COLORADO DEPARTMENT OF PUBLIC HEALTH AND ENVIRONMENT
ADVANCED TECHNOLOGY FUND RESEARCH GRANT
FINAL EVALUATION REPORT

submitted 11 March 2011
revised 22 April 2011

I. ORGANIZATION INFORMATION

1. Organization Name

University of Colorado Denver

2. Project Title

Trash to Treasure: Using Crumb Rubber from Recycled Tires for Storm Water Pollution Control

3. Name of Project Manager

David C. Mays, P.E., Ph.D.

4. Project Manager e-mail address and phone number

david.mays@ucdenver.edu
303-352-3933

5. Name of person(s) completing this report

David C. Mays, P.E., Ph.D.
Z. Jason Ren, Ph.D.
Emily P. Rhodes

6. E-mail address and phone number of person(s) completing this report

david.mays@ucdenver.edu
303-352-3933

zhiyong.ren@ucdenver.edu
303-556-5287

emily.rhodes@ucdenver.edu
950-250-5540

CONTENTS

II. WORK PLAN

Please use the format provided in the table below for your goals and objectives as listed in your Scope of Work. Only the deliverables due since your Bi-Annual Report are included. Indicate the date each deliverable was completed, or briefly describe why the deliverable was not completed.

Deliverable	Completion Date	If Deliverable Not Completed, Explain Why/Progress Made
Goal #1: Test Crumb Rubber Filters for Storm Water Pollution Control → Evaluate Removal of Storm Water Pollution	1/31/2011	
Goal #2: Evaluate Market Potential for Crumb Rubber Filters → Estimate Filter Service Life		The crumb rubber filter design used in this study is not recommended, so its service life was not estimated.
Goal #3: Transfer Technology to Business and Public Sectors → Report Research to Professional Organizations	12/17/2010	
Goal #3: Transfer Technology to Business and Public Sectors →Technology Transfer in Colorado	2/9/2011	

III. PROGRAM SUMMARY

1. Executive Summary

→ *provide overall summary of entire project*

Between February 2009 and January 2011, a team at the University of Colorado Denver performed a study to evaluate the feasibility of using crumb rubber from recycled tires for storm water pollution control. The objective of this project was to kill two birds with one stone: Recycle tires and protect water quality. The project was organized around three goals, (1) test crumb rubber filters for storm water pollution control, (2) evaluate the market potential for crumb rubber filters, and (3) transfer technology to the business and public sectors.

The primary focus was Goal 1, which was approached through a series of laboratory experiments that focused on zinc leaching, the principal concern for environmental applications of tire crumb rubber, and on filter performance compared to traditional sand filters. With regard to zinc leaching, this study provides a new level of understanding on the mechanistic basis for zinc leaching from tire crumb rubber. With regard to filter performance, 100% crumb rubber filters constructed following Urban Drainage and Flood Control District specifications were shown to be similar to sand filters that were evaluated in parallel. Crumb rubber filters did have increased flow rates and decreased clogging compared to sand filters, which is consistent with the larger size of tire crumb rubber used compared to filter sand. However, considering the balance of evidence, the 100% crumb rubber filters evaluated in this study are *not* recommended for storm water pollution control, because they leach zinc but do not convey superior filtration performance. The study did, however, generate a comprehensive set of zinc leaching measurements, which will provide guidance for environmental applications of tire crumb rubber. The study also suggests future research on mixed media models, in which crumb rubber is combined with sand or soil.

2. Project Description and Overview

→ provide a description of the project and why it was important for recycling in Colorado

In October 2008, the Colorado Department of Public Health and Environment (CDPHE) issued a request for proposals through their Advanced Technology Grant program. The goal of this program was to develop innovative uses of recycled materials, particularly waste tires, with the aim of supporting economic growth in the Colorado recycling industry while mitigating the environmental impact of Colorado's waste tire stockpile—one of the nation's largest. Professors David Mays and Jason Ren of the University of Colorado Denver responded to this request with a proposal entitled, "Trash to Treasure: Using Crumb Rubber from Recycled Tires for Storm Water Pollution Control." It addressed CDPHE's recycling objectives while also supporting environmental protection of streams and aquatic habitats. Preliminary work by others suggested that granular media filters using crumb rubber provided similar pollution removal as sand, with two potential advantages: (1) reduced clogging, and (2) improved removal of hydrophobic contaminants (i.e., oil and grease). Therefore, the goal of this study was to evaluate the feasibility of using crumb rubber instead of sand in storm water pollution control filters. In short, the goal was to kill two birds with one stone: Recycle tires and protect water quality.

After the grant was awarded, Dr. Mays and Dr. Ren interviewed several candidates for the graduate student research assistantship supported by this grant. The successful candidate was Emily Rhodes, an M.S. candidate in the Environmental and Sustainability Engineering program, a Colorado native with a prior degree in mathematics and a personal dedication to water quality partially stemming from her previous experience as a whitewater rafting guide. Starting in early 2009, the team met for an hour essentially every week through January 2011. Two additional rounds of interviews identified excellent undergraduate research assistants: Jeffrey Gee in summer 2009, and Philip Robinson in summer 2010. Ms. Rhodes earned 18 credit hours toward her M.S. degree for her work on this project, and Mr. Gee and Mr. Robinson each earned 3 credit hours toward their B.S. degrees. The team then set out to address the three goals outlined in the Scope of Work:

- Goal 1: Test crumb rubber filters for storm water pollution control.
- Goal 2: Evaluate market potential for crumb rubber filters.
- Goal 3: Transfer technology to business and public sectors.

The remainder of this report will be structured around these three goals.

3. Description of Work Completed

→ describe steps taken to meet the goals of the project

3.1. Test Crumb Rubber Filters for Storm Water Pollution Control (Goal 1)

Evaluating the technical feasibility of crumb rubber filters was the major task in this project, and required the majority of time and materials. As outlined in the Scope of Work, our investigation addressed two major topics, (1) zinc leaching, and (2) filter performance. Both were investigated using the custom-designed parallel filter apparatus shown in Figure 1. Complete details on this apparatus will be provided in the forthcoming M.S. thesis of Ms. Rhodes, who is scheduled to complete her graduate study at the University of Colorado Denver in May 2011. These two major topics will now be discussed in turn.

3.1.1. Zinc Leaching

Figure 1: Parallel filter apparatus, showing tire crumb rubber media on the left, and filter sand on the right.

Our first experimental task was to determine whether crumb rubber *adds* contamination to storm water, which was decision point #1 in our Scope of Work. The short answer is yes.

To address this question, we first consulted the literature on environmental applications of tire crumb rubber, which indicated that zinc leaching is the major concern. Zinc is added to tires during manufacturing, representing approximately 1% of tires by weight. For example, our contact at Michelin indicates their tires are approximately 1.6% zinc oxide by weight, equivalent to 1.3% zinc. The Environmental Protection Agency (EPA) has a maximum contaminant level (MCL) of 5 mg/L for zinc, which is the maximum concentration allowable in potable water. None of our experimental results had zinc concentrations above this MCL. However, while up to 5 mg/L of zinc are considered safe for human consumption, these levels are not considered safe for aquatic habitats, where the zinc can upset the steam ecology at much lower levels. Accordingly, the EPA has established a stream discharge standard of 0.117 mg/L, less than 1/40th of the MCL. Many of our experimental results, and data in the literature, exceed this more stringent standard. An overview of our measurements is provided in §4.1 below, and full details will be provided in the forthcoming M.S. thesis of Ms. Rhodes.

3.1.2. Filter Performance

Our second experimental task was to determine whether crumb rubber filters are effective for storm water pollution control, which was decision point #2 in our Scope of Work. The short answer is yes and no.*

To address the question of filter performance, we used the parallel filter apparatus to compare 100% crumb rubber and sand filters for the physical and chemical parameters listed in our Scope of Work: flow rate, clogging, suspended solids, metals, nutrients, chemical oxygen demand, oil and grease, and pathogens. The filter apparatus was constructed following Urban Drainage and Flood Control District specifications. An overview of our measurements is provided in §4.2 below, and full details will be provided in the forthcoming M.S. thesis of Ms. Rhodes.

* Yes, because crumb rubber filters provided pollutant removal with reduced clogging compared to sand. No, because our results have not confirmed the other expected benefit of crumb rubber filters, namely superior removal of oil and grease. Improved oil and grease removal was expected given the hydrophobic nature of crumb rubber, oil, and grease, which presumably would increase their affinity for each other.

3.2. Evaluate the Market Potential for Crumb Rubber Filters (Goal 2)

Before undertaking the experimental work described above, we first set out to determine whether there is substantial demand for crumb rubber filters, which was decision point #3 in our Scope of Work. The short answer is yes.

Although this was listed as goal 2 and decision point 3, it was evaluated first, because it was considered important to determine the potential market for crumb rubber filters before investing substantial resources in their development. Undergraduate research assistant Mr. Gee addressed this question in the summer of 2009, by formalizing the general methodology outlined in our proposal. His report, "Using Crumb Rubber from Recycled Tires for Storm Water Pollution Control: Regulation Summary and Market Report" was submitted to CDPHE on 8/31/2009, and is also included as an appendix to this report (§12.1). According to this report, replacing all the sand in Colorado's 132 existing storm water filters would require 1.3 million waste tires (2.4% of Colorado's current waste tire inventory). The report also estimated the *potential* demand for crumb rubber filters at 11 million tires (20% of current inventory).

3.3. Transfer Technology to the Business and Public Sectors (Goal 3)

Our third goal was to transmit the results of this study to Colorado's business sector—tire recyclers—and to the public sector—local, state, and national governments. Near the beginning of the project, we consulted with AcuGreen, the tire recycler who donated the materials used in our experimental study. We also consulted with personnel from EPA's Denver office, who were investigating other environmental aspects of tire crumb rubber. As the project developed, we established contact with Michelin Tire Company, who provided helpful data that we used to analyze zinc leaching. In the final month of the project, we presented our results to Denver's Urban Drainage and Flood Control District (UDFCD), a local governmental agency responsible for quantity and quality management of storm water in metropolitan Denver. We intend to maintain contact with these businesses and governments by providing them with a copy of this report, of Ms. Rhodes's M.S. thesis, and of the peer-reviewed technical article that we plan to submit based on this work. Additional details are provided in §8 below.

4. Describe the Measures or Indicators Used
→ methods or lab testing used to achieve results of the project

This section provides an overview of our measurement techniques required to test crumb rubber filters for storm water pollution control (Goal 1). Complete details will be provided in the forthcoming M.S. thesis of Ms. Rhodes. The methods used to evaluate the market potential for crumb rubber filters (Goal 2) are provided in Mr. Gee's report, included as an appendix to this report (§12.1). The methods used to transfer technology to the business and public sectors (Goal 3) are provided in §8 below.

4.1. Zinc Leaching

In order to understand the variables that control zinc leaching from tire crumb rubber, we performed three leaching tests, (1) EPA's synthetic precipitation leaching procedure, (2) batch leaching tests in laboratory beakers, and (3) column leaching tests in our parallel filter apparatus (Figure 1). In addition, we performed a modeling study to assist with interpretation of results.

4.1.1. Synthetic Precipitation Leaching Procedure (SPLP)

The SPLP is an EPA-approved standard method to measure leaching from solids into water that replicates precipitation—that is, storm water that has not yet accumulated any solutes or contaminants from the ground surface. A known mass of crumb rubber is added to a known volume of water (i.e., synthetic precipitation), and then agitated by rotation for 18 hours, before the concentration in the water is measured. We performed the SPLP for small, medium, and large crumb rubber.

4.1.2. Batch Leaching Tests

The SPLP provided insight into the relationship between leaching and crumb rubber size, but did not reveal information about leaching dynamics, because all samples were collected after 18 hours. Therefore, we performed three groups of batch leaching tests, in which a known mass of crumb rubber is added to a known volume of water, from which samples were extracted after various durations. These tests also compared leaching rates for agitated versus quiescent water and for washed versus unwashed crumb rubber.

4.1.3. Column Leaching Tests

Building on the SPLP and batch leaching tests, three column leaching tests were performed using the parallel filter apparatus. In these tests, a new batch of washed or unwashed crumb rubber was added to the filter column, which was then gradually saturated from below in order to drive out any entrapped air bubbles. Medium-sized crumb rubber was used in all tests, and no agitation was provided to the crumb rubber (although it was not quiescent because water was flowing through the columns). Thereafter tap water was added to the top of the filter at a known flow rate, and samples were collected at increasing times.

4.1.4. Leaching Modeling

In order to develop a more mechanistic understanding of the leaching process, a preliminary leaching model was developed, and then fitted to one of the three column leaching tests. The model shows that the leaching history—concentration versus time—is consistent with the simultaneous action of two processes: (1) a non-equilibrium sorption model describing the transfer of zinc from the crumb rubber to the water and its subsequent transport in the water, and (2) a particle mobilization model describing the initial mobilization of very small particles, perhaps from tire wear, into the infiltrating water. The model was implemented using the software HYDRUS-1D, which is available free of charge from the U.S. Department of Agriculture.

4.2. Filter Performance

In order to determine whether crumb rubber filters are effective for storm water pollution control, we performed seven filtration tests on the parallel filter apparatus (Figure 1). In each test, one column was filled with medium-sized crumb rubber, and the parallel column was filled with filter sand meeting UDFCD criteria for sand filters. Flow rates were measured my clocking the time required to fill a graduated vessel. Clogging was measured by reading hydraulic head levels in a series of piezometers. Pollutant removal was measured by measuring the influent and effluent concentrations, sometimes with a single representative effluent concentration, and sometimes with time series of effluent concentrations.

5. Summary of Unanticipated Outcomes or Roadblocks
→ *describe how the outcomes or roadblocks impacted the project*

Several unanticipated outcomes and roadblocks were encountered during this project:

- Crumb rubber floats. This was a surprise, because the density of crumb rubber (1130-1160 kg/m^3) is larger than that of water (1000 kg/m^3), so it should sink. It does, in fact, after sufficient agitation, or when the water includes a trace of detergent. But when dry crumb rubber is added to water, it likely contains small air bubbles that render it buoyant. As a result, we had to modify our filter column to prevent floating at the top.
- Crumb rubber is not uniform. On several occasions, we had difficulty repeating our experimental results. Although we cannot categorically rule out human or instrumentation error, it appears likely that the difficulty achieving more repeatable results is caused by physical or chemical differences in the crumb rubber itself, even within the same bag. The non-uniformity of crumb rubber has also been noted in the technical literature.
- Zinc analysis is difficult. This was a surprise, because Hach Company (Loveland, Colorado) provides an EPA-approved test kit for zinc analysis, which we presumed could be used successfully by a conscientious, detail-oriented graduate student like Ms. Rhodes. This presumption turned out to be false. Instead, we shipped out leaching and filter samples for analysis by a commercial laboratory, which had the effect of delaying the schedule, so our experiments were not complete by our initial target of 8/27/2010.
- Industry interest was inconsistent. The former tire recycling company AcuGreen was very supportive of this project, writing a support letter for our proposal, and providing all the crumb rubber that we needed. AcuGreen's successor company, Caliber Recycled Products, initiated e-mail contact with our team, demonstrating that they too were interested. However, by January 2011, when it came time to present our results to an industry-government audience, Caliber Recycled Products was no longer in business, and none of the other tire recyclers we contacted (see §8 below) attended our workshop on 2/9/2011. As a result, the only attendee at that workshop was from UDFCD.

6. Summary of Findings and Results
→ *based on work completed*

This section summarizes the results for the zinc leaching and filter performance tests (Goal 1). Complete details will be provided in the forthcoming M.S. thesis of Ms. Rhodes.

6.1. Zinc Leaching

Our experimental and modeling results were presented in the session entitled "Metal Sorption on Organic and Inorganic Surfaces: From Laboratory to Model to Field" at the American Geophysical Union's Fall Meeting in San Francisco, California in December 2010, which is included as an appendix to this report (§12.2.2). Key leaching results are summarized below:

6.1.1. Synthetic Precipitation Leaching Procedure (SPLP)

Results from a suite of metals confirmed that zinc was the only leachate of concern. Zinc results were above the EPA stream discharge limit of 0.117 mg/L, but below the MCL of 5 mg/L. In particular, these results showed a definite trend: More leaching from small crumb rubber, less leaching from large crumb rubber. In particular, the leaching from large crumb rubber was approaching the EPA stream discharge limit. Since the SPLP was considered an extreme test—with slightly acidic pH and extended agitation—these results were not considered sufficiently adverse to obviate the remainder of the project.

6.1.2. Batch Leaching Tests

Results can be summarized as follows:

- zinc concentrations ranged from 0.2 to 4.5 mg/L
- leaching increased with time
- no significant difference between agitated versus quiescent samples
- no significant difference between washed versus unwashed samples
- large variability between replicates

6.1.3. Column Leaching Tests

After an initial pulse in which the zinc concentration rises as high as 2.7 mg/L, effluent concentrations rapidly dropped to a value no more than double the EPA stream discharge limit of 0.117 mg/L. Washed crumb rubber also showed an initial pulse, but its magnitude was only about half the magnitude of the unwashed crumb rubber, suggesting that some of the initial pulse resulted from very small particles, perhaps from tire wear, that were removed during washing. The long-term effluent concentrations, however, were similar for washed or unwashed crumb rubber. Like the batch leaching tests, these column leaching tests had large variability between replicates.

6.1.4. Leaching Modeling

Results of this model were presented in our December 2010 poster, which is included as an appendix to this report (§12.2.2). The key insight from this modeling exercise was that a single mass transfer coefficient may be sufficient to explain the long-term leaching after the initial mobilization of very small particles has passed. Further analysis is required to confirm this hypothesis. But, if confirmed, it suggests that slower leaching rates could result in higher effluent zinc concentrations.

6.2. Filter Performance

Results of the filtration tests are summarized in Table 1. It should be noted that, as in the batch and column leaching experiments, there is large variability between replicates. With only two exceptions, the performance of tire crumb rubber filters was similar to the parallel sand filters. The two exceptions, where tire crumb rubber filters were superior, were

Table 1: Summary of performance of tire crumb rubber and sand filters.

Parameter	Tire Better	Similar	Sand Better	Comment(s)
Flow Rate	✓			Only sand filter clogged.
Clogging	✓			Only sand filter clogged.
TSS[a]		✓		Both filters performed well.
Metals		✓		Both filters performed well.
Nutrients		✓		Both filters performed poorly.
COD[b]		✓		Both filters performed poorly.
Oil and Grease		✓		Both filters performed well.
Pathogens		✓		Both filters performed well.

[a] TSS is Total Suspended Solids
[b] COD is Chemical Oxygen Demand

flow rate and clogging. These advantages almost certainly result from the fact that the tire crumb rubber used was larger than the filter sand, which would therefore give it higher flow rates and greater resistance to depth clogging—measured by increased head loss distributed over the depth of the granular media. Using unequal media sizes was a deliberate choice for two reasons. First, we chose to compare a standard size of tire crumb rubber to a standard size of filter sand, in this case, following UDFCD specifications. Second, previous research by others had indicated that larger tire crumb rubber had similar pollution removal efficiency as smaller sand, and therefore conveyed the benefit of increased flow rates and decreased clogging without detriment to pollution removal.

7. Financial Summary
→ *indicate how funds were spent during the project, including any matching/in kind funding*

Grant Budget Table

Description	Grant Funds Spent	Matching/In Kind Amount Spent (if any)	Total Amount
Personnel Salaries and Wages	$52,123.36		$52,123.36
Fringe Benefits	$3,819.32		$3,819.32
Tuition/Fees	$9,278.75		$9,278.75
Travel Costs	$1,071.40		$1,071.40
Materials/Supplies/Equipment (under $5,000)	$12,202.66		$12,202.66
Equipment Purchases (over $5,000)			
Contractors/Subcontractors			
Consultants			
Training/Educational classes			
Marketing/Advertising			
Other Direct Costs			
Indirect Costs	$13,843.34		$13,843.34
Total Project Cost:	**$92,338.83**		**$92,338.83**

8. Communication to Colorado Businesses and Communities
→ *how are the results going to be communicated*

Following the Scope of Work, in January 2011 we contacted the two organizations that had written support letters in our 2008 proposal to invite them to a workshop on storm water filtration with tire crumb rubber. Mr. Ken MacKenzie of UDFCD accepted this invitation. Response from the private sector was comparatively muted. Mr. Richard Cookson of Caliber Recycled Products (the successor company of AcuGreen) replied to our invitation, but indicated that his company was no longer in the tire recycling business. This prevented us from scheduling the workshop before the official project completion date of 1/31/2011. We identified three Colorado tire recycling companies, and e-mailed them invitations on 1/27/2011, about two weeks before the workshop on 2/9/2011. Two companies did not reply to our e-mail. The third did not attend the meeting, but requested an electronic copy of our presentation (see §12.3.3). We sent the presentation by e-mail shortly after 2/9/2011.

Although it is not a Colorado-based business, we have also established contact with the Michelin tire company. They expressed interest in our research, and provided data regarding the quantity of zinc in Michelin tires that was helpful in the leaching modeling.

In addition to these efforts to present this project to industry, this work has been presented many times to date, including one report to CDPHE, two posters at research meetings, and three talks to academic and government audiences (see §12). Complete technical details will also be provided in the M.S. thesis of Ms. Rhodes, and in our forthcoming peer-reviewed manuscript.

9. Recycling Impact in Colorado
→ *how are the results of the project going to impact future recycling in Colorado*

Considering the balance of evidence, the 100% crumb rubber filters evaluated in this study are *not* recommended for storm water pollution control, because they leach zinc but do not convey superior filtration performance. We cannot, therefore, claim any immediate recycling impact in Colorado. The study did, however, suggest future research on mixed media filters, in which crumb rubber is combined with sand or soil.

10. On-Going Research and Development
→ *indicate if further research will be needed and how it will be completed and funded*

The work reported here suggests three areas of continued research:

1. Leaching modeling. The HYDRUS-1D modeling reported in our December 2010 poster is a preliminary effort based on a single column leaching test. Additional analysis of the SPLP, batch, and column leaching tests could lay the foundation for a general, mechanistic model of zinc leaching from tire crumb rubber, validated against an extensive set of experimental measurements. Such a model would provide the understanding necessary for judicious use of tire crumb rubber not only for storm water filtration, but also in other environmental applications. The project team intends to perform such an analysis in preparation for a peer-reviewed manuscript submission.
2. Mixed media filters. Since zinc leaching is the major drawback of 100% crumb rubber filters, a possible solution would be to mix the tire crumb rubber with another granular

medium that would absorb aqueous zinc leached from the tire crumb rubber. One approach would be to blend the media within the filter—work along these lines has already been performed by several investigators, including Shauna Kocman, James Guo, and Anu Ramaswami of the University of Colorado Denver. Another approach would be to engineer the filter such that the 100% tire crumb rubber does not drain directly to a receiving water body, but rather infiltrates through soils or aquifer materials first, allowing the natural granular media to absorb aqueous zinc. We are not aware of previous attempts to use this approach in engineered storm water filters, although it has been recognized that infiltration into soils mitigates zinc leaching from tire crumb rubber used under artificial turf fields.

3. Use larger sand. Since the major advantage of tire crumb rubber appears to be its hydraulic performance—rather than its ability to remove hydrophobic contaminants—it may be advantageous to test traditional sand filters using larger sand, either as a complete replacement, or as a blended amendment to the standard size. If successful, such an approach would convey the benefit of tire crumb rubber without the concerns regarding zinc leaching.

11. Conclusion

→ final comments on the project and thoughts on the Advanced Technology Grants Program

This work allows us to make the following conclusions and recommendations:

- The 100% crumb rubber filters evaluated in this study are *not* recommended for storm water pollution control because they do not convey superior filtration performance and leach zinc.
- Zinc leaching from 100% crumb rubber filters resulted in effluent concentrations that were consistently below the drinking water MCL of 5 mg/L, but above the more stringent EPA stream discharge limit of 0.117 mg/L.
- Mixed media filters including tire crumb rubber show promise, based on work by others, but such a design should be evaluated for zinc leaching before deployment.
- If used in a mixed media filter, crumb rubber should not be used on the top layer without some mechanical constraint to prevent loss by floating.
- Based on our column leaching tests, washing tire crumb rubber reduces zinc leaching, during the initial pulse. This is consistent with our conceptual model that attributes this initial pulse at least partially to very small particles. Washing is therefore recommended.

Our team is grateful to CDPHE's Advanced Technology Grant program for supporting research and development on beneficial uses for recycled materials. Although the particular filter design evaluated in this study is not recommended, the work generated perhaps the most detailed measurements to date on zinc leaching from tire crumb rubber, and identified three specific areas where future research is needed. This grant also provided excellent research experience for three students at the University of Colorado Denver, supporting our mission to provide teaching, training, and research for the benefit of the State of Colorado.

12. Appendix

→ *Manuals, Brochures, Print Advertisements, Pictures, Educational Materials, etc.*

This section lists reports, posters, and talks documenting the evolution of the project. They will be submitted in a separate document "ATG Final Report CU Denver Mays APPENDIX.pdf".

12.1. Report

1. "Using Crumb Rubber from Recycled Tires for Storm Water Pollution Control: Regulation Summary and Market Report," by Jeffrey Gee, David Mays, Jason Ren, and Emily Rhodes, submitted to CDPHE on 8/31/2009.

12.2. Posters

1. "Tire Crumb Rubber in Storm Water Filtration," presented by Emily Rhodes at the Research and Creative Activities Symposium at the University of Colorado Denver's Anschutz Medical Campus on 4/30/2010.

   → *Ms. Rhodes won the 2010 outstanding graduate student research award, and was therefore invited to give a talk at this symposium. That talk was given again at the 2010 AWWA/WEF Student Conference at the University of Colorado Boulder (see below).*

2. "Zinc Leaching from Tire Crumb Rubber," presented by Emily Rhodes in the session entitled Metal Sorption on Organic and Inorganic Surfaces: From Laboratory to Model to Field at the American Geophysical Union's Fall Meeting in San Francisco, California on 12/17/2010.

   → *Poster focusing on measurements and modeling of zinc leaching from crumb rubber.*

12.3. Talks

1. Presentation by Emily Rhodes at a research seminar at the University of Colorado Denver on 6/30/2009.

   → *This talk provides an introduction to the project, including filtration theory.*

2. Presentation by Emily Rhodes at the AWWA/WEF Student Conference at the University of Colorado Boulder on 5/18/2010.

   → *This talk was also given as Ms. Rhodes's award presentation at the Research and Creative Activities Symposium at the University of Colorado Denver's Anschutz Medical Campus on 4/30/2010 (see above).*

3. Presentation by Emily Rhodes at a workshop, held at the University of Colorado Denver on 2/9/2011, for local industry and regulatory professionals concerned with tire recycling and storm water.

   → *This talk summarizes the entire project, except for a few final experimental results.*