Final Report

Recycled Material Research Center

University of Wisconsin - Madison

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Project: Long-Term Drainage Performance of Mechanically Stabilized Earth Retaining Walls with Recycled Materials

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Executive Summary

With the expansion of transport, commercial, and residential infrastructure to support the needs of a growing populous, greater amounts of construction materials are required. This places an increased amount of stress on natural resources. While the demand for aggregates continues to increase, construction and demolition wastes generated from industrial operations and construction activities, such as crushed concrete from demolition, continue to increase as well. Much of the wastes are produced from either Portland cement concrete or asphalt concrete demolition, representing a large potential source of aggregates for infrastructure projects such as mechanically stabilized earth (MSE) walls. Although showing solid strength and stiffness properties, utilization of recycled concrete and asphalt aggregates is limited due to drainage complications and corrosive leachate.

The objective of this study was to evaluate the drainage capability of concrete and asphalt aggregates, chemical clogging potential associated with tufa formation, and the corrosivity of the aggregate leachate to MSE wall reinforcements. Laboratory experiments conducted to complete these objectives include materials characterizations, gradation and particle breakage evaluation, rigid and flexible wall saturated column testing, calcareous tufa precipitation experiments, geotextile permittivity testing, pH and electrical resistivity testing. Computer modeling was utilized as well with the support of laboratory data. Numerical variable saturated flow models were developed to understand the drainage capabilities of the recycled aggregates to a greater degree using simple MSE wall geometry. Geochemical block modeling was utilized to understand the saturation of calcite in the leachate solution and to model the maximum precipitation potential of the leachate.

Results provided information regarding the drainage capabilities of recycled materials as well as the corrosivity of the leachate produced. Column testing and variable saturated flow modeling classified recycled concrete aggregates as fair to very poor draining materials at the tested gradations, while cleaner reclaimed asphalt aggregates were found to be excellent to good draining materials, highlighting the importance of minimizing fines and fine sand if good drainage performance is desired. In addition, recycled concrete aggregates were found to break more easily compared to virgin aggregates. From tufa precipitation experiments, it was observed that leachate from concrete aggregates possesses high potential for tufa precipitation over extended periods and multiple drainage cycles. It was confirmed that tufa precipitation can occur without evaporation, concentrated CO_2 environment, or large temperature swing. The amount of tufa that can be precipitated is proportional to the leachate passing through the aggregates. Therefore, the drainage capacity of the aggregates controls the tufa precipitation to a great extent. Blending of concrete and granite aggregate assists in lowering the potential for tufa formation, although it may not be as practical in the field. Corrosivity testing showed that concrete aggregates struggled to meet both pH and electrical resistivity standards per WisDOT, while asphalt aggregates were better able to meet these standards.

Project Objectives

The central objective of this project was to provide greater context and information regarding the potential usage of recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) as backfill aggregates within the reinforced zones of mechanically stabilized earth (MSE) retention walls. Specifically, the project aimed to achieve the following objectives:

Objective 1: Evaluate the drainage capacity of RCA and RAP through a battery of flexible and rigid wall saturated hydraulic conductivity testing as well as variably saturated computer modeling.

Objective 2: Understand the potential for RCA leachate to precipitate calcareous tufa over extended periods and associated clogging risk.

Objective 3: Evaluate the corrosivity of RCA and RAP to MSE wall reinforcements

Summary of Activities and Findings

In this project, 8 RCA and 2 RAP samples were collected from different locations in Wisconsin. The samples included aggregates stockpiled for different ages, from freshly crushed to 7 years. All samples utilized in the experimental evaluations conformed to the gradation specifications of Type B MSE wall backfill as designated by WisDOT (see Fig. 1 and Table 1). The following sections summarize the tests and results obtained under the three objectives.

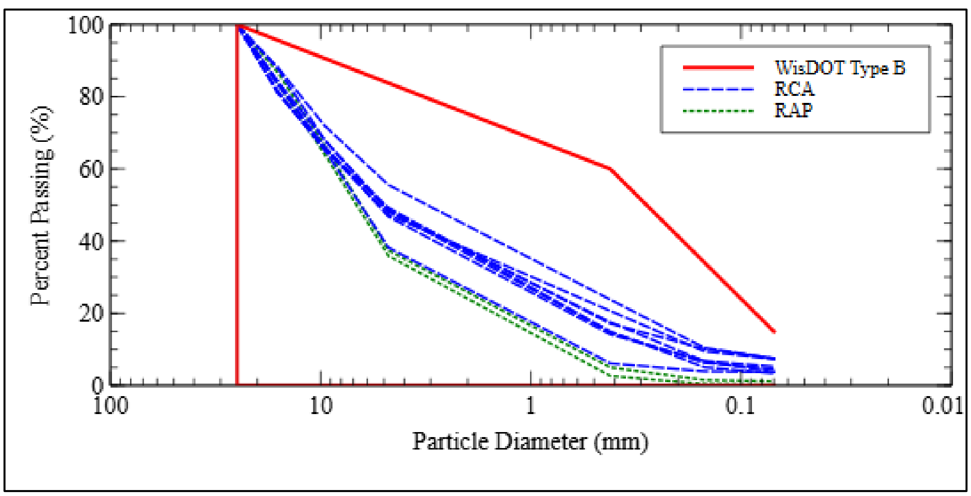

Figure 1. Grain size distribution curves of all materials and WisDOT Type B backfill specification bounds.

Table 1. Summary of gradation indices and values associated with saturated hydraulic conductivity column testing.

Sample*	Source	AASHTO Class.	C_u	C_c	D10 (mm)	D30 (mm)	D60 (mm)	% Fines
DC-10	RCA	A-1-a	50.3	1.2	0.14	1.13	7.18	7.48%
DC-1	RCA	A-1-a	35.5	0.9	0.20	1.13	7.23	3.78%
DC-7	RCA	A-1-a	43.2	0.6	0.13	0.67	5.76	7.49%
MC-1	RCA	A-1-a	30.7	0.8	0.25	1.22	7.64	3.39%
DC-6	RCA	A-1-a	49.6	0.8	0.16	0.98	7.75	7.28%
DC-8	RCA	A-1-a	14.9	1.4	0.56	2.56	8.35	3.73%
RC-1	RCA	A-1-a	32.0	0.9	0.24	1.26	7.53	4.56%
RC-2	RCA	A-1-a	33.0	1.0	0.23	1.37	7.69	5.25%
DRAP-1	RAP	A-1-a	12.1	1.5	0.72	3.09	8.66	0.17%
DRAP-2	RAP	A-1-a	13.4	1.5	0.61	2.73	8.19	1.15%

Objective 1: Drainage Capacity Analysis

This objective is to evaluate the drainage performance of RCA and RAP as MSE wall backfill materials. Tasks here focused on estimating the drainage capacity based on physical properties characterizations, hydraulic conductivity measurements, and numerical flow simulations. Chemical properties of RCA were further studied in later tasks.

According to the current WisDOT specifications, two types of backfill gradations, namely Type A and Type B, are utilized within the reinforced zone of MSE walls. Type A consists of predominately gravel sized particles and is used within 1 foot of the facing panel of modular block MSE walls. Type B is used in the rest of the reinforced zone for modular block MSE walls and also the entirety of the reinforced zone for concrete panel MSE walls. The specified gradation bounds for Type B are rather wide, with all RCA and RAP samples tested meeting the specification. With these materials potentially exhibiting large variability, empirical methods that can estimate their drainage performance from gradation may be helpful in the design of MSE walls.

Before correlating gradation to drainage performance, several issues should be clarified. First, it was found that the recycled materials, especially RCA, can exhibit noticeable particle breakage (Fig. 2), leading to fines generation that can reduce drainage performance. Therefore, changes to the gradation from compaction should be considered when estimating the drainage performance. Second, when measuring the saturated hydraulic conductivity, flexible wall permeameter is better suited for RCA than rigid wall. All RCA samples tested in this study showed significant heterogeneity, causing strong sidewall leakage effect in the rigid wall setup even when the permeameter diameter to maximum grain diameter ratio conformed to ASTM standards. It was found that rigid wall permeameter could overestimate the saturated hydraulic conductivity by an order of magnitude. The sidewall leakage also induced fines migration in RCA samples, which was not observed in the flexible wall setup. The difference between rigid wall and flexible wall results is much less for RAP, which in general has less fines content and heterogeneity as well as higher hydraulic conductivity than RCA. Finally, it should be emphasized that there is a lack of consistent methods to classify a material's drainage capacity as good versus bad. Ideally, the drainage performance should be evaluated within the specific application taking into account the material's hydraulic conductivity as well as the structure geometry and size.

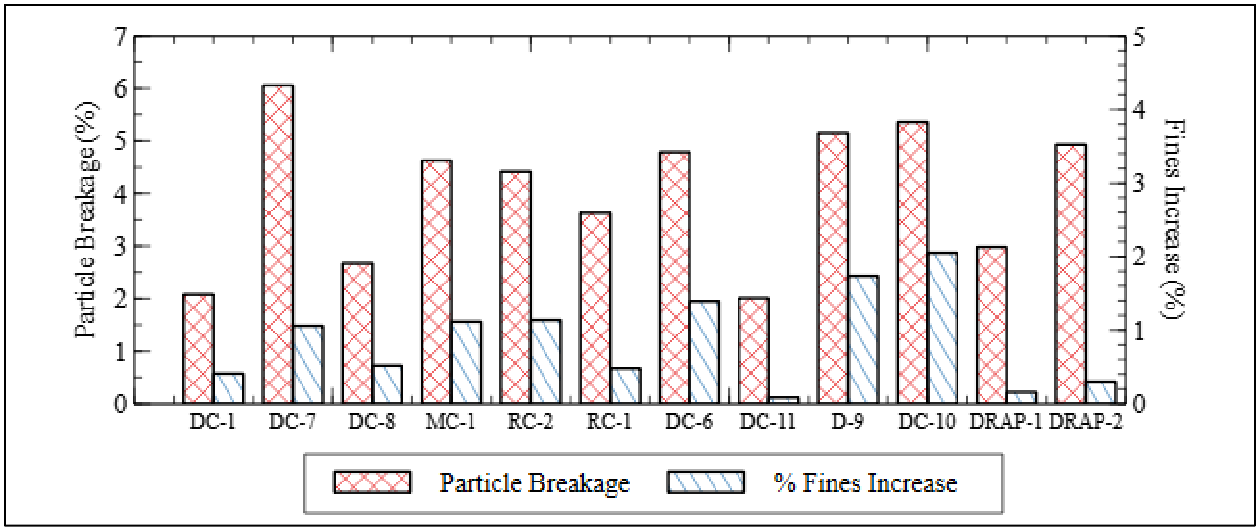

Figure 2. Particle breakage and percent fines increases (mass %) for the tested materials. Particle breakage was calculated utilizing Hardin breakage indices.

Utilizing standards outlined in Terzaghi and Peck as well as Casagrande and Fadum, which is solely based on the material's saturated hydraulic conductivity, all materials tested in both flexible wall and rigid wall permeameters are considered good draining materials (Casagrande and Fadum 1940; Terzaghi et al. 1996). However, different classifications were obtained based on the drainage performance of a 10-meter tall by 7-meter-wide rectangular backfill structure, simulated by 1-dimensional variably saturated flow simulation and experimentally measured material properties. The drainage classification in this case was taken based upon the modeled time to 50% drainage of allowable water (i.e., defined in the results as time to from 100% to 50% effective degree of saturation), based on drainage standards developed by AASHTO and Seeds et al. (Seeds and Hicks 1991). Results of these simulations classified the RAP aggregates as good draining materials. RCA, however, could be classified at best fair draining materials and at worst very poor draining materials. Results of these analyses are summarized in Table 2.

Table 2. Qualitative drainage evaluation of RCA and RAP aggregates.

Material	Saturated Hydraulic Conductivities (cm/s)	Terzaghi et al. Classification	AASHTO Drainage Classification
RCA	5.8E-3 – 1.1 E-4	Good	Fair to Very Poor
RAP	1.3E-3 – 1.2E-3	Good	Good

It should be noted that all materials tested conformed to MSE wall reinforced Type B backfill gradation standards. Maximum acceptable percent fines for Type B backfill is 15% by mass. Most samples tested had fines content <6% with the exception of three RCA samples that had ~7.5%. Nonetheless, based on the drainage performance evaluation above, RCA Type B backfill cannot be relied upon as a free-draining material without additional drainage design considerations. To this end, several empirical methods were also evaluated for predicting the laboratory saturated hydraulic conductivity from sample gradation. The optimized Hazen equation, which uses D_{10} to estimate hydraulic conductivity, was found to produce the closest results when an optimized Hazen coefficient of 2.02 was used for RCA and 25.7 for RAP.

<u>Objective 2: Ambient Precipitation of Calcareous Tufa and Clogging</u>

Drainage issues caused by tufa formation have been observed for RCA road base in the field. Tufa is solid calcium carbonate material grown from calcium bearing solutions. Mechanisms for tufa formation from RCA leachate investigated in previous laboratory studies include direct reaction between the leachate with carbon dioxide (CO_2) and evaporation. Although both are possible mechanisms, their processes are slow in field conditions and require ample air flow and large quantities of stagnant solution that are unlikely to be found in roadway drainage systems. In fact, natural tufa is formed via a different mechanism, i.e., calcium carbonate precipitation from supersaturated solutions. With this mechanism, tufa can grow out of flowing water and the process can be rapid as long as there is a surface favorable for tufa growth.

For RCA used in the field, tufa formation can be initiated by rainwater passing through the material. Rainwater is mildly acidic (pH 5-6) due to dissolved CO_2 from the ambient air. Upon contacting RCA, rainwater will initially leach calcium out of the residual cement and cement paste. As the leachate passes through RCA that is alkaline in nature, the pH will be raised to >11. This increase in pH will cause the leachate to become supersaturated with calcium carbonate. When the leachate exits the RCA and is exposed to an open environment, it will degas CO_2 and precipitate tufa. As such, tufa formation is most likely found in drainage systems. Here, a surface that is favorable for tufa growth is required initially. Minerals, metals (with oxide passivation layer), and surfaces with biofilm buildup are all common places to initiate tufa growth. Once initiated, tufa can continue to grow out of the supersaturated solution.

To quantify the tufa formation potential of RCA through this mechanism and clarify discrepancies between previous laboratory studies and field observations, experiments using a seepage cell setup were performed. In this setup, air-equilibrated water simulated rainwater flow through a seepage cell containing RCA. The water exiting the cell is drained into an aluminum pan containing materials commonly used in MSE wall systems, including geotextile, geogrid, and galvanized steel. The tufa formation potential is evaluated by analyzing the outlet solution composition using ICP-OES and geochemical modeling. Direct observations and characterizations of tufa growth on different material surfaces were also conducted. It should be noted that, as the seepage cell was operated continuously, 22 days of the flow is roughly equivalent to 10 years of Southern Wisconsin precipitation that the RCA is expected to experience in the field.

Results from the experiment showed substantial growth on the surface of the geosynthetic reinforcement materials, galvanized steel bars, and the aluminum pan. Characterizations confirmed that the growth was calcareous tufa. Based on solution analysis, the leachate had more or less constant tufa precipitation potential at around 0.5 grams per day over the course of the experiment. This suggests that, when used in MSE walls, water drained through RCA backfill will have the ability to precipitate tufa in the drainage system over extended periods. The permittivity of the non-woven geotextile used in the seepage cell was evaluated after the experiment, which showed 34% reduction comparing with the pristine geotextile (Fig. 3). However, it should be noted that the same geotextile used in the hydraulic conductivity testing under Objective 1 also showed reduction in permittivity due to fine particle clogging. RCA having larger fines content and smaller D_{10} resulted in greater reduction and the highest reduction (DC-1) was similar to that from the tufa experiment. This highlights the importance of clean, resilient backfill material that minimizes the number of fines present and does not break down under dynamic compaction energy, independent of whether tufa precipitation is of concern.

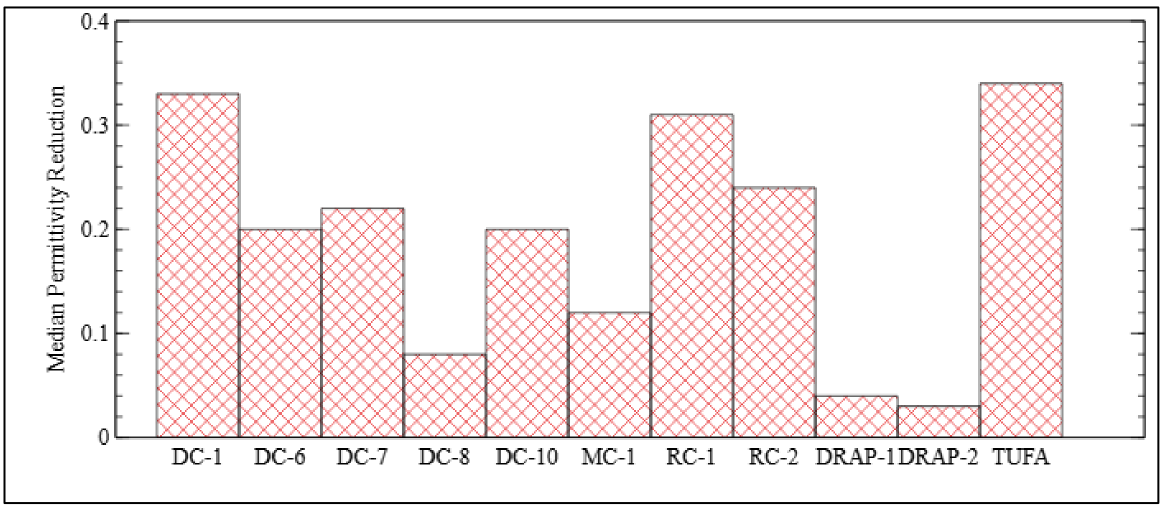

Figure 3. Median permittivity reduction of geotextile samples with material clogging and calcite tufa growth.

Although the leachate from RCA backfill can generate tufa precipitation over extended periods, the quantity of tufa that can be precipitated in reality is proportional to the amount of leachate passing the structure. If the RCA tested in this study was used in a MSE wall, a significant amount of time will be needed for the leachate to reach the bottom of the backfill under normal precipitation conditions. Based on the 1-dimensional variably saturated flow simulation under Objective 1 and using precipitation data in Madison, WI from April 2018 to October 2018, it would take roughly 150 days before the bottom of the backfill of a 10-meter tall MSE wall to experience the first wetting cycle (Fig. 4; The upper node indicates the top of the wall and the lower/interface nodes represent the bottom of the wall). The amount of leachate that will pass through the backfill in a year like 2018 is very limited due to the limited drainage capacity of RCA.

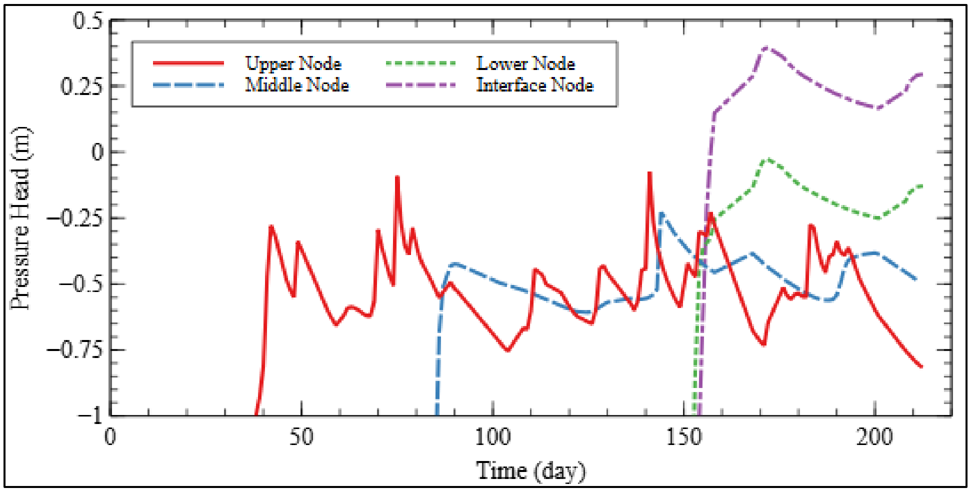

Figure 4. Pressure head versus time results of the model dependent on location within the reinforced zone.

In summary, tufa precipitation from RCA leachate can occur without evaporation, concentrated CO_2 environment, or large temperature swing, and can persist for extended periods after construction. However, the tufa precipitation issue needs to be considered together with drainage design. Highly drainable RCA will have high potential to generate tufa growth in the drainage system, and vice versa.

Objective 3: Corrosivity Evaluation

Current WisDOT specifications require the leachate from MSE wall backfill to have a pH between 4.5-9 when geosynthetic reinforcements are used, 5-9 in the case of aluminized steel (type 2) reinforcements, and 5-10 for galvanized steel. In addition, for aluminized and galvanized steel, the backfill electrical resistivity should be higher than 1500 and 3000 Ω·cm respectively. In the case of RCA backfill, the concern is the high leachate pH, resulting from the dissolution of calcium hydroxide and the hydration of residual cement, could be corrosive to the reinforcements. For geosynthetic reinforcements, the high pH solution can hydrolyze the polymeric compounds, leading to strength degradation. For steel reinforcements, aluminum and zinc can form flaky hydroxide in alkaline solutions, leading to the loss of the protective coating on the steel surface. The presence of soluble salts in RCA, such as chloride salts used for deicing and sulfates from the environment, will further accelerate the steel corrosion once the proactive coating is dissolved.

In the tufa precipitation experiment, zinc hydroxide ("white rust") was found on the galvanized steel bar after a single day of contacting the RCA leachate, hinting at the alkaline corrosiveness of the leachate produced. Indeed, based on the leachate pH testing, none of the RCA samples met either the galvanized steel ($pH<10$) or the geosynthetic/aluminized steel ($pH<9$) reinforcement requirements as specified by WisDOT. However, the RAP aggregates, had lower pH levels compared to their RCA counterparts and met standards for galvanized steel reinforcement, but not geosynthetic/aluminized steel reinforcement. The dolomitic virgin aggregate showed similar results to RAP. The only material that met $pH<9$ was the granitic virgin aggregate sample.

Although none of the RCA specimens outright met any of the pH standards, there was an observable trend amongst the pH levels and the stockpile time of the sample. It was found that fresher RCA samples produced higher pH levels, ranging between 10.8 to 11.3 for samples stockpiled for under a year. Samples stockpiled for over a year observed lower pH levels, ranging between 10.5 to 10.6. This difference in pH is likely attributed to carbonation weathering, where exposed calcium hydroxide reacts with atmospheric or aqueous carbon dioxide to produce calcite. However, the reduction in pH is limited due to the structural nature of the stockpile. It can be expected that the outer area exposed to the atmosphere and rain will be carbonated relatively quickly. However, that level of carbonation may not be achieved for material closer to the core of the stockpile.

After observing that RCA did not meet any of the pH requirements for metallic reinforcement and that RAP and the virgin aggregates met either one or both requirements, blending aggregates was tested. RCA was blended with RAP, dolomitic, and granitic virgin aggregate at various percentages to observe whether pH levels could be reduced to acceptable levels. The procedure was first conducted with DC-11, an older RCA that was stockpiled for 3 years. As shown in Fig. 5, the results showed that none of the RCA blends with the dolomitic virgin aggregate or the RAP aggregate produced acceptable pH results. However, the granitic virgin aggregate blend produced a pH lower than 10 when the RCA mass percentage was at or below 40%. This test was repeated for a fresher RCA, MC-1. The results showed a similar trend; however, because of the high RCA pH, acceptable pH levels were only achieved below 20% RCA mass percentage. In summary, these results show that with the combination of stockpiling and blending, RCA aggregate blends can produce leachates with pH levels acceptable to DOT requirements. However, such practices, especially blending, might not be practical in many applications.

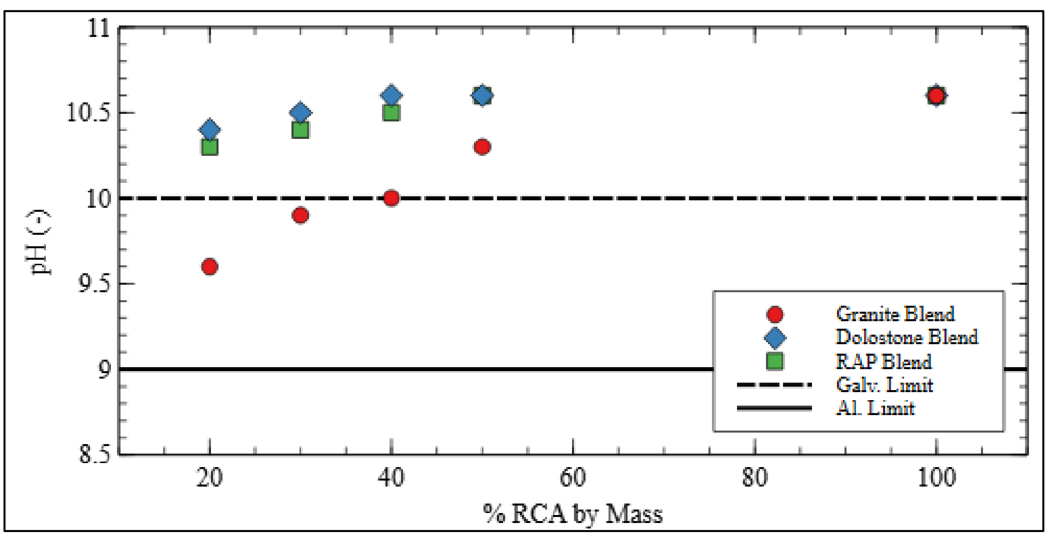

Figure 5. Leachate pH levels versus percent DC-11 RCA (3 years stockpiled) present in the blend.

Electrical resistivity testing of the obtained aggregate samples was performed complimentary to the pH evaluation. Results showed that RAP aggregates met all minimum resistivity requirements for galvanized steel and aluminized metals as outlined by WisDOT.

Fresh RCA samples showed mixed results, with some samples meeting the aluminized metal requirement and some not meeting any of the requirements. This difference in the results correlated again with the time the RCA was stockpiled. The longer the material was stockpiled for, the greater the minimum resistivity value was.

The increase in resistivity after stockpiling was most likely due to exposure to rain, during which soluble salts were washed away. Another battery of testing was performed to evaluate how the pH and electrical resistivity of the material changed after washing. RCA samples were washed and drained multiple times with 1 liter of deionized water, and the leachate pH and electrical resistivity were measured during each washing cycle. This testing was performed on both a young and an old sample and showed that the electrical resistivity of the material significantly changed each time the material was washed. Each sample met the stricter minimum resistivity requirements of the galvanized steel after 1 or 2 washes (Fig. 6). Results of the testing show that washing RCA prior to utilization may assist in lowering the corrosive nature of the leachate produced. Furthermore, if the MSE wall has good drainage, natural precipitation is expected to quickly reduce the electricity resistivity of the backfill materials. However, pH of the RCA samples did not show sufficient changes after washing to meet the specification. The hydration of residual cement particles in RCA causes the leachate to be persistently alkaline. Since the internal volume of the backfill do not have sufficient access to ambient air to neutralize the alkaline solution, the alkaline leachate poses corrosion risks to the reinforcements, which is a challenge for utilizing RCA for MSE walls.

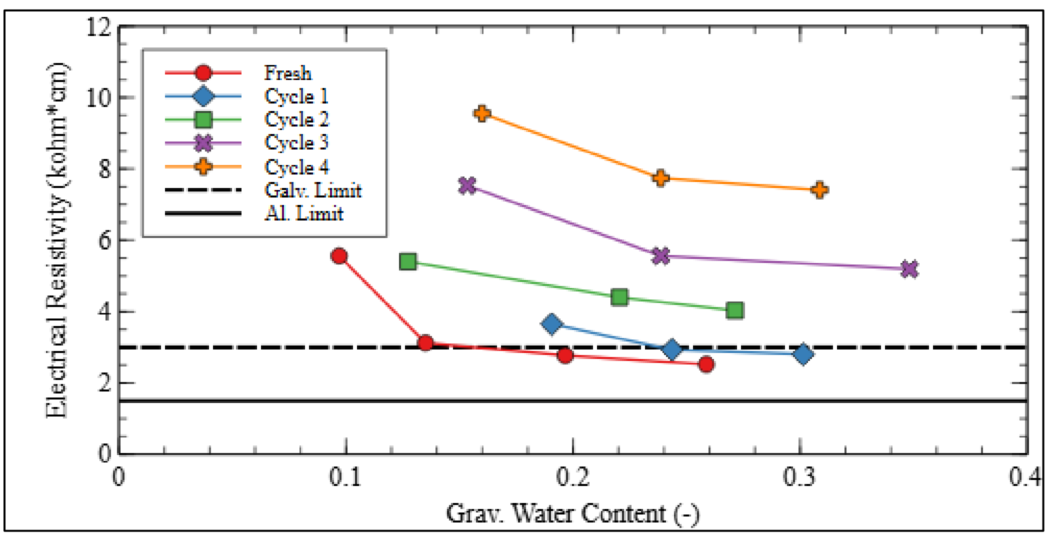

Figure 6. Electrical resistivity versus gravimetric water content for DC-11 washing cycles.

Publications:

Klink, T. S., Likos, W. J., and Wang, B. (2020). “Particle Breakage and Fines Generation of Recycled Concrete Aggregates Subjected to Compaction.” *GeoCongress 2020*, American Society of Civil Engineers, 124–130.

Klink, T., Sreenivasan, K., Hosseini, P., Likos, W., & Wang, B. (2021). "Semi-Empirical and Laboratory Evaluation of Saturated Hydraulic Conductivity for Recycled Aggregates." *Journal of Geotechnical Testing, In Review.*

Klink, T. Ragipani, R., Likos, W., and Wang, B. (2021). "Tufa Precipitation out of Recycled Concrete Leachate via Seepage". *Prepared for Submission*

Student Theses:

The work funded by this proposal was included in the following M.S. theses:

Klink, T. Drainage Characteristics of Recycled Materials for Mechanically Stabilized Earth Walls M.S. Thesis. University of Wisconsin – Madison.

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