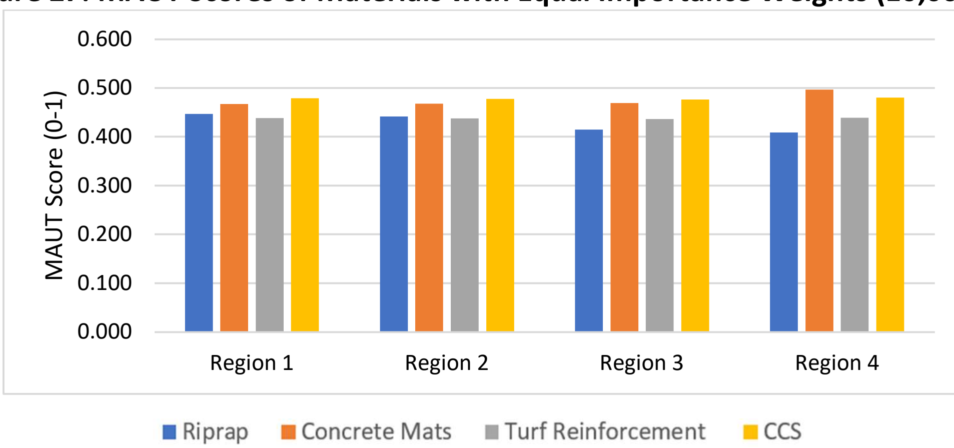


Figure 28: MAUT Scores of Materials with Equal Importance Weights (280,000sf)

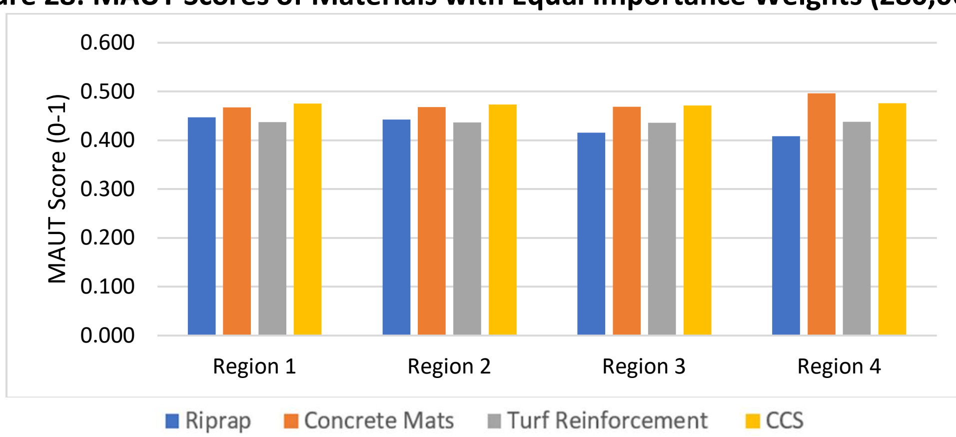


Figure 29: MAUT Scores of Materials with Equal Importance Weights (1,600,000sf)

As seen in Figure 27, Figure 28, and Figure 29 for channel applications, CCS scored the highest overall, with the exception of region 4 which TCBM performed better in. This was likely since TCBM are cheapest in the southern regions of the state due to their distribution stemming from this region. This also shows that CCS is a material with a good balance of all characteristics in question. Finally, there was also low variance by project size, suggesting that the low emphasis on construction cost can create a near uniform distribution of MAUT scores. These results, while useful, do not reflect the typical importance rankings given to these characteristics by DOTs when considering potential projects. Therefore, a second test was needed to simulate this.

The second scenario was meant to simulate the weight of importance that a DOT would appoint to each material characteristic when deciding what type of material to use. The weights associated with this scenario are shown in Table 15:

Table 15: Weights Associated with a Typical DOT Decision Matrix (0-10 scale)

Metric	Importance
Construction Cost $	10
Installation Time (hr)	4
Maintenance Cost (NPV over 50 years)	6
Maintenance Time	1
Shear Strength (psf)	10
Manning' Roughness, n	3

As from Table 15 DOTs typically value higher performance (strength) and low cost of installation. This is followed by maintenance cost, installation time, roughness of material, and maintenance time. A second MAUT analysis was performed using these weights and the results were as follows:

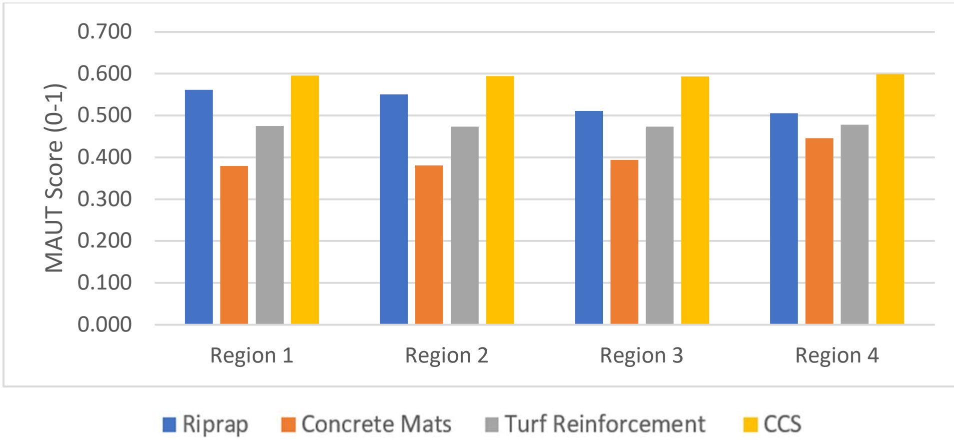


Figure 30: MAUT Results of Medium Project with Realistic Weights Scenario (10,000sf)

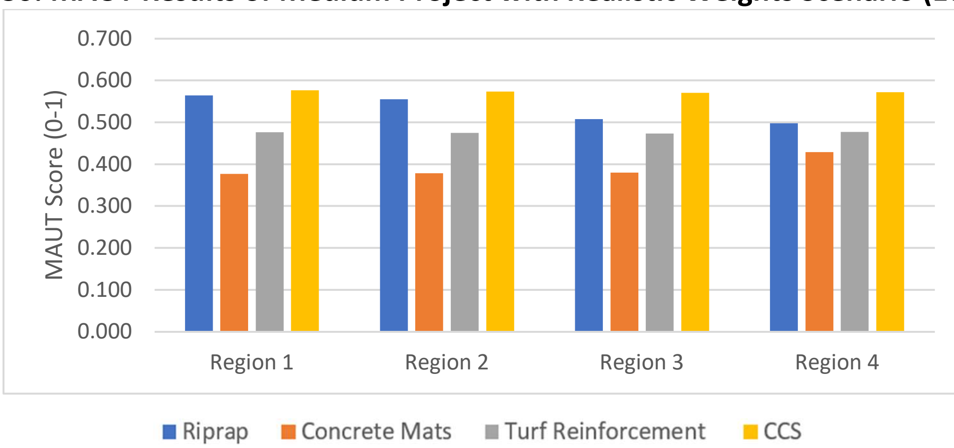


Figure 31: MAUT Results of Medium Project with Realistic Weights Scenario (280,000sf)

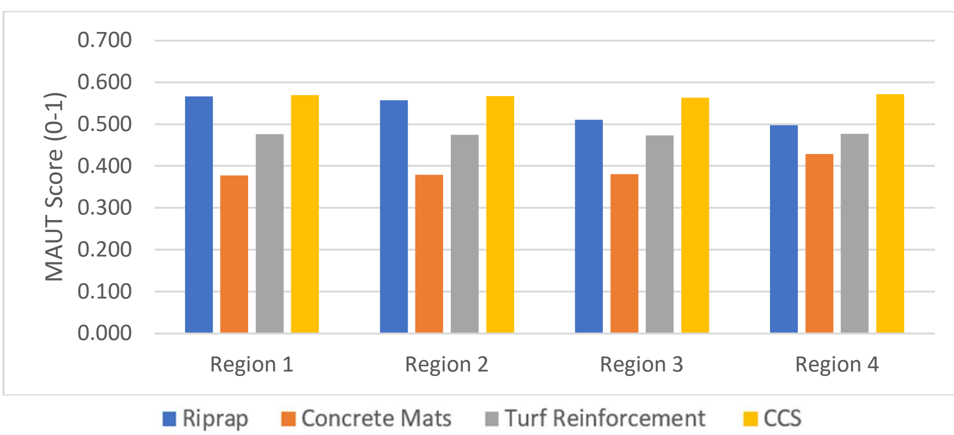


Figure 32: MAUT Results of Large Project with Realistic Weights Scenario (1,600,000sf)

As one can see from Figure 30, Figure 31, and Figure 32 the results of this simulation revealed the effectiveness of CCS as a potential alternative to class 2 riprap. While CCS was the best overall, this scenario also showed that riprap is still a valid option in northern regions of the state but less so in the south as its unit price increases. Riprap was second overall, however as the projects move south it becomes closely tied with TRM. With this small of a difference it becomes clear that altering the importance weights of the MAUT analysis has the potential to alter the outcome of the suggestion. With this in mind the Channel Armoring Material Selector tool was created to give users the ability to alter these weights and inputs for themselves.

4.4 ANALYSIS

This analysis showed that the materials analyzed all varied in performance in each category. This is typical as most engineered products are created with a specific goal in mind. For example, TRMs and CCS are primarily meant to protect soil from erosion until permanent vegetation is able to develop extensive root systems, whereas riprap and TCBMs are meant more as erosion armoring for channels. The MAUT tests were run to compare the four materials based on a cumulative score of all 6 characteristics of construction cost, construction time, maintenance cost, maintenance timeline, strength of material, and lining roughness. The first showed that if all attributes were considered equally then CCS would be the recommended material for all projects regardless of location and project size. These were followed by riprap, then TCBM and finally TRM. However, the second MAUT test simulated importance rankings similar to that of a typical DOT and the results were more varied. CCS still scored the best overall but TCBM and riprap had more variability by region. Riprap was the second ranked material in region one but as the projects move south block mats begin to overtake and outperform riprap. This is due to the geographic relationship between riprap unit prices and concrete block mats. Concrete block mats are distributed from the south while riprap comes from primarily the northern half of the state. This means that TCBMs are less expensive in the south and riprap is less expensive in the north.

As these results suggest, the recommended material for a given project can change drastically based on the location of the work being performed and the personal preference of the client and contractor. As a result, it was decided to use the analysis tools created for this investigation and write a computer program that could be used by a contractor or potential client to assess the best materials to use given these parameters and the geometry of the project itself. Channel Armoring Material Selector (CAMS) is a spreadsheet-based program that takes user inputs and suggests the best material to be used, based on the analysis methods developed for this comparative analysis. The resulting tool can be applied to any project and use the best materials for a client or contractor's personal preference that still is structurally sound enough to perform the task in question. Figure 33 shows the home screen of the program.

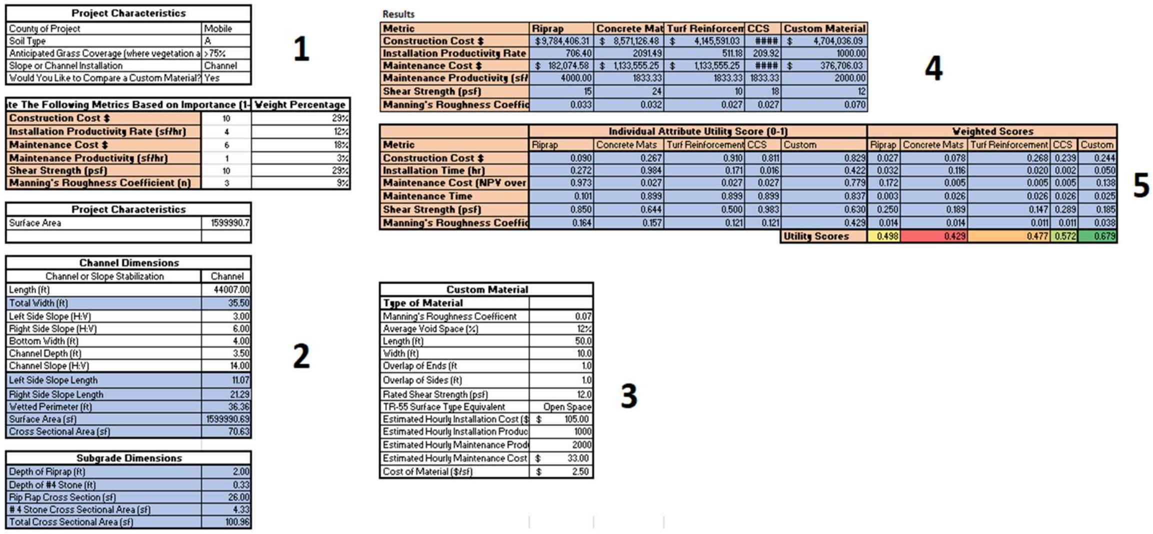


Figure 33: Main Input Screen of CAMS Program

In CAMS the user can alter all values in white cells and the blue values are calculated based on the project parameters entered by the user. The user can decide the location, soil characteristics, and anticipated vegetation coverage of the project. Once these values are added the user can select the importance ranking for each of the six material characteristics from the analysis. Finally, the user is asked to enter the geometric parameters of the channel to be armored so that the necessary quantities can be calculated for each material. The result is a list of each of the six characteristics of the materials as well as a list of the material quantities needed for the project entered. Finally, a MAUT score is given for each characteristic and the overall effectiveness of each material given the importance weight entered by the user.

4.4.1 CAMS Walkthrough

The Channel Armoring Material Selector (CAMS) is meant to be used by future project managers in Alabama to ensure they use the most effective material for armoring a channel. Figure 33 shows the main screen of the program. In the top of the first column the user is asked to enter in the project characteristics and importance rankings, shown in Figure 34. The county, soil type and anticipated grass coverage are used to retrieve rainfall data and anticipated runoff into the channel being created. The importance ratings are used for the MAUT scoring process.

Project Characteristics	
County of Project	Mobile
Soil Type	A
Anticipated Grass Coverage (where vegetation allowed)	>75%
Would You Like to Compare a Custom Material?	Yes

Rate The Following Metrics Based on Importance (1-10)		Weight Percentage
Construction Cost $	1	17%
Installation Time (hr)	1	17%
Maintenance Cost (NPV over 50 years)	1	17%
Maintenance Time	1	17%
Shear Strength (psf)	1	17%
Manning's Roughness Coefficient (n)	1	17%

Figure 34: Project Location and Characteristics Importance Ranking Inputs (1)

Once these are entered the user is directed to enter in the dimensions of the channel in question. See Figure 35. These inputs are used to determine the maximum flow in the channel for shear strength requirements and to determine the amount of material needed to armor the channel.

Channel Dimensions	
Channel or Slope Stabilization	Channel
Length (ft)	44007.00
Total Width (ft)	35.50
Left Side Slope (H:V)	3.00
Right Side Slope (H:V)	6.00
Bottom Width (ft)	4.00
Channel Depth (ft)	3.50
Channel Slope (H:V)	14.00
Left Side Slope Length	11.07
Right Side Slope Length	21.29
Wetted Perimeter (ft)	36.36
Surface Area (sf)	1599990.69
Cross Sectional Area (sf)	70.63

Figure 35: Channel Geometry Entry for Uses (2)

If the user selects the custom material option from Figure 34 they are also asked to enter the characteristics of another hypothetical alternative. The entry screen requires the user to enter most of the data that is determined by the program for the other four materials. See Figure 36. The main purpose is to incorporate new alternatives into the MAUT evaluation, not to determine the characteristics of the given material.

Custom Material	
Type of Material	**Rolled Erosion Control Practice**
Manning's Roughness Coefficent	0.07
Average Void Space (%)	12%
Length (ft)	50.0
Width (ft)	10.0
Overlap of Ends (ft	1.0
Overlap of Sides (ft)	1.0
Rated Shear Strength (psf)	12.0
TR-55 Surface Type Equivalent	Open Space
Estimated Hourly Installation Cost ($/	$ 105.00
Estimated Hourly Installation Product	1000
Estimated Hourly Maintenance Produ	2000
Estimated Hourly Maintenance Cost ($	$ 33.00
Cost of Material ($/sf)	$ 2.50

Figure 36: Custom Material Entry Screen (3)

Once all the entries are made the user is presented the raw values for each material. This allows the user to see how the single attributes compare to one another before the MAUT scores are assigned. Figure 37 shows an example of this.

Results

Metric	Riprap	Concrete Mats	Turf Reinforcement	CCS	Custom Material
Construction Cost $	$ 70,221.26	$ 58,572.75	$ 30,387.29	$ 30,453.55	$ 31,025.06
Installation Productivity Rate (sf/hr)	666.56	1666.39	476.11	204.05	1000.00
Maintenance Cost $	$ 1,137.79	$ 8,788.92	$ 8,788.92	$ 8,788.92	$ 2,354.04
Maintenance Productivity (sf/hr)	4000.00	1833.33	1833.33	1833.33	2000.00
Shear Strength (psf)	15	24	10	18	12
Manning's Roughness Coefficient (n)	0.033	0.032	0.027	0.027	0.070

Figure 37: Results Screen (4)

Directly beneath the single attribute results are the MAUT utility scores. These scores show how each material performs relatively to each other and their overall weighted scores based on the desired characteristics that the user inputs. These weighted scores are displayed with a color-coded display to show the desired material in green and least desired in red. Figure 38 shows an example of this.

	Individual Attribute Utility Score (0-1)					Weighted Scores				
Metric	Riprap	Concrete Mats	Turf Reinforcement	CCS	Custom	Riprap	Concrete Mats	Turf Reinforcement	CCS	Custom
Construction Cost $	0.093	0.331	0.907	0.906	0.894	0.027	0.097	0.267	0.266	0.263
Installation Time (hr)	0.324	0.980	0.199	0.020	0.543	0.038	0.115	0.023	0.002	0.064
Maintenance Cost (NPV over 50 years)	0.979	0.021	0.021	0.021	0.826	0.173	0.004	0.004	0.004	0.146
Maintenance Time	0.101	0.899	0.899	0.899	0.837	0.003	0.026	0.026	0.026	0.025
Shear Strength (psf)	0.850	0.644	0.500	0.983	0.630	0.250	0.189	0.147	0.289	0.185
Manning's Roughness Coefficient (n)	0.164	0.157	0.121	0.121	0.429	0.014	0.014	0.011	0.011	0.038
					Utility Score	0.506	0.446	0.478	0.599	0.720

Figure 38: MAUT Scores (5)

CAMS is a tool that has the potential for real-world applications with the Alabama DOT and contractors in the state. The assessment of potential materials for use in construction projects is always a challenging task for estimators. Having a means to assess to the overall effectiveness of materials that accounts for performance and cost in a cumulative manner would be invaluable for project managers in future projects. However, for CAMS to be the best tool possible the catalog of materials and applications must be expanded to deliver the best encompassing projection of potential materials for use in not just channel armoring but in all aspects of erosion control and construction at large.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This investigation analyzed possible alternatives to class 2 riprap to facilitate a more cost-effective and efficient decision process for material selection for channel armoring. The motivation for this was to ensure that Alabama Department of Transportation (ALDOT) projects are utilizing materials that are both structurally sound and cost-effective. In addition, this analysis also considered secondary characteristics, such as lining roughness and long-term maintenance cost, for the infrastructure being installed. This analysis looked at individual attribute values and then combined them into a Multi-Attribute Utility Theory test to evaluate all characteristics of a given material in a cumulative manner. This analysis method was then used to create a computer program that could be used by DOTs, contractors, and other clients to select the best material for their desired project outcome.

Cost data for riprap installations was collected from ALDOT bid tabulations dating from January 2020 to November 2021. This data was used to create a regression function to model the economies of scale for class 2 riprap in the state. All other product unit prices were obtained by contacting distributors and manufacturers directly as no bid tabulation data existed for these products. Specification sheets for each product were used to determine installation cross sections as well as rated shear strength of each product. For riprap, this strength was determined using the FHWA Hydraulic Design Manual from Roadside Channels (FHWA, 2005). Rates of production and maintenance were collected from RSMeans (Gordian, 2022), an online database commonly used in the industry for construction bid creation. Finally, equivalent roughness was determined using the coefficients from Manning's Equation (Manning's n for Channels, 2006). All material characteristic values were evaluated over 4 regions from Arevalo's county map and over three project sizes based on the equivalent area that could be covered by historic riprap bid data. These individual attributes were combined for a cumulative score using Multi-Attribute Utility Theory (MAUT) tests to give an overall ranking of each material for a given region and project size.

The individual characteristics of each material revealed the strengths and weaknesses of each. Some were engineered as armoring materials such as riprap and tied concrete block mats, while others were created to protect soil allowing permanent vegetation to germinate such as turf reinforcement mats and cellular confinement systems. These individual characteristics were assessed in a combined score for each material over the four analysis regions and project sizes in a MAUT model. This model showed that given equal importance of all six characteristics cellular confinement systems (CCS) were the best overall product to be used in the state of Alabama regardless of project location or size. However, this was determined to not be a "realistic" scenario, leading to a second MAUT model being created for this purpose. The realistic scenario valued construction cost and strength higher than characteristics such as maintenance and roughness of lining material. The results were more varied than before, but CCS still outperformed the other materials. However, there was more variability in the other three materials based on the region of the project due to the geographic relationship of TCBM and riprap unit prices.

The analysis methods developed in this experiment were utilized to create an Excel based computer program that could be used by interested parties in selecting a project's erosion control materials. This program, named Channel Armoring Material Selector (CAMS), is meant to be adopted in industry after publication of this paper. ALDOT was the original party that expressed interest in this analysis, and CAMS should be introduced to ALDOT representatives to serve as an industry tool for future projects. Furthermore, the analysis tools outlined in this paper are meant to be expanded upon. Other aspects of materials could be considered such as a life cycle assessment of the environmental impacts from the manufacturing, transportation, installation, service life, and replacement of the materials. Also, the catalog of materials should be expanded to include all commercially available erosion control practices in Alabama enabling the absolute best material to be used for each application.

This analysis is meant to be a starting point for further analysis. The catalog of materials, assessment characteristics, and MAUT model are not complete and can be built upon in future work. Currently the models are limited by the catalog of materials and the applications that they were designed for in the analysis. It is hoped that industry professionals will find CAMS a useful design tool and continue to grow it just as programs like LCA Pave and others have done. If further development occurs there is a likelihood that these models could be transferred to other construction applications beyond erosion control. It is the duty of construction engineers to continuously strive to find the best materials for use in infrastructure implementation. Tools such as CAMS aim to aid in that process and continue to improve the effectiveness of future projects.

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