Shear strength of shredded tires as applied to the design and construction of a shredded tire stream crossing

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Shear strength of shredded tires as applied to the design and construction of a shredded tire stream crossing

by

Megan Alissa Gebhardt

A thesis submitted to the graduate faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Civil Engineering (Geotechnical Engineering)
Major Professors: Dr. Bruce H. Kjartanson and Dr. Robert A. Lohnes

Iowa State University
Ames, Iowa
1997
Graduate College
Iowa State University

This is to certify that the Master's thesis of

Megan Alissa Gebhardt

has met the requirements of Iowa State University

Signatures have been redacted for privacy
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CHAPTER 1.
INTRODUCTION

Scrap tire stockpiles have grown in the United States leading to a significant disposal problem. The most recent survey conducted by the Scrap Tire Management Council reported that 850 million tires are stockpiled in the United States, with an additional 250 million tires still being generated each year (1995). Despite the dramatic 44% increase in scrap tire markets between 1990 and 1994, proper management of scrap tires is still a major solid waste management issue.

The use of scrap tires in civil engineering applications has been found to give both cost and engineering benefits in several projects. In these applications, the scrap tires have replaced natural resources used in construction and have often been found to perform better than the material they replace. “However, there are still several impediments to a broader civil engineering use of scrap tires including: lack of standard engineering data, unclear long term environmental implications, and the experimental nature of most major projects to date” (Scrap Tire Management Council, 1995, p 9).

Tires yield properties such as high frictional resistance, strength and resiliency. These properties can be used beneficially in construction, often at a lower cost than other materials. “Recent research indicates that shredded tires do not show any likelihood of being a hazardous material or having adverse effects on groundwater quality” (Scrap Tire Management Council, 1995, p 9).

The research described herein investigates the shear strength of shredded tires ranging from 40 mm to 1.4 m in length. The shear strength properties interpreted are used in a stability analysis for a shredded tire stream crossing. Design issues for the stream crossing are defined for this analysis. The shear strength properties have been investigated for pure tire shreds as well as tire shreds in contact with glacial till.
CHAPTER 2.
BACKGROUND AND LITERATURE REVIEW

2.1 Scrap Tire Problem

2.1.1 The Generation of Scrap Tires

The scrap tire problem in the United States is due to two principle factors. The first key factor is the large increase in the number of automobiles coupled with the use of radial tire technology in tire fabrication which uses little to no reclaimed rubber. Secondly, the price of plastic substitutes for reclaimed rubber have declined relative to the price of rubber reclaim. The stockpile problem has prompted 34 states to develop tire funding programs aimed at eliminating continued stockpile growth. Raising funds through taxation and the development of new markets for scrap tire materials are two approaches currently used at the state level to reduce the tire problem. The fees or taxes imposed on vehicles or vehicle transfers are used to provide grants and loans, subsides, and cleanup funds. Within the last 10 years, the environmental movement and a proliferation of state regulations have focused national attention on the need to develop alternate methods of scrap tire reuse.

2.1.2 Markets for Scrap Tires

Additional recycling and reuse of tires is essential to controlling the stockpile problem. By definition, “a scrap tire is that tire which can no longer be used for its original purpose” (Scrap Tire Management Council 1995). The use of tires as fuel continues to be the most significant market for scrap tires. In recent years however, there has also been a noticeable increase in ground rubber as an aggregate substitute in asphaltic concrete and shredded tires in civil engineering applications.

More than 10 million scrap tires were used in civil engineering applications in 1996 (Scrap Tire Management Council 1995). The civil engineering market encompasses a wide range of potential uses for scrap tires. Whole tires can be used as break waters or artificial reefs. Shredded scrap tires can be used to replace natural resources currently
used in construction such as clean fill, gravel and sand. The tire shreds are used as subgrade fill, in embankments, landfill construction, and drainage systems.

2.2 Shredded Tire Stream Crossing

2.2.1 Background

There are several documented cases where shredded tires have been used successfully as drainage structures (Edil and Bosscher, 1994). Most of these projects make use of tire chips or shreds ranging from 13 to 152 mm in size. Utilizing larger tire shreds has distinct advantages over the smaller shred materials when used as subsurface drainage structures: the production costs are significantly less; and there is a growing body of evidence that suggests that larger shreds perform better as drainage structures.

Direct material and labor cost for larger shreds used in this study are $12 per ton (Kersten 1997). In comparison, the cost reported by Edil and Bosscher (1994) for manufacturing tire shreds 25 by 50 mm to 100 by 450 mm in size ranges from $30 to $65 per ton. A ton of tires equals approximately 100 passenger car tires.

Field tests and visual observations of a full scale stream crossing, constructed at Dodger Enterprises in Fort Dodge, Iowa is used in conjunction with laboratory results to provide design guidelines for the construction of stream crossings. A stream crossing creates a roadway across a ravine without restricting stream flow. Figure 1 shows a cross section of the stream crossing. The results of the field tests and the research described herein are used to analyze the performance issues and develop design guidelines for a stream crossing.

2.2.2 Design Issues

Several design issues are evaluated:

- Size and shape of ravine
- Maximum potential flows and drainage area
- Volume of shredded tires and depth of backfill
- Stream crossing slopes
- Traffic loads
- Hydraulic stability under maximum potential flows
Laboratory measurements of the shear strength and compressibility are used for a slope stability analysis. This analysis includes slope stability under maximum flow and traffic load conditions. Permeability, potential for plugging, and settlement information are found in Zimmerman (1997). Maximum flow potential, compaction, and stream diversion procedures are left to the discretion of the engineer.
2.2.3 Bishop’s Modified Method

Bishop’s Modified Method is based on a stability analysis proposed by Fellenius which uses the limit equilibrium method. The procedure for the analysis is as follows:

a) Assume a surface of failure of radius, R, center, O (Figure 2).

b) The mass above the assumed surface of failure is divided into slices.

c) Determine the strength parameters for the slope material.

d) Determine the forces N, T, W and P acting on each slice

where N = Normal force component

T = Tangential force acting on the sides of the slices

T_n = Tangential force component

W = Weight of the slice

P = Normal force acting on the sides of the slice

e) The equation for Bishop’s modified method is:

\[ F_s = \frac{\sum ((c_n b_n + (W_n - u_n b_n) \tan \phi_n) \sec \alpha_n/(1 + (\tan \phi_n \tan \alpha_n/F_s)) \Sigma W_n \sin \alpha_n)}{\Sigma W_n \sin \alpha_n} \]

where: \( n \) = nth slice

\( c_n \) = cohesion of soil layer

\( b_n \) = width of the slice

\( u_n \) = pore water pressure

\( \phi_n \) = angle of internal friction for soil layer

The factor of safety, \( F_s \), is estimated initially and successive trials are conducted until there is convergence on the solution. The procedure is repeated using potential failure surfaces until the surface with the minimum factor of safety is identified. A slope stability computer program, GSLOPE, using this method is used to analyze the stream crossing.

2.3 Shear Strength

“Shear strength between two particles is the force that must be applied to cause a relative movement between the particles” (Lambe and Whitman, 1979, p 122). A direct shear test is used in this study to measure the shear strength of shredded tires. During a
Figure 2. Bishop's Modified Method
direct shear test, a known normal force is applied and a shearing force is progressively increased until the specimen fails. Normal force acts perpendicular to the plane or surface. Shear force is that which acts parallel to plane or surface passing through a body.

The Mohr-Coulomb failure envelope is a straight line relationship that yields information regarding the stability of a soil mass. Strength is expressed by the Mohr-Coulomb failure law:

$$\tau = c + \sigma \tan \phi$$

where $\tau$ is the shear stress on the failure plane, $\sigma$ is the normal stress on the failure plane, and $c$ and $\phi$ define a linear relationship called the failure envelope. The intercept, $c$ is called the cohesion intercept and $\phi$ is called the friction angle or angle of shearing resistance (Lambe and Whitman 1979). This failure criterion for soils is used in this study to analyze the shear strength of shredded scrap tires. The results are used to analyze slope stability of shredded tires as applied to the design of a stream crossing.
CHAPTER 3.
LABORATORY SHEAR STRENGTH TESTING

3.1 Materials

3.1.1 Shredded Scrap Tires

The shredded scrap tires used in this study were obtained from Dodger Enterprises of Fort Dodge, Iowa. They are classified as “No. 1 Grind” which consists primarily of passenger car tires. The particle size distributions for the test specimens are shown in Figures 3 and 4. The bars on these figures represent the number of shreds for the size indicated along the x axis and the curve represents the cumulative size distribution. The shreds ranged from 25 to 432 mm in width, and 40 mm to 1.4 m in length for the first mixture and 20 to 483 mm in width, and 50 mm to 1.1 m in length for the second mixture. The tire shreds were measured with a tape measure, with the longest dimension recorded as the length. The original steel belting, lead wire and other reinforcing protruded from the rubber. These shreds have been suggested for use as road bases, ravine crossings, and underground drainage structures. Two separate batches containing the No. 1 grind were used for testing shear strength. Visual inspection of the tire shreds after over 60 preliminary tests on the first batch revealed that the treads seemed to have worn on the surface. Therefore, a second batch of shredded tires was acquired for testing. For the shear testing of pure shredded tires, both the first and second batch was used. The second batch was used for testing tires in contact with glacial till.

3.1.2 Glacial Till

The glacial till was classified using the Unified Classification System as a sandy silt (ML) with Atterberg limits tests. A maximum dry unit weight of 18 kN/m³ and optimum moisture content of 13.5 percent were measured in a standard proctor density test using ASTM D 698. Particle size distribution and proctor curves are found in Appendix C.
3.2 Large-Scale Direct Shear Apparatus

Conventional procedures used in testing soils could not be used due to the large size of the tire shreds and the small dimensions (60 by 60 mm) of a standard direct shear box used for soil testing. A large-scale direct shear apparatus was constructed to measure the shear strength properties of shredded scrap tires. The apparatus had plan dimensions of 0.91 by 0.91 m, with an inside area of 0.83 m². The total height was 0.81 m, with the top half measuring 0.61 m and the bottom 0.20 m. The tire shreds were sheared by displacing the top section of the box relative to the fixed bottom section. Figures 5 and 6 show the direct shear machine testing set-up. For testing shredded tires, 4 steel rollers 1.3 cm in diameter were placed between the top and bottom sections of the box to minimize

Figure 3. Histogram for first batch of shredded tires.
friction resistance. The rollers ran along grooves on each side of the bottom part of the shear box. Tests with the empty shear box were conducted to measure frictional resistance of the rollers. The results of these tests can be found in Appendix A. The frictional resistance was minimal (0.028 kPa) compared to the shear force (>5 kPa) recorded during testing; therefore no correction was made for friction.

3.2.1 Application of Normal Force

The normal force was applied with a series of five concrete blocks, weighing an average of 4.7 kN each. The normal force was applied by lifting one concrete block with a crane and placing it on top of the shredded tire specimens. Consecutive blocks were added to conduct tests with normal loads of 4.6, 9.3, 14.1, 18.7, and 23.4 kN.
Figure 5. Direct shear testing equipment

Figure 6. Direct shear box.
3.2.2 Application of Shear Force

An Enerpack hydraulic actuator connected to a hydraulic pump was used to apply the shear force 0.10 m above the separation between the top and bottom sections of the box (see Figure 6). The actuator and load cell were centered along the width of the apparatus. The actuator was displaced at a rate of 1mm/min. This rate is generally accepted for shearing of granular soils (Bauer et al, 1993). The shear force was measured with a load cell connected to a Fluke 8842A digital multimeter. The voltage readings were converted to kN through calibration of the load cell and entered into a spreadsheet. Shear stress versus horizontal displacement graphs were generated for tests at the various normal loads.

3.2.3 Horizontal Displacement

The direct shear box was designed for a maximum horizontal displacement of 0.23 m. Horizontal displacement was measured manually with a metal pin attached to the top section of the shear box and a scale attached to the fixed bottom section. A board was placed at the front end of the bottom section to prevent the tire shreds in the top section from spilling out into the open section beyond the shear box with large displacements.

3.3 Test Procedure

The objectives of the direct shear tests were to determine the shear strength of shredded tires and the shear strength of shredded tires against glacial till. Shear stress versus deformation curves for all tests performed are found in Appendix B. In order to validate the reliability of the measurements made with the direct shear apparatus, direct shear tests were conducted on a material with known shear strength properties, in this case Hallett 1 inch washed gravel.

3.3.1 Hallett Washed Gravel

Shear tests were conducted at normal stresses of 12.6 and 23.9 kPa with Hallett 1 inch washed gravel using the large scale direct shear apparatus. Friction angles of 42°
and 47° were determined from the data. These results are in the Appendix A. Friction angles for gravel typically range from 34 to 48 degrees (Das, 1993). Friction angles of Hallett gravel measured in this range validated the use of the large-scale direct shear apparatus for testing the shredded tires. The calculated normal load for these tests included the weight of the gravel above the failure plane.

### 3.3.2 Shredded Tires

After each test, the shear box was emptied and materials from previous tests were removed. The tires were placed randomly in the direct shear apparatus at an uncompressed height approximately level with the top of the shear box. The normal load was then applied. The irregularity and compressibility of the shredded tires made it difficult to keep the concrete blocks level. Tire shreds were rearranged in the shear box several times before each test until the concrete block was as level as possible. Successive blocks could then be placed for testing at increased normal loads. The tires were then allowed to compress for 20 minutes under constant load. This compression time was determined by means of a creep test that was carried out for each normal load. The results can be found in Appendix C.

After the compression of the tires was complete, the vertical distance from the top of each corner of the shear box to the top of each corner of the concrete weights was measured with a tape measure. The vertical distances were again measured at the end of each test to calculate vertical deformation of the tires. A table of these measurements is included in Appendix C.

The shear force was applied and the reading displayed on the multimeter was recorded every 2.5 mm of horizontal displacement. Shear forces were calculated by subtracting the initial multimeter reading, with zero shear force applied, from the values recorded during shear. A calibration factor was applied to convert from millivolts to kN. Initial tests were run to a displacement of 51 mm and results showed favorable repeatability. Because the shear stress versus horizontal displacement graphs generated
did not exhibit a peak shear stress, further tests were performed to larger displacements. Appendix B includes results of the tests performed.

### 3.3.3 Shredded Tires on Glacial Till

The shear strength of shredded scrap tires in contact with glacial till was also investigated. These shear strength parameters were measured so that they may be used in slope stability analysis. Direct shear tests were carried out with five different normal loads with the soil at moisture contents dry and wet of optimum.

Tests were first performed with the soil at 8 percent moisture content. The soil was placed in the bottom section of the apparatus and hand tamped with a square steel plate attached to a steel rod. The soil was compacted level with the top of the bottom section with an approximate dry unit weight of 14.5 kN/m$^3$. Shredded tires were then randomly placed on top of the soil until level to the top of the apparatus. This allowed the interface of the shredded tires with soil to be located along the box separation plane. The normal load was then applied and the testing was carried out. After each test, the tires were removed and the top section was lifted so that the grooves and rollers could be cleaned. A layer of soil was also removed, replaced, and compacted level for the next test.

After testing with the 8 percent moisture content glacial till was completed, the moisture content of the remaining glacial till was increased to 15 percent and placed in the apparatus using the procedures described above. Using a garden hose, the soil was saturated until water ponded on the surface. This was done to simulate a saturated subgrade condition, as would be expected at the base of a stream in a ravine. The tire shreds were then placed in the top section of the shear box and testing was conducted following the procedures previously described. After each test, the tires were removed and a representative sample of soil was collected from the top layer to determine its moisture content. Results of all tests can be found in Appendix B.
3.4 Data Analysis

3.4.1 Failure Criteria

The Mohr-Coulomb failure criterion was used to describe the direct shear test results. Two failure envelopes were developed for both the tests on shredded tires and shredded tires in contact with glacial till. The first envelope was generated using the maximum shear stress from the shear stress vs. horizontal displacement graphs. If a maximum shear stress was not reached for a test, the shear stress at the largest horizontal displacement of that test was used. For the second envelope, failure was taken at a horizontal displacement equal to 10% of the length of the shear, in this case 91 mm. This standard, specified in ASTM-D 3080-72, is used when no clear maximum shear stress occurs.

Figures 7, 8, and 9 summarize shear stress versus horizontal displacement graphs generated for tests using shredded tires and tires in contact with glacial till. The shear stress versus horizontal deformation curves for shredded tires exhibit a maximum shear stress at high normal stresses. For the direct shear tests using tires in contact with glacial till, a clear peak is not evident in every test. For the tests conducted with glacial till dry of optimum, the shear stress versus horizontal deformation curves exhibit a maximum for normal stresses of 5.5, 11, and 28 kPa. For tests conducted with till wet of optimum, no peak failure stresses were reached.

3.5 Results

3.5.1 Shredded Scrap Tires

A linear regression through the laboratory data was used to interpret the friction angle and cohesion intercept. For the failure envelope using the maximum shear stress as failure (Figure 10), a friction angle of 38° with a cohesion of 3.1 kPa was calculated for shredded tires. The R² value was 0.98. The same friction angle and R² were calculated if a cohesion of zero was included in the regression with the failure envelope using the 10% criterion as failure (Figure 11). This shows that the cohesion intercept decreases as horizontal deformation decreases. This is consistent with results reported by Humphrey
et al (1993) on shreds 38-76 mm in size in a direct shear box with a maximum displacement of 35.6 mm. Humphrey et al (1993) suggest that a low or zero cohesion intercept should be used in design because it appears that significant deformation is needed to develop the cohesion. However, the shear box used by Humphrey et al (1993) was limited to a maximum displacement less than 10% of the width of the shear box and the authors admit that the choice of failure is rather arbitrary.

Table 1 shows the results of this study as compared to studies conducted by Foose et al (1996) and Humphrey et al (1993) on pure tire shreds. Foose et al (1996) measured the shear strength of tire shreds grouped by lengths of 50, 100 and 150 mm. Since the

Figure 7. Direct shear tests for shredded tires.
Figure 8. Directs shear tests for tires in contact with glacial till at 8% moisture content.
strength envelopes were similar, a best fit straight line through the combined data was used to define the strength envelope in Foose’s study. Humphrey et al (1993) reported failure envelopes for tires shreds of different sizes from three tire chips suppliers.

3.5.1.1 Nonlinearity of Strength Envelope

Prior research has interpreted linear strength envelopes for tire shreds. However, a nonlinear strength envelope was reported by Edil et al (1996) for soil reinforced with tires shreds with high matrix unit weights. Similar envelopes as sited by Foose et al (1996) were reported by Gary and Ohashi (1983), Gray and Al-Refeai (1986), Maher and Gray (1990), and Benson and Khire(1994). Edil et al (1996) defined two friction angles: $\varphi_1$ defined the slope of the initial portion of the strength envelop and $\varphi_2$ defined the slope

Figure 9. Directs shear tests for tires in contact with glacial till at 18-22% moisture content.
of the latter. The critical normal stress as defined by Maher and Gray (1990) occurs at the transition of $\varphi_1$ and $\varphi_2$. However, shear strength tests conducted have not always exhibit a clearly defined transition point.

Two Mohr-Coulomb envelopes were also generated using data from Foose et al (1996), Humphrey et al (1993), and the results of the shear strength of shredded tires in this study. The first failure envelope (Figure 12) is generated using the failure criterion at maximum shear stress found in this study and the second failure envelope (Figure 13) is generated using the 10% failure criterion. In Figure 12, a power function curve with an equation of $y = 2.05x^{0.7}$ was regressed through these data points yielding an $R^2$ value of 0.96. In Figure 13, a power function curve with an equation of $y = 1.4x^{0.79}$ was regressed.

![Mohr-Coulomb failure envelope for shredded tires using maximum shear stress.](image)

Figure 10. Mohr-Coulomb failure envelope for shredded tires using maximum shear stress.
yielding an $R^2$ value of 0.94. As shown in both figures, the failure envelope begins to curve with lower angles at higher normal stresses. This failure envelope indicates three important points regarding the shear strength of tire shreds:

1. Shear strength of tire shreds appears to be independent of shred size.
2. The shred size dictates the normal stress at which tires can be tested in the laboratory. The shred size dictates the dimensions of the shear box in which it is tested and therefore dictates the normal stress applied. That is, the normal stress that can practically be applied is a function of shred size. A larger-sized shred can not be tested in the same apparatus that a smaller-sized shred for two reasons: a) the larger shreds do not fit and b) the boundary effects could influence the shear strength.

3. In design the shear strength at 10% deformation is more critical. Using the failure envelope in Figure 13, normal stress can be used to calculate the shear strength of shredded tires at failure using the equation:

\[ \tau = 1.4 \sigma^{0.79} \]

3.5.1.2 Angle of Repose

Prior to direct shear testing, the angle of repose for an uncompressed tire pile of No. 1 Grind was measured with a Brunton compass. The angle of repose for the specimens used in this study averaged 38° with a maximum angle of 51° and a minimum of 32°. Table 2 lists angles of repose for the four types of tire shreds manufactured at Dodger Enterprises. Edil and Bosscher (1992) have reported angles ranging from 37-43° for loose tire chips and as high as 85° for compacted chips. Foose et al (1996) have also observed stable stockpiles having slopes steeper than 1:1. Both studies indicate that higher friction angles may exist in the field; but there is not a correlation between shred length and angle of repose. Foose et al (1996) suggests that it may also be that shredded tires have significantly higher cohesion in the field or that the Mohr-Coulomb failure criterion may not be an appropriate description for tire shreds. The nonlinear relationship, \( \tau = 1.4 \sigma^{0.79} \), found in this study verifies that Mohr-Coulomb failure criterion is not appropriate.
3.5.2 Shredded Scrap Tires in contact with Glacial Till

The shear strength of shredded scrap tires in contact with soil was tested on glacial till at 8% and 18-22% moisture contents. A linear regression through laboratory data was used to interpret the friction angle and cohesion intercept. Figures 14 and 15 show the results with the till at 8% moisture content using the failure criterion for maximum stress and the 10% failure criterion respectively. For the failure defined at maximum shear stress, a friction angle of 39° with a cohesion intercept at 0.6 kPa was found. For the 10% failure criterion, a friction angle of 37° with zero cohesion was found. As shown in Figures 16 and 17, friction angles of 33° were interpreted for both failure envelopes for tires in contact with glacial till at higher moisture contents. However, a cohesion intercept of 2.1 kPa resulted using maximum shear stress as the defining failure criterion and a cohesion intercept of 0.7 kPa using the 10% failure criterion. The cohesion intercept was expected to be closer to zero. Upon removal of the tire specimens after testing, the soil surface was observed to have been gouged by the tires. Because the surface of the glacial till was saturated for this part of testing, it was more likely to be gouged by the tires during shearing. Therefore, the tires were more interlocked with the glacial during the testing at higher moisture contents. The writer explains the cohesion intercept to be a result of this occurrence.

Foose et al (1996) reported interface friction angles between shredded tires and portage sand. In Foose’s investigation, 5, 10, and 15 cm sized tire shreds were used. The surface of the tire shreds was set level with the shear plane by mounting tire shreds on a piece of plywood. “The average interface friction angle was 34° with unit weight of soil matrix at 15.2-15.7 kN/m³ and an average interface friction angle was 39° for unit weight at 16.8 kN/m³” (Foose, 1993). Foose reported a cohesion of zero. Table 3 shows the results of the research for large tire shreds on glacial till described in this study along with that of Foose’s using portage sand.
Table 2. Angle of repose for tire shreds

<table>
<thead>
<tr>
<th>Tire Shred Length (cm)</th>
<th>&lt; of repose (max)</th>
<th>&lt; of repose (min)</th>
<th>&lt; of repose (ave)</th>
<th>aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-183</td>
<td>51</td>
<td>32</td>
<td>38</td>
<td>1.4-7.5</td>
</tr>
<tr>
<td>38-47</td>
<td>72</td>
<td>34</td>
<td>46</td>
<td>10-20</td>
</tr>
<tr>
<td>33-56</td>
<td>31</td>
<td>28</td>
<td>30</td>
<td>1-2.6</td>
</tr>
<tr>
<td>23-86</td>
<td>35</td>
<td>30</td>
<td>34</td>
<td>1-2.7</td>
</tr>
</tbody>
</table>

3.6 Conclusions

3.6.1 Shear Strength of Shredded Tires

The objective of this study was to measure the shear strength of larger-sized shredded scrap tires. The parameters measured will be used to analyze the use of larger-sized tire shreds as stream crossing drainage structures. Two different failure criteria were used in this study, yielding similar results. For pure shredded tires, a friction angle of 38° and a cohesion intercept of 3.1 kPa was obtained for large deformation while the same friction angle of 38° and a zero cohesion intercept were interpreted using the 10% failure criterion. From the data examined, the shear strength of tire shreds appears to be independent of tire shred size. The normal stress that tire shreds are subjected to is the governing factor in determining shear strength at failure. At higher normal stresses, this study shows through published data that the Mohr-Coulomb failure envelope for tire shreds is not linear. Using the equation:

\[ \tau = 1.4\sigma^{0.79} \]

shear strength for shredded tires can be determined at any normal stress. This equation yields shear strength properties at smaller deformations and is more useful in design.

3.6.1.1 Validity of using Mohr-Coulomb Criterion in interpreting the Shear Strength of Tire Shreds

The angle of repose observed in stable stockpiles is generally greater than measured friction angles for tire chips and shreds. This indicates that the friction angle or
cohesion of tire shreds may be greater in the field. It may also indicate that Mohr-Coulomb failure criterion is not accurate in interpreting the shear strength of tire shreds. The nonlinearity of the shear strength envelope also indicates that Mohr-Coulomb failure criterion may not be accurate.

Figure 12. Nonlinear strength envelope generated from research on tire shreds and maximum failure criterion from this study.
Table 3. Direct shear test results for shredded tires against soil

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Soil Type</th>
<th>Soil Density (kN/m³)</th>
<th>Friction Angle (degrees)</th>
<th>Cohesion Intercept (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foose Portage sand</td>
<td>15.2-15.7</td>
<td>34</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Foose Portage sand</td>
<td>16.8</td>
<td>39</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>This Study at peak failure</td>
<td>Glacial till</td>
<td>14.5</td>
<td>39</td>
<td>0.6</td>
</tr>
<tr>
<td>This Study at 10% failure</td>
<td>Glacial till</td>
<td>14.5</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>This Study at peak failure</td>
<td>Glacial till</td>
<td>14.5</td>
<td>33</td>
<td>2.1</td>
</tr>
<tr>
<td>This Study at 10% failure</td>
<td>Glacial till</td>
<td>14.5</td>
<td>33</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Figure 13. Nonlinear strength envelope generated from research on tire shreds and 10% failure criterion found in this study.
Figure 14. Mohr-Coulomb envelope for tires in contact with glacial till at 8% moisture content using maximum stress failure criterion.
Figure 15. Mohr-Coulomb failure envelope for tires against glacial till at 8% moisture content using 10% failure criterion.
Figure 16. Mohr-Coulomb envelope for tires in contact with glacial till at 18-22% moisture content using maximum stress failure criterion.
Figure 17. Mohr-Coulomb failure envelope for tires in contact with glacial till at 18-22% moisture content using 10% failure criteria.

3.6.2 Shear Strength of Shredded Tires in Contact with Glacial Till.

For direct shear tests on shredded tires against glacial till dry of optimum, friction angles of 39° and 37° with cohesion intercepts of 0.6 and 0 kPa respectively were interpreted. For shredded tires in contact with glacial till wet of optimum, a friction angle of 33° with cohesion intercepts 2.1 and 0.7 kPa were interpreted.
CHAPTER 4.
SLOPE STABILITY ANALYSIS FOR STREAM CROSSING

4.1 Slope Stability Analysis

Three separate stream crossings, 2.7m, 3.9m, and 5.7m deep are analyzed with GSLOPE. Geometries were programmed for 20°-60° slopes for each of these cases under the water level under three separate water level conditions: dry, water level at 50% height of tire layer, and water level at 75% height of tire layer. The strength parameters for tire shreds were interpreted from the nonlinear shear strength envelope in Figure 13. The normal stress was taken at the midpoint of the tire shred level, using the full height of soil fill and half the height of the tire layer. For each normal stress, the angle and intercept of a line drawn tangent to the strength envelope was used as the friction angle, \( \varphi \), and cohesion intercept, \( c \), respectively for the shredded tires. The cohesion intercepts and friction angles entered for the analysis are found in Table 4. The unit weight of the tire shreds depends on the amount of compression from the normal stress. Tire shreds approach maximum compression at approximately 45% compression (Zimmerman, 1997). For case 1, at normal stress = 23 kPa, tires are at 47% compression. For cases 2 and 3, tires shreds are at 50% compression. The unit weight of the tire shreds in case 1 at 5.6 kN/m\(^3\), is therefore lower than the unit weight of tire shreds in cases 2 and 3 at 6 kN/m\(^3\). The strength parameters for top layer of glacial till were taken from laboratory tests at 10% moisture content shown in Figure 13. The normal stress for this layer of glacial till was entered as 16 kN/m\(^3\). For the bottom layer of glacial till, the strength parameters were taken from the shear strength tests described previously for tire shreds in contact with glacial till at 18-22% moisture content using the 10% failure criterion. The normal stress for the bottom layer was entered as 20 kN/m\(^3\). Normal loads at 40 kN were placed 3 meters apart on the top soil layer to simulate traffic loads in all cases.

An additional analysis was conducted to examine the sensitivity of the side slopes to the shear strength parameters. For this analysis, the strength parameters for tire shreds
were interpreted from the linear shear strength envelope in Figure 11. In these trials, friction angle was entered as 38° and the cohesion intercept as zero for each normal stress. All other data was entered the same and the analysis was conducted as explained in the above paragraph.

Bishop's Modified Method was used in the computer program GSLOPE for the slope stability analysis. A radial search was conducted with an 8 by 8 grid of centers, O. Using this search, the radius is varied until a minimum Factor of Safety, \( F_s \), is found for each of the centers defined. Figure 18 shows a stream crossing with the grid of centers contoured with Factors of Safety found in an analysis.

![Figure 18. Slope stability analysis factor of safety grid.](image)

**4.2 Results**

Figures 19, 20, and 21 show slope stability results for the three stream crossing configurations using the data in Figure 13. \( F_s \) decreases with increasing water level and slope angle in each case. Figure 22 compares the three stream crossings with a water level at 50% of the tire shred layer. At slope angles less than 30°, the 3.9 meter stream crossing appears to be most stable, followed by the 5.7 m, and 2.7 m stream crossings respectively. The 2.7 m stream crossing is under the least amount of normal stress, thus giving the tire
shred layer a lower compression and unit weight. This explains the lower factor of safety for a smaller crossing structure.

Figure 23 shows slope stability results for three stream crossing configurations using the data in Figure 11. The results are similar to the results using the nonlinear strength envelope shown in Figure 22. $F_s$ decreases with increasing water level and slope angle in each case. The factors of safety are slightly lower than the factors of safety found in the analysis using the nonlinear strength envelope. However, the difference in factors of safety found is minimal.

![Figure 19. Results for 2.7 m stream crossing.](image-url)
Figure 20. Results for 3.9 m stream crossing.
Figure 21. Results for 5.7 m stream crossing.
Figure 22. Comparison of slope stability results for stream crossings with the water height at 50% height of tires using data from Figure 13.

<table>
<thead>
<tr>
<th>Normal Stress (kN/m³)</th>
<th>c (kPa)</th>
<th>φ (degrees)</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>1.4258</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
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</tr>
<tr>
<td></td>
<td>4.7</td>
<td>33</td>
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<tr>
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<td>52</td>
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<td>1.3002</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>29</td>
<td>1.4054</td>
</tr>
</tbody>
</table>
This indicates two points regarding the sensitivity of slope stability analysis to shear strength parameters:

1) Minimal sensitivity to cohesion was determined in this slope stability analysis

2) Using the full height of soil backfill to calculate the normal stress for the slope stability analysis is justified. That is, the normal stress calculated did not account for lower normal stresses along the side slopes of the stream crossings. The data in Figure 11 was found at low normal stresses in the laboratory. Since the factors of safety using the shear strength parameters at a low normal stress did not alter significantly from those at higher normal stresses, not accounting for lower normal stresses along the side slopes in the analysis is justified.

Figure 23. Comparison of slope stability results for stream crossings with water level at 50% height of tires using 10% criterion from Figure 11
4.3 Conclusions

Constructing a stream crossing using shredded tires would be economical in some cases. This analysis was conducted under the assumptions that the ravine would be no deeper than 5.7 m and that the roadway the crossing created would be unpaved. These limitations allow for construction in a low traffic area such as on a farm. The stream crossing should have side slopes no greater than 26° (2:1). The maximum water level in the ravine should not exceed 50% of the height of the tire layer on the upstream side. This analysis has also shown that the factors of safety were not sensitive to cohesion.
CHAPTER 5.
CONCLUSIONS

Civil engineering markets for use of shredded scrap tires lack design guidelines needed for project completion. The results of this testing show that shredded tires exhibit frictional behavior that could be used in construction. Previous research in shear strength of shredded tires has been conducted on tire shreds and chips much smaller in size. Since the shred size does not appear to dictate the shear strength of shredded tires, it would be more cost effective to use larger shreds in construction. Other research projects have indicated that larger shreds also offer a better drainage medium.

The shear strength testing performed on large size shredded tires concludes:

- The 10% failure criterion should be used in design because it requires less deformation of the shredded tires.
- The shear strength of tire shreds appears to be independent of tire shred size.
- At higher normal stresses, the Mohr-Coulomb failure envelope is not linear.
- Using the equation: $\tau = 1.4 \sigma^{0.79}$ shear strength of shredded tires can be found at any normal stress.
- Mohr-Coulomb failure criterion is not accurate in interpreting the shear strength of tire shreds.
- The friction angle for shredded tires in contact with glacial till dry of optimum is $37^\circ$ with a cohesion intercept of 0 kPa.
- The friction angle for shredded tires in contact with glacial till wet of optimum is $33^\circ$ with a cohesion intercept of 0.7 kPa.

The shear strength properties measured in this study have been further analyzed for the slope stability of shredded scrap tires used in the construction of stream crossings. The slope stability analysis showed minimal sensitivity to shear strength parameters interpreted at low normal stresses. The side slopes for a shredded tire stream crossing should not exceed 26 degrees. The water level in the ravine should not exceed 50% the
height of the shredded tire layer. Due to the limitations imposed on the stream crossings in this study, it recommended that construction of shredded tire stream crossings is limited to low traffic roadways that do not require paving.
Figure A-1. Direct shear test results for Hallett gravel.
Figure A-2. Direct shear test results for Hallett gravel.
Calibration of load cell to the Fluke 8842A digital multimeter using the Satec universal testing machine.

<table>
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<th>Multimeter reading (1) (mv)</th>
<th>Multimeter reading (2) (mv)</th>
<th>Multimeter readings (ave) (mv)</th>
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<td>0.075</td>
</tr>
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<td>-1.061</td>
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<td>-2.207</td>
<td>-2.2045</td>
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<td>-3.342</td>
<td>-3.3405</td>
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<td>-5.623</td>
<td>-5.648</td>
<td>-5.6355</td>
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</table>

Figure A-3. Calibration of load cell.
Figure A-4 Frictional effects of rollers.
APPENDIX B

DIRECT SHEAR TEST RESULTS

Figure B-1. Direct shear test on shredded scrap tires.
Figure B-2. Direct shear tests on shredded scrap tires
Figure B-3. Direct shear Tests on shredded scrap tires.
Figure B-4. Direct shear tests on shredded scrap tires.
Normal Stress = 28 kPa

Figure B-5. Direct shear tests on shredded scrap tires.
Figure B-6. Direct shear tests for shredded scrap tires on 8% w glacial till at various normal loads.
Figure B-7. Direct shear tests for shredded scrap tires on 18-22% w at various normal loads.
APPENDIX C

DISPLACEMENT AND SOIL DATA

The average vertical displacement for all tests recorded below is 2.34 cm.

**Shredded Tires**

Normal Load = 4.58 kN

<table>
<thead>
<tr>
<th>Test #</th>
<th>RF</th>
<th>RB</th>
<th>RA</th>
<th>LF</th>
<th>LB</th>
<th>LA</th>
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<tbody>
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<td>1</td>
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Normal Load = 9.25 kN

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</tr>
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<td>4.92</td>
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Normal Load = 14.06 kN

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<th>LA</th>
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<td>1.59</td>
<td>2.54</td>
<td>2.07</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>3.02</td>
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<td>0</td>
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Normal Load = 18.68 kN

<table>
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<td>2.86</td>
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Normal Load = 23.40 kN

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<td>1.91</td>
</tr>
<tr>
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<td>1.91</td>
<td>1.27</td>
<td>1.59</td>
<td>1.27</td>
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<td>0.95</td>
</tr>
<tr>
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<td>1.91</td>
<td>1.59</td>
<td>1.75</td>
<td>3.49</td>
<td>0.64</td>
<td>2.07</td>
</tr>
<tr>
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<td>Not recorded</td>
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</tr>
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</table>

Figure C-1 Vertical displacement of shredded tires in centimeters.
Shredded Tires on 8\% mc Glacial Till

Normal Load = 4.58 kN

<table>
<thead>
<tr>
<th>Test #</th>
<th>RF</th>
<th>RB</th>
<th>RA</th>
<th>LF</th>
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Normal Load = 9.25 kN

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Normal Load = 14.06 kN

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Normal Load = 18.68 kN

<table>
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<th>LF</th>
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Normal Load = 23.40 kN

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Shredded Tires on 18-22\% mc Glacial Till

<table>
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<th>RB</th>
<th>RA</th>
<th>LF</th>
<th>LB</th>
<th>LA</th>
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<tbody>
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<td>2.22</td>
<td>3.81</td>
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<td>9.25 kN</td>
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<td>4.13</td>
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The concrete weight was measured at the beginning and end of each test at each corner. RF = Right Front, RB = Right Back, RA = Right Average, LF = Left Front, LB = Left Back, LA = Left Average

Figure C-1 Vertical displacement of shredded tires in centimeters.
A creep test was performed to determine the time required for the normal load to settle when placed on top of tires. Each corner of the concrete block was measured. RF = right front, LF = left front, RB = right back, LB = left back.

<table>
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<th>Time (minutes)</th>
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<th>Displacement (RF) (cm)</th>
<th>Displacement (LB) (cm)</th>
<th>Displacement (LF) (cm)</th>
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<tr>
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<table>
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<th>Time (minutes)</th>
<th>Displacement (RB) (cm)</th>
<th>Displacement (RF) (cm)</th>
<th>Displacement (LB) (cm)</th>
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Figure C-2 Test performed to determine displacement of shredded tires during testing.
Figure C-3 Particle size distribution for glacial till.
Figure C-4 Proctor curve for glacial till
REFERENCES


Humphrey, D.N., “Civil Engineering Applications of Chipped Tires,” Nebraska DEQ Seminar, Omaha, Nebraska, November 15, 1995.


Ng, Kam Weng, “Field tests and analyses of high density polyethylene pipes for highway applications,” MS Thesis, Iowa State University, Ames, Iowa, 1997.


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