RECYCLED TIRE BALES FOR WALL CONSTRUCTION: A MULTIDISCIPLINARY PROJECT FOR ENGINEERING DESIGN EDUCATION

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Introduction

The Design Engineering Practices Introductory Course Sequence (EPICS) program is a two semester, six credit-hour sequence that is required of all first and second-year students at the Colorado School of Mines (CSM). During the Design (EPICS) sequence, students working in teams are guided through a hands-on experience of basic, sound engineering practices that incorporate creativity and inventiveness, technical thinking, decision-making, communication skills, and graphical demonstration. The sequence is consistent with current views about engineering design education. Douglas[1] views engineering design as a *creative* process to convert ideas into "processes for producing new materials." Pahl and Beitz[2] consider the integration of technical, psychological, systematic, and organizational aspects of engineering design as "prerequisites for the physical realization of solution ideas." Ullman[3] views engineering design in terms of managing people and information. These themes continue to repeat themselves throughout discussion of engineering design. Horenstein[4] defines the results of the design process more specifically as "a set of desired specifications." Bieniawski[5] recognized that many skills required for engineering design, frequently not taught in formal classroom settings, are developed only through practice. He describes a process of developing behavioral standards necessary to produce a quality product. Our sequence, on the cutting edge of engineering design methodologies, provides students with a broad-based introduction concerning engineering design, technical communications and teamwork early in their academic career.

This report summarizes several years of research and engineering activities conducted by undergraduate students to fulfill their requirement for engineering design throughout their curriculum. During the past 4 years 42 undergraduate students at various levels of their education and from various disciplines on campus have directly participated in the process of creating a noise abatement wall from recycled tire bales. As we write this report we summarize the progress of the various teams and reflect on the value of the project to their overall learning objectives. Two questions evolve from this project that focus our discussion on the relationship between an authentic engineering design and the mission of the engineering design stem at CSM:

- How does this project represent an authentic engineering design experience for engineering students?
- What value does an authentic engineering design experience offer to engineering students and design courses?

The design stem at CSM encompasses a four-year program in engineering design studies, which emphasizes the technical skills levels of the students, summarized in Figure 1. The Design (EPICS) program implements the first two years of the stem sequence. The first-year focuses on visualization studies that coincide with conceptual design in the industry. Second-year design moves to resource assessment, focusing on data acquisition and processing of information to advance the project. Third-year design takes place in the student's major discipline and gives students the opportunity to use their technical and economic knowledge to assess equipment and processes. By their fourth years, teams should be well positioned to synthesize the information necessary to optimize their designs. The centerpiece of each design course is an open-ended problem that students work in teams to solve. To help students become skilled at this process, mentors have students learn through practice. Although the mentor's primary role is to apprentice students through their difficulties, mentors also furnish instruction or information in carefully selected topics. "Hands-on" application of engineering skills facilitates students' learning and introduces them to a progression of projects similar to a decision-making strategy used in the industry.

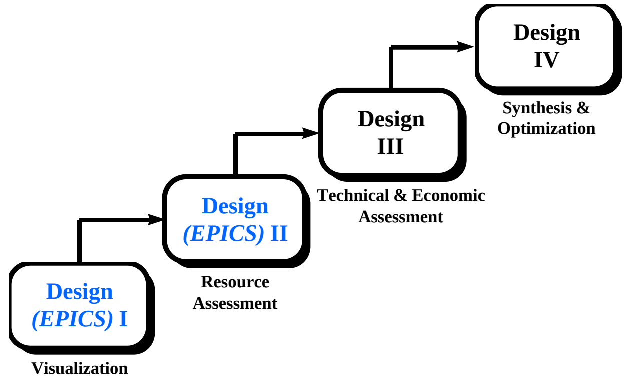

Figure 1: *Overview of Design Stem Sequence*

Conceptual Design for Noise Abatement Wall: A First-Year Design

Transportation departments throughout the United States have received an increasing number of requests for barriers along highways to reduce traffic noise. Urban roads account for 20 percent of the road mileage, but 70 percent of the road traffic, according to a study of highway noise in the United States[6] It is no wonder that the number of requests for noise abatement structures continually increases. Dr. Russell Law, an alumnus of CSM and an engineer for the Nevada Department of Transportation (NDOT) requested that student teams[7] develop innovative, cost effective, and aesthetic noise walls that would address this growing problem. One of our first-year design teams, the Wolverines (Gina Alkes, Jeremy Hamer, Brent Lyon, Lauren Scott, and Hawk Vanek) proposed a tire bale wall to reduce noise along Nevada highways.

Midway Tire Disposal, one of the largest tire disposal and recycling facilities in the western United States, has been in operation since 1989. In the late nineties, Vernie Houchen, owner of Midway, purchased an Encore tire baler as a way to increase their tire disposal capacity. Each baler compresses and bands approximately 100 tires to one-fourth the original volume, pictured in Figure 2. Tire bales consist of a mixture of air and tire rubber, which varies based on the baling process. The bailing process produces a non-homogeneous material that challenges researchers with the analysis and modeling of bale properties using discrete or intrinsic properties. The size of the tire bales (approximately 30in by

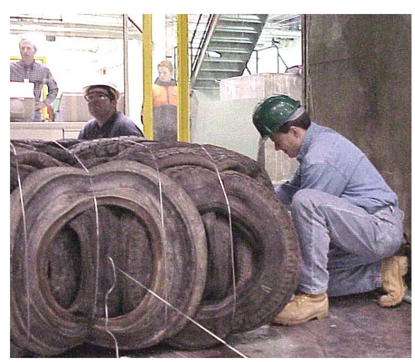

Figure 2: *Typical Tire Bale Illustrating the Non-Homogeneous Nature of the Material*

46in by 56 in and weighing one ton) also presents a challenge for measuring these properties.

Engineering designs using tire bales as construction material, however, rely on knowing properties of the bales. The Wolverines' conceptual design led to a grant through the Colorado Advanced Material Institute (CAMI) Tire-Tap Program to study properties, the market, and design issues for tire bale construction.

Engineering a Tire Bale Wall

Project Integration and Synthesis: A Senior Design Issue

The engineering strategy for this project evolved from a feasibility work package that assessed tire bales for wall construction specifically for noise abatement walls. The engineering strategy included assessing previous research, testing materials in laboratories, and constructing a prototype in the field. Complexity of testing procedures and data acquisition warranted collaboration between the senior design team (Sean Davis, Patrick Freemyers, Taylor Geortz, and Jeremy Lee), project mentors, engineers and consultants.

The team assumed that bales and other materials could be delivered to a construction site by truck. Construction techniques would be very similar to standard building practices. The team envisioned that adequate drainage could be produced using a gravel base with a pipe drain system, illustrated in Figure 3. While on site the bales could be moved into position using a crane or forklift with at least a two-ton capacity. Because of the size and mass of the tire bales, the bales would be stacked in a staggered pattern with no other reinforcement or joining material, illustrated in Figure 4. After the tire bales were in place and completely stable, the wall would be encapsulated in an aesthetically pleasing material. Covering the bales would help the wall blend into its surroundings as well as protect the tires from the elements. The covering would also prevent small animals from using the crevices between tires for their homes.

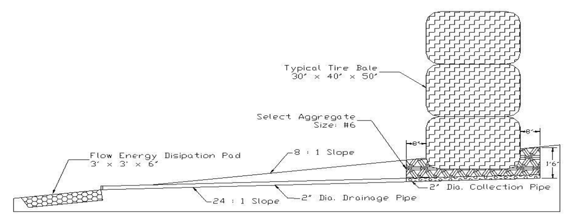

Figure 3: *Construction Drawing for Drainage System Compatible with a Tire Bale Wall.*

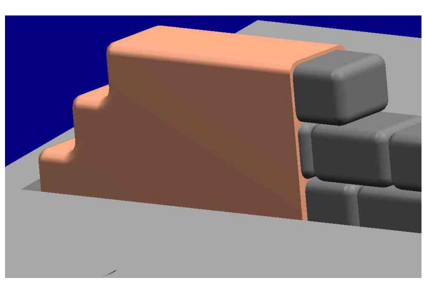

Figure 4: *Schematic Drawing of Proposed Tire Bale Noise Abatement Wall*

The strategy included research to gather data and information collected from various studies for analyzing the technical, safety, and economic issues for the construction of walls from tire bales. The study identified both advantages and disadvantages of tire bales as a construction material. Equally important, data and information about the properties of recycled tire bales and issues of wall construction were documented for this study. These data can be useful in determining where this industry needs to proceed in the future, specifically to market recycled tire bales as a viable alternative for wall construction.

Market Issues and Property Data: Resource Assessment by Second-Year Design Teams

Second-year teams, subcontracting for Design (EPICS) II credit, took on the challenge of exploring the properties, market, and design issues for tire bale construction. Literature research conducted by these teams focused on a review of the literature concerning options for recycling tires. Market opportunities were identified for not only tire recycling but also for tire bale construction. Research into construction literature focused on design issues and difficulties. Specific tests, measurement instruments and methods proposed for testing were selected from the literature.

Tire bales form elastic, durable, highly insulating material resistant to graffiti, according to team International Funk (Diana Abdul Rahman, Hadi Balhareth, Chad Chenoweth, Luke Choi, and Jacinta Gisclair). These properties suggest bales are ideal materials for retaining walls and impact barriers, erosion control and residential construction. Based on TCLP tests, the EPA has noted that tires meet TCLP Regulatory Limits and Standards for Drinking Water. The team also reported that the risk of a bale catching fire is low based on a test burn, conducted by the City of London Fire Department (Ontario, Canada).

As a result of their research, Team Tire (Mac McKee, Keith Lopez, Doug Klein, Justin Stolte, and Ben Lengerich) recommended the use of bales in soil elevation, erosion control, and sound wall projects. Each of these construction scenarios provides Midway Tire Disposal an opportunity to sell tire bales at a market price of twenty-five dollars. These projects would minimize damage or harm to the environment. In fact, recycling of tires would help protect the environment by reducing landfill disposal. To market the largest number of bales, the team recommended focusing on the government sector because of the size of government projects.

Team R.R. (Michelle Manichanh, Wesley Reynolds, Lowell Good, Adam Goodworth, and Leonard Molina) narrowed the testing objectives to mechanical, thermal, and insulation tests. They found that the strength of the bales depends on the bales' ability to sustain a load without extreme deformation or failure. Response of these bales to stress would answer questions concerning the bales' structural integrity. To assess the insulation properties, Team R.R. proposed studies of sound absorption through testing to measure reflective, refractive and absorption properties necessary for assessing acoustical performance of the bales.

Fun and Learning as We Tested Materials

In order to design and build a noise abatement wall, the team needed to measure properties of the tire bales, which included strength, thermal, and acoustic properties. The materials testing work package focused on collecting data and information through experimental methods. Properties such as size and weight formed the basis for the construction of walls. Analysis of strength and stability governed structure integrity of the wall. Properties related to acoustics, off gassing, and thermal conductivity provided data to evaluate the performance of bales in wall construction. This project utilized laboratory testing and model development to determine the properties and to analyze the influence of variations in bale composition.

The senior design team conducted several tests to define properties through various laboratories within the Denver area. Important to the mechanical properties, stress-strain relationships would define the amount of deformation and maximum loads that each bale can support. Mechanical tests were conducted at the Materials Engineering and Research Laboratory (MERL) at the Bureau of Reclamation, pictured in Figure 5. Attempts to burn bales, conducted under the supervision of the Colorado Springs Fire Department, quantified ignition temperatures and emphasized issues of safety associated with construction of walls out of tire bales.. Acoustical properties would vary depending on the composition of the bale. Tests were conducted at the Johns Manville Technical Center Acoustical Laboratories to measure acoustical properties under laboratory conditions and at Midway Tire Disposal (at the prototypical wall) under field conditions with the help of Compliance Solutions. Results from this work package have created a database of material properties specific to applications of tire bales as a construction material.

Figure 5: *Fred Fraikor, Director of CAMI at CSM Checking Final Condition of Tire Bale Following Test At MERL Facility*

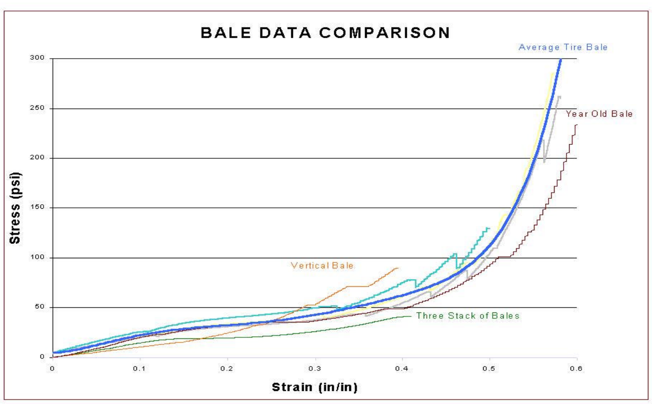

Figure 6: *Stress-Strain for Various Tire Bales and Configuration*

From mechanical load tests the team developed a series of stress-strain diagrams. The relationship, shown in Figure 6, confirmed that the bales exhibited a fairly constant stress until approximately 0.3in/in strain. Beyond this point stress increased dramatically until the bands broke. Since there was no apparent failure of the material, just a constant deformation with increased stress, the team was not able to find the ultimate stress for the bales. Without these values, we determined that using tire bales in wall construction as load-bearing material would not be ideal.

The team tested the amount of sound absorbed by the bales. Initially they conducted tests in an acoustic laboratory to set baseline acoustic properties. Results of the laboratory test, conducted by the Johns Manville Technical Center Acoustical Laboratories, included third-octave band absorption data and the Sound Absorption Average (SAA) and Noise Reduction Coefficient (NRC) single number ratings. An SSA rating of 0.37 and NRC rating of 0.40 were reported for the small-scale noise barrier. These ratings indicated a barrier constructed from tire bales would significantly reduce the noise levels. Due to the irregular surfaces of the bales, barrier construction did not create a structure with a closely fitting array. During testing, air gaps were present along all interior surfaces of the array. Such gaps introduced greater numbers of partially exposed surfaces than would be experienced in a vertical configuration such as a highway barrier. As a result, acoustical results may be biased toward enhanced performance for this test. After construction of a prototypical wall along Interstate 25, field noise data obtained by Compliance Solutions confirmed an approximate 42 percent reduction in highway noise. Field tests were conducted in accordance with ASTM standards[8,9,10]

Fundamental Modeling of Thermal Properties: A Third-Year Design Study

A third-year mathematics and computer science team (Rebekah Zeck, Aaron Shock, Derek Hudson, and Ryan Sandusky) focused on developing a thermal model to determine effective conductivity for tire bales. These activities focused on developing a classic thermal model to determine effective conductivity for tire bales. Thermal properties of the tire bales would vary depending on the composition of the bale. The mixture of air and rubber would create resistance to the flow of heat through the bale. Effective conductivity, however, might characterize heat transfer through the bale similar to methods used in the oil and gas industry for determining porosity through oil fields. Combined with laboratory testing, a reasonable thermal model would create a potentially valuable tool to assess thermal and insulating properties as well as variations based on properties of the bales.

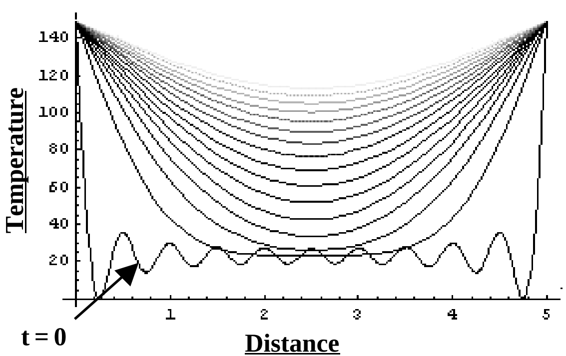

Figure 7: *Temperature Profile through Cross Section of Tire Bale Based on Thermal Model*

Simulation activities produced a mathematical representation of temperature distributions within the bale. The model, representing temperature as a function of position and time, was developed using Visual Basic because of its compatibility with Excel files and potential end-user applications for future research. Temperature distribution through the cross section of the bale using an effective diffusivity of 0.0202 ft^2/h approached the wall temperature with time, illustrated in Figure 7. Lines on the figure corresponded to families of temperature values for one dimension as a function of time. The simulation determined that after several hours the temperature profile approached a flat line equal to the temperature of the wall. These data verified that the model generates temperature distributions through a material over time.

Having confirmed the model, it could now be used to back out estimates of effective thermal properties from experimental temperature profiles. The team proposed to use the model to back out effective diffusivities for the tire bales. By adjusting thermal properties used in the model until the model results adequately represented the experimental data would generate an appropriate value for effective diffusivity. Thus the model would ultimately define effective thermal properties of tire bales based on experimental temperature profiles.

Testing at the Prototypical Wall

The prototype construction work package focused on constructing and testing a wall built from tire bales. A section of wall was constructed to test various configurations for noise


Figure 8: *Prototypical Tire-Bale Wall for Noise Abatement*

abatement. In addition to testing the reduction of noise, instrumentation was used to assess the structural integrity of the wall. Long-term tests would determine how well wall coatings would endure movement of bales due to natural conditions such as rain and wind and external conditions such as contact with moving objects. Several undergraduate students (Jeremy Lee, Adam Dressel, Darcy Wardle, and Neil Shea) supervised construction of a prototypical wall along Interstate 25 at Midway Tire Disposal in Colorado. The team proposed that the prototype would be approximately 9ft tall (four bales high) and 200ft. long, pictured in Figure 8. Deformation due to self-weight and rain and snow load would be negligible based on data obtained from the compression testing. The factor of safety corresponding to tipping of the wall due to wind load was 1.72.

Wall Coverings: Resource Assessment by Second-Year Design Teams

Teams of second-year students explored coverings to improve the aesthetics of the noise abatement wall. Their studies focused on identifying materials that can be used to cover the bales with minimum impact to the noise reduction. These teams developed a strategy to assess various materials that might serve to improve the appearance of the tire bale wall.

Radial Sound Redux (Adrien Butler, David Robertson, Christopher White, Brian Flannery, and Kevin Keil) considered potential materials to cover the tire bales as a method of improving their aesthetic quality. Paint would be thin and form fitting and would not appreciably increase the aesthetics of the tire bales. They discovered that panels need to be fabricated and could be expensive to install. They might be distracting if used for advertising or decoration, posing a safety hazard. Panels would help reduce the transmission of sound but their hard, flat surface would increase the deflection. Vegetation would require constant maintenance that would detract from its usefulness. Woodchips might not be aesthetic and would be difficult to apply. Woodchips and vegetation could add to the fire danger. Woodchips, vegetation and artistic decoration would be irregular so they would reduce deflection but would do little to hinder transmission. Drapes might weather poorly due to degradation from the sun or tatter due to the wind. They would also require a fire retardant additive or coating. Radial Sound Redux recommended a spray-on plastic or stucco, which would cover the bales, would blend into the environment and would be relatively easy to maintain. The coating would be applied in 200 ft sections, which would be separated by concrete dividers.

The Minegers (Nathan Hedrick, Jennifer Smith, OJ Bullard, Matt Hutchinson, and Jeremy Haberer) also considered various applications to improve the aesthetics of the tire bale wall including paint, drapes, rubber coatings, and stucco. They decided that the best solution was a tarp covering system. The system would include posts, the tarp and an external façade to break up the monotony along the barrier wall. The posts would be anchored to the ground using a break away design on a cement footer. The tarp would be fastened to the poles with screws through a series of grommets for easy replacement following an accident. The trap material would be a heavy-duty canvas with a Kevlar coating to reduce fire potential. Although the façade could be tailored to a community, an X cross bracing was proposed to strengthen the structure.

How does this project represent an authentic engineering design experience for engineering students?

Sometimes projects develop in response to research or marketing; sometime projects evolve from the creativity of an engineering design team. The Tire-Bale Project falls in the second category and illustrates the learning opportunities generated by the creativity of a first-year engineering design team (5 students) at CSM. The team visualized a unique and creative solution to the noise generated along the highways – a tire-bale wall. The effort of this team set in motion an engineering design project that involved 42 students working in 8 teams at various levels of their engineering education.

Based on the conceptual design, the Design (EPICS) Division procured funding from the CAMI, Tire-Tap Program. The project was contracted to a senior design team (4 students) from the Engineering Department, Civil Specialty. This team assumed the management role to synthesize the various design studies for the project. Second-year design teams assessed literature resources for information on tire bales. Three teams (15 students) explored the literature for information on properties, test methods, and market for tire bales. They identified testing procedures to measure structural, thermal and acoustic properties of the bales. They concluded that tire bales represented a realistic potential for construction with an emphasis on the government sector.

The definitive opportunity for the project centered on the construction of a prototypical wall at Midway Tire Disposal. A team of students (4 students) supervised construction of a 200 ft wall that successfully reduced the volume of noise from the interstate by approximately 40 percent.

Although functionally superior to other materials for noise abatement, an appropriate description of a tire bale wall is ugly. Two teams of second-year students (10 students) assessed potential covering to improve the aesthetics of the wall. Stucco and plastic spray on materials would offer the most beneficial solution to the aesthetics problem.

This project began and evolved through student involvement in the project as they practiced engineering design. With guidance from mentors, faculty, engineers, and others, these students designed and implemented an engineering design project that demonstrated the potential of a new resource, tire bales, to solve problems of interest to society, noise along the highways. The project combined technical, social, economic and political aspect characteristic of engineering problems. This project exemplified the advantages of an authentic engineering problem to practice engineering design.

This project not only created an environment for authentic engineering design but also confirmed the methodology underlying the design stem at CSM. The project created a situation in which students could explore and research a new material with very little recorded information. The first-year team demonstrated its creativity by visualizing a solution to the noise problem along the highways. The second-year teams gathered resources from the literature and the industry to feed the feasibility study for construction of a tire bale wall to reduce the noise. A third-year team developed a mathematical model to analyze the performance of tire bales based on thermal properties measured though experimental studies. The senior design team managed and synthesized the data and information from these other teams. Their effort came together with the construction of a 200 ft tire-bale wall that significantly reduced noise along the interstate. Having demonstrated the functional advantages of the wall, the project returned to the next issue, public acceptance of the tire bale wall. Second-year teams assessed various materials that improve the appearance of the walls. Students at various levels of their engineering education participated in the tire-bale project and addressed project issues based on their technical skills. This project illustrated the contributions of team members with varying levels of expertise to reinforce the advantage of engineering design project throughout the curriculum.

What value does an authentic engineering design experience offer to engineering students and design courses?

This project brought to various engineering design teams at CSM many of the characteristics of authentic engineering design. The Tire-Bale project evolved from the creativity of the first-year design team responding to the request for a new wall to abate noise along highways. This team converted its idea into a device for producing new materials, described as the basis for design by Douglas[1]. The senior design team took on the technical systematic and organizational aspects that Pahl and Beitz[2] indicated were the prerequisites for implementation of their solution. Each team assumed the responsibility to manage people and information consistent with Ullman's views[3]. The real focus of the project, however, conformed to Horenstein's definition[4] that the teams develop the desired specification for tire bales as a wall construction material. Equally important to the project, teams learned through the practice advocated by Bieniawski[5]. The Tire-Bale Project exemplified the authentic engineering design experience the Design (EPICS) Division hopes to initiate through the design stem at CSM.

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Biographical Information

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Robert Knecht spent 25 years in the industry focusing on technical and management support for minerals, energy and waste projects. He currently directs an engineering design program based on a curriculum that focuses on projects from industry. His projects require students to implement a design methodology in teams to resolve open-ended problems and to communicate both in written and verbal forms the results of their work.