REDUCTION OF pH LEVELS FROM ROADWAY UNDERDRAIN OUTLETS

MDOT RESEARCH PROJECT NO. OR17-205

MDOT CONTRACT NO. 2016-0065

By

Nishantha Bandara, Ph.D., P.E.

Elin Jensen, Ph.D.

Nicole Villeneuve, Ph.D.

Megan Roden

Department of Civil and Architectural Engineering

Lawrence Technological University

21000 West Ten Mile Road

Southfield, Michigan 48075

December 31, 2020

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. SPR-1696	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Reduction of pH Levels from Underdrain Outlets		**5. Report Date** December 31, 2020
		6. Performing Organization Code N/A
7. Author(s) Nishantha Bandara, Ph.D., P.E. Elin Jensen, Ph.D. Nicole Villeneuve, Ph.D. Megan Roden		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Lawrence Technological University 21000 West Ten Mile Road Southfield, MI 48075		**10. Work Unit No.** N/A
		11. Contract or Grant No. Contract 2016-0065 Z4
12. Sponsoring Agency Name and Address Michigan Department of Transportation (MDOT) Research Administration 8885 Ricks Road P.O. Box 33049 Lansing, Michigan 48909		**13. Type of Report and Period Covered** Final Report, 5/1/2018 to 12/31/2020
		14. Sponsoring Agency Code N/A
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MDOT research reports are available at www.michigan.gov/mdotresearch.		

16. Abstract

Many government and private highway agencies have identified the benefits of using recycled aggregate in highway construction. The use of recycled aggregates in highway construction, not only decreases the demand for virgin aggregates, it offers a sustainable solution. However, previous research has identified some environmental concerns of using recycled aggregate in highway construction. This research study aimed to identify and quantify the concerns and offer mitigating or alternative solutions. A comprehensive literature review, a survey of state-of-the-practice and review of MDOT collected field data identified the key environmental concerns as high pH levels (> 10-11) in the pavement drainage discharge as well as high amounts of solids deposited at the drain outlets with the potential for clogging the pavement drainage layer. A field and laboratory investigation was conducted in this study to extend an existing MDOT field study. Results of this study show that Recycled Crushed Concrete Aggregate (RCCA) bases produce leachate with high calcium ion concentrations and high pH levels. Limestone (LS) and Slag Aggregate (SA) bases produce leachate with lower levels of soluble particles and pH levels. The leachate from RCCA bases can produce calcite deposits on filter fabrics and drainage pipes and outlets. At the same time, highly alkaline leachate is known to be harmful to vegetation and aquatic life. This research shows the alkalinity of the leachate quickly dissipates within 100 feet of the drainage outlet as it likely becomes diluted by rainwater runoff. Several recommendations were developed based on the accumulative findings from the field and laboratory investigation as well as the documented practices by other states. These include recommendations for RCCA base thickness, blending of RCCA with LS and SA, washing of RCCA before use, and other suggestions for planning and construction. Some of these recommendations can be readily implemented by MDOT and other recommendations can be considered for inclusion in future specifications and special provisions.

17. Key Words Environment, construction, recycled aggregate, pavement, bases, drainage	**18. Distribution Statement** No restrictions. This document is also available to the public through the Michigan Department of Transportation.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 118	**22. Price** N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This project was funded by the Michigan Department of Transportation (MDOT). The authors would like to acknowledge the support and effort of Mr. Harold Zweng, MDOT Project Manager for this project, for his continuous assistance and support during the project. The authors also wish to acknowledge the MDOT Research Advisory Panel (RAP) members – Mr. Michael Townley, Mr. John Staton, Ms. Barbara Barton, Mr. Christopher Potvin, and Mr. Eric Mueller for their continuous support. The authors also wish to acknowledge the following staff and students from Lawrence Tech. for their assistance during field sample collection, laboratory leachate study and other tasks. These include Roger Harrison (Project Engineer, Department of Civil and Architectural Engineering), Abdulla Ali and Christopher Bragg (LTU graduate students), Alexis Willing, Logan Delonis, Gillian Neubert, Chase Smith, Erik Washburn, and Jeffrey Busick (LTU undergraduate students).

Research Report Disclaimer

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Highway agencies around the world have realized the benefits of using recycled aggregate in highway construction. These benefits include reduced demand for virgin aggregates and the benefits of sustainability when using recycled materials. Previous research, including those conducted by Michigan Department of Transportation (MDOT) and other DOTs suggested the above benefits, but unfortunately they also identified some weaknesses. Some of these weaknesses include highly alkaline effluent from underdrain discharge and the formation of calcite deposits at the drainage outlets. Higher pH (>10) effluent renders the area around drainage outlets unsustainable for vegetation and aquatic life where the loss of vegetation initate an associated increased risk of soil erosion. Hence high pH due to RCCA gives cause for direct as well as indirect environmental concerns. The objectives of this research study are to characterize the effluent through chemical analysis and to develop solutions to reduce the pH levels of the effluent and calcite formation at the drainage outlets. A comprehensive literature review and a survey of highway agencies including state DOTs, were conducted to identify previous research findings and experiences. A field investigation program was designed to supplement previously collected MDOT field data. During several rainfall events, water samples from the underdrain outlets and 100-feet downstream of the outlet were collected to determine their pH and Total Dissolved Solids (TDS) levels. Samples were then preserved with an acid solution for further laboratory chemical analysis to identify any hazardous materials in the effluent. A large-scale laboratory column leachate test was designed to supplement the findings obtained from the field investigation. Analysis of field and laboratory test results show, highly alkaline drainage discharge (pH≈12.0) from Recycled Crushed Concrete Aggregate (RCCA) open-graded base layers and slightly alkaline discharge (pH≈8-9) from roadways constructed with Limestone (LS) and Slag Aggregate (SA) open-graded base layers. The pH and TDS levels of the discharge from RCCA bases decreased with time. Using the laboratory test results a relationship with pH and TDS was developed for RCCA materials to predict the critical pH value for calcite formation. Several solutions for high alkalinity and calcite formation were evaluated during the laboratory study including blending of RCCA aggregate, washing of RCCA aggregate, and changing the thickness of the base layers. The results show 6-inch RCCA bases perform better than 16-inch bases in terms of pH levels of the effluent and calcite formation. The blending of RCCA with LS or SA lowered the pH and potential for calcite formation for 16-inch thick RCCA bases. Washing of RCCA material prior to construction also produced positive results for 16-inch RCCA bases. These solutions were not effective for 6-inch RCCA bases. All the field and laboratory test results showed that the effluent was free of hazardous materials with no heavy metals content exceeding Environmental Protection Agency (EPA) hazardous waste guidelines. Several recommendations, including solutions for the planning and construction of projects with recycled aggregates, were identified and are provided in this report. Some of these recommendations can be readily implemented by MDOT and some need to be included in the specifications or special provisions.

CHAPTER 1 INTRODUCTION

The application of recycled aggregates for reconstruction and rehabilitation roadway projects has been recognized by highway agencies as beneficial compared to the application of virgin aggregates. The benefits include, but are not limited to, decreased demand for mining of virgin aggregate, decreased construction waste volumes in landfills, and potentially decreased transportation cost when recycled materials are obtained locally. Since the 1980's, the Michigan Department of Transportation (MDOT) has implemented the application of recycled aggregates as pavement base material in the form of recycled crushed concrete aggregate (RCCA) manufactured from concrete pavements, and slag aggregates (SA) manufactured from the waste products from the iron production.

Recently, MDOT has observed high pH values and significant soluble discharges when pavement structures were manufactured with RCCA or SA base material. Both recycled materials RCCA and SA contain calcium silicate hydrate that when interacting with rainwater runoff can produce leaching liquids of high pH values. In addition, both materials are manufactured by crushing creating the potential for debris and soluble material being transported with the rainwater as the pavement system drains following a rain event.

High pH values in the drainage water may cause a significant buildup of precipitates that in urban areas may mix with additional stormwater runoff and can enter the storm sewer system. The effluent, with elevated pH levels, precipitates, and soluble particles, is potentially an illicit discharge under MDOT's National Pollutant Discharge Elimination System (NPDES) permit.

This study aims to provide MDOT with a guideline for how to use recycled materials in pavement systems while mitigating the adverse factors of high pH values and large amounts of solubles in the underdrain effluent. A targeted combined field and laboratory study was conducted to characterize the effluent from underdrains and test implemention of remedial actions.

1.1 Research Approach

The primary study objectives are:

1. Investigate national research and best practices on this topic.
2. Determine the sources and causes of high pH, soluble particles, and precipitate.
3. Propose practical methods to reduce pH levels and soluble particles at current or future sites thereby meeting or attaining lower levels to comply with the NPDES permit.

To achieve the above objectives, the following tasks were identified in the RFP:

Task 1: Review available literature to determine national best practices.

Task 2: Review relevant data collected by the State of Michigan.

Task 3: Design a sampling and data collection program to augment existing data.

Task 4: Analyze collected data from both a statistical and scientific perspective (i.e. water chemistry, geology).

Task 5: Prepare reports and recommendations as outlined below:

a. Report results of the literature review, including national best practices and examples/references.
b. Report data analyzed, both existing MDOT data as well as newly collected data as part of the project.
c. Describe the sampling and test methods used.
d. Recommend possible solutions with an emphasis on those that are proven, cost-effective, low maintenance, and practical for the Michigan roadway environment.
e. Design guidelines addressing new materials and construction.
f. Generate treatment system design guidelines.

CHAPTER 2 LITERATURE REVIEW

Pavement drainage effluent having relatively high pH levels, precipitants, and soluble particles due to the use of recycled aggregate in road bases is an environmental concern. Many agencies around the U.S. are dealing with these issues (DRU, 2012). Generally, the crushing and fracturing of hardened concrete expose unreacted quicklime and cement. When mixed with water, the resulting chemical reaction produces soluble particles with high pH levels. At the same time, due to the use of fly ash and the steel slag in Portland cement concrete may produce leachate with heavy metals. These elevated pH levels and soluble particles in the effluent may exceed the criteria for surface water quality standards. A comprehensive literature review was conducted to consider the findings of previous studies in the design of the experimental and field investigation for this study. The relevant literature is synthesized below.

2.1 US EPA Guidelines

According to the United States Environmental Protection Agency (EPA), for a waste type to be categorized as a hazardous waste (and regulated as such), it must exhibit at least one of four characteristics: toxicity, ignitability, corrosivity, or reactivity.

Corrosivity is characterized by pH levels of the waste material and the threshold levels are either $pH \leq 2.0$ or $pH \geq 12.5$ (EPA, 2005). pH quantifies the acidity or alkalinity of a solution on a logarithmic scale on which 7 is neutral, lower values are more acid and higher values more alkaline (USGS, 2020). The pH is equal to $-\log_{10} c$, where c is the hydrogen ion concentration in moles per liter. Typical rainwater has a pH value of about 5.6 and distilled water has a pH value of about 7.0. Ordinary Portland Cement concrete is highly alkaline with pH of pore solutions ranging from 12.5-13. The pH value often decreases with aging due to carbonation or due to use of road salts. Concrete constructed with supplemental cementitious materials can have initial pH values either higher or lower than the normal range depending on the materials used (Vollpract et al. 2016).

Toxicity is characterized by concentrations of heavy metals in the waste materials. The EPA threshold limits for most commonly observed heavy metals are shown in Table 2.1.

Table 2.1: EPA Threshold Limits for Heavy Metals (EPA, 2005)

Heavy Metal	EPA Allowable Limit (ppm or mg/L)
Arsenic (As)	5.0
Barium (Ba)	100.0
Cadmium (Cd)	1.0
Chromium (Cr)	5.0

Heavy Metal	EPA Allowable Limit (ppm or mg/L)
Lead (Pb)	5.0
Mercury (Hg)	0.2
Selenium (Se)	1.0
Silver (Ag)	5.0

2.2 General Studies

Caltrans Division of Research and Innovation (DRI) conducted a survey among state departments of transportation and highway agencies in Canadian provinces related to the reuse of returned concrete and crushed concrete as aggregate (DRI, 2012). Most of the agencies allow for use of crushed concrete as aggregate for new concrete or base/subbase layers. Approximately, half of the respondents to the survey pointed out problems associated with using crushed concrete aggregates. These problems include high pH levels and groundwater leaching. Furthermore, none of the surveyed transportation agencies in the U.S. or other countries allowed reusing plastic concrete.

A study sponsored by the Michigan Department of Transportation (MDOT) is titled "Using Recycled Concrete in MDOT's Transportation Infrastructure – Manual of Practice" (Van Dam et al., 2011). This *Manual of Practice* provides guidelines for using RCCA in pavement applications with specific information on using it in base layers, asphalt paving layers, and concrete paving layers. This report discusses some concerns arising from the use of RCCA as base layers, such as leachate and alkalinity (high pH values) of the effluent. These negative effects associated with using RCCA can be reduced by limiting fine graded RCCA materials in drainage base applications. Alkalinity decreases with time, and at the time of the study in 2011, it was not considered a major concern. Yet vegetation may not flourish where the runoff is directly discharged.

A technical brief published by CPRoad Map of Iowa State University (CPRoad Map, 2018) summarizes the current status, advantages, and disadvantages of using recycled concrete aggregate in pavement base applications. In 2012, 34 states allowed the use of RCCA in pavement base applications, and only six of the responding states did not permit the use of RCCA. The performance of RCCA compared to natural aggregate were similar in terms of structural and gradation properties. However, there are several drainage and environmental concerns associated with the use of RCCA as a pavement base application. When RCCA is used in drainable layers, the high pH of the effluent and calcium carbonate precipitate in drainage pipes and filter fabrics were reported. The mechanism of the precipitate is a result of the dissolution of calcium hydroxide, Portlandite, into the water from freshly exposed crushed concrete surfaces and later precipitation of calcium carbonate (dissolved calcium hydroxide reacts with atmospheric carbon dioxide). Therefore, the amount of precipitate is directly proportional to the amount of exposed cement paste surface, and the amount of water flowing through the base layer. The amount of precipitate decreases with time as the available calcium hydroxide is depleted. Approximately 50% of the material deposited in the drains and outlets is crusher dust and other insoluble particles produced by crushing operations. Therefore, a significant amount of precipitate can be reduced by washing RCA prior to use in pavement base applications (CPRoad Map, 2018).

The presence of the dissolution of RCCA's portlandite [$Ca(OH)_2$] and the chemical process for creating calcium-rich water that will precipitate calcite when exposed to atmospheric carbon dioxide can be explained by a simple model proposed by Bruinsma et al (1997). Portlandite within RCCA base layers dissolves with water and yield high concentrations of Ca^{2+} and OH^{-}ions, which raises the pH levels of water to levels of 10 to 12. Since there is no supply of carbonate (CO_3^{2-}), the formation of calcite within the base does not occur. However, when atmospheric carbon dioxide mixed with water it forms carbonic acid as shown in Equation 2.1.

$CO_2 + H_2O = H_2CO_3$ Equation 2.1

Then carbonic acid reacts with Ca^{2+} ions in the effluent to precipitate calcite at the end of underdrain outlets as shown in Equation 2.2.

$H_2CO_3 + Ca^{2+} + OH^{-} = 2H_2O + CaCO_3$ Equation 2.2

As a primary suggestion, CPRoad Map (2018) recommends washing recycled crushed concrete aggregate, prior to construction, in order to reduce the particles created during the crushing procedure. Other suggested solutions to reduce the drainage problems include (CPRoad Map (2018):

- Production and stockpiling – select the crusher type to reduce the generation of fines and good stockpile and material management practices
- Washing – Wash or use other dust removal techniques (air blowing) to remove crusher dust to control precipitate
- Avoid using fine RCCA – Selectively grade the RCCA to eliminate fine RCCA particles (materials passing #4 sieve). Finer materials have the greatest surface area and potential for precipitate formation.
- Blend with virgin aggregates – Use virgin aggregate to partially replace RCCA (particularly smaller particle size)
- Use high-permittivity filter fabrics to wrap drain pipes – Use filter fabrics with initial permittivity of twice the minimum required size to account for clogging
- Use effective drainage design features – Design the drainage system to allow insoluble particles to settle in a granular filter layer at the bottom of the trench than entering the drainage pipe. This can be achieved by placing the pipe in the granular filter layer rather than placing it at the bottom of the trench.

- Use daylighted base designs – Consider using daylighted base designs, where a drainable base layer is extended to the shoulder to drain directly to the ditch without using pipes.
- Stabilize the base – Stabilize the base with cement or asphalt to reduce the dust and leachate

2.3 Field Studies

A study conducted by the Solid Waste Research Program at the University of Wisconsin-Madison (Chen, 2012) investigated the environmental concerns of leachate alkalinity and hazardous elements from recycled crushed concrete aggregate (RCCA) base courses. The research focused on pH and heavy metal concentrations of leachate from field sites in the early flush and long-term leaching scenario. Laboratory column leaching tests were also conducted to understand the leaching mechanism. Two RCCA samples, one freshly crushed and one stockpiled RCCA, and one natural limestone aggregate sample were included in the study. A new road section paved with the above aggregates was installed at the University of Wisconsin-Madison campus. Field leaching tests were performed using a gravity lysimeter collection well systems located at the newly constructed road site. Leachate was pumped out after each sampling session to prevent interference between rain flushes. The leachate samples were analyzed immediately for pH, electrical conductivity (EC), redox potential (Eh), and also subjected to a chemical analysis. The results of field leaching tests are as follows. The pH values of effluent from freshly crushed RCCA base started with a value of 12.6 and remained constant for the first few rainfall events which exceed EPA's hazardous waste threshold of 12.5. The pH values of effluent from stockpiled RCCA started at 7.3, gradually increased to 11.9, and then decreased to 10.6. The pH values of effluent from natural aggregate bases remained within a range of 6.5 to 8.5. Chemical analysis of effluent from these in-situ pavement systems at all the sampling sessions show higher concentrations of elements Selenium (Se), Lead (Sb), and Chromium (Cr) exist from RCCA than natural aggregates bases. However, the concentration of these elements was significantly below the EPA's hazardous waste threshold levels shown in Table 2.1. The study measured concentrations of 0.2 mg/L, 0.02 mg/L, and 0.2 mg/L for Se, Pb, and Cr, respectively.

An earlier study conducted for the Minnesota Department of Transportation (MnDOT) reviewed a number of field and laboratory projects in Minnesota to assess the performance and environmental impact of using recycled concrete aggregates in pavement bases (Snyder, 1995). The study focused on the impact of deposits from the base material on the drainage capacity of the aggregate layers, drainage structures, and filter fabrics. The below list summarizes the findings from eleven (11) field and laboratory studies performed in Minnesota since the middle of the 1980s until the time of the study report:

i. Mitigation of Precipitate/Drainage Problems

The laboratory and field tests showed that calcium-based compounds are present in sufficient quantities in recycled concrete aggregates to be leached and precipitated in the presence of atmospheric carbon dioxide. This precipitate potential is directly related to the amount of freshly exposed cement paste surface. Also, selective grading to eliminate fines or blending with virgin aggregate does not eliminate precipitate potential but can significantly reduce it. The analysis of recovered precipitate showed the presence of insoluble noncarbonated-based compounds. Therefore, it seems washing the recycled aggregate before using them in pavement layers should reduce the crusher dust and other fines but will not completely eliminate the precipitate. Field studies showed that precipitate accumulations can cause significant reductions in typical drainage filter fabrics. The use of high permittivity filter fabrics and the use of unwrapped pipe drains with trenches backfilled with granular materials may provide better long-term performance. Some of the specific recommendations for the use of RCCA in pavement bases are as follows.

a. Eliminate the inclusion of RCCA fines (#4-minus) in drained, unstabilized pavement base layers
b. Design the drainage systems to accommodate a limited quantity of crushes fines from both natural and RCCA material
c. Blend open-graded RCA products with virgin aggregates to reduce precipitate potential
d. Use drain pipes that are either unwrapped or wrapped in filter fabrics with high initial permittivity.
e. Restrict the use of unstabilized RCA fines (#4-minus) in areas that are above any drainage layers

ii. Testing of precipitate potential

This report mentions the recommendation from the Michigan Department Transportation (MDOT) (Muethel, 1987) to use the calcium ion concentration to determine the precipitate potential of recycled concrete aggregates. It also mentions research by the University of Minnesota using pH and calcium ion concentration to predict the formation of calcium carbonate precipitate.

iii. Corrosion of Rodent Guard Screens

This report suggests the use of rodent guards fabricated from plastic or other corrosion-resistant materials.

iv. Environmental concerns

Although the effluent from the RCA at the drainage outlets is extremely alkaline, it has not been reported as being sufficiently alkaline to be considered an environmental hazard.

Also, it is reported that the effluent is effectively diluted to a safer level at a short distance from the drainage outlet.

A study completed for the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University (Cavalline, 2018a) investigated the use of recycled concrete materials in the United States. This study focused on two benchmark surveys among, i) state DOTs and ii) concrete industry participants. The findings are summarize as:

a. Agencies and contractors are interested in increasing the use of RCA
b. Production and use of RCA is common on most projects involving concrete pavement removal
c. There are opportunities to increase the total volume of RCA use
d. The threshold for economical recycling appears to be relatively low (i.e., less than 5,000 cubic yards)
e. Unbound applications of RCA are the most common, with bases being the predominant use
f. Agencies rely on state and federal regulatory agencies for environmental compliance
g. Most agencies have less stringent technical requirements for RCA when the RCA is obtained from the agency's own infrastructure
h. There appears to be a lack of knowledge and experience on how to utilize RCA as an engineered material in concrete mixtures
i. Barriers that appear to restrict the use of RCA include the following:
    a. Restrictive specifications
    b. Complex permitting regulations
    c. Lack of knowledge on how to use RCA without compromising performance
    d. Lack of knowledge on how to address potential environmental concerns related to RCA while in service

To address some of the issues of using RCA in pavements, CP Tech Center has developed several *Tech. Briefs.* Some of those *Tech. Briefs* are summarized below.

The technical brief titled "Protecting Water Quality through Planning and Design Considerations" (Cavalline, 2018a) addresses the water quality concerns of concrete recycling through planning and design considerations. The following environmental impacts may ascend from recycled concrete stockpile runoff and drainage from insitu RCA layers

a. Can be highly alkaline (i.e., high pH due to dissolved calcium hydroxide)
b. Contain chemical contaminants
c. Potentially cause the formation of deposits of suspended solids or precipitates in drainage systems or other downstream features

The following table lists the potential planning and design considerations to mitigate the environmental impacts of using RCA in pavement layers.

Table 2.2: Planning and Design Considerations for RCA Use (Cavalline, 2018a)

RCA Use	Consideration	Mitigation Strategies
Unbound Bases	Contamination/pollutants from the source concrete	• Use of concrete from known agency sources • Pre-qualification of the source material
	High-pH leachate	• Place drainage outlets away from receiving waters • Use hardy vegetation and bioswales near drain outlets • Consider temporary use of pH adjustment products, such as pH ("shock") logs, at potentially problematic locations (after construction)
	Pollutants in leachate	• Construct drains away from receiving waters • Utilize bioswales or mechanical sediment traps
	Sediments and solid precipitate	• Use daylighted bases • Pre-qualify geotextile fabric per AASHTO M 319-02 • Wrap trench (rather than the pipe) in geotextile fabric • Consider eliminating rodent screens • Consider blending RCA with natural aggregate • Utilize mechanical sediment traps at outlet structures • Utilize chemical coagulant products, such as "floc" logs, at local problematic locations (after construction)
Fill (beneficial reuse of fines)	High-pH leachate	• Construct away from receiving waters • Utilize hardy vegetation and bioswales in the surrounding area
	Pollutants in leachate	• Construct away from receiving waters • Utilize hardy vegetation and bioswales in the surrounding area
New RCA concrete mixtures	Contamination/pollutantsfrom the source concrete	• None required

This technical brief also provided the following guidelines for the qualification of source concrete for RCA usage.

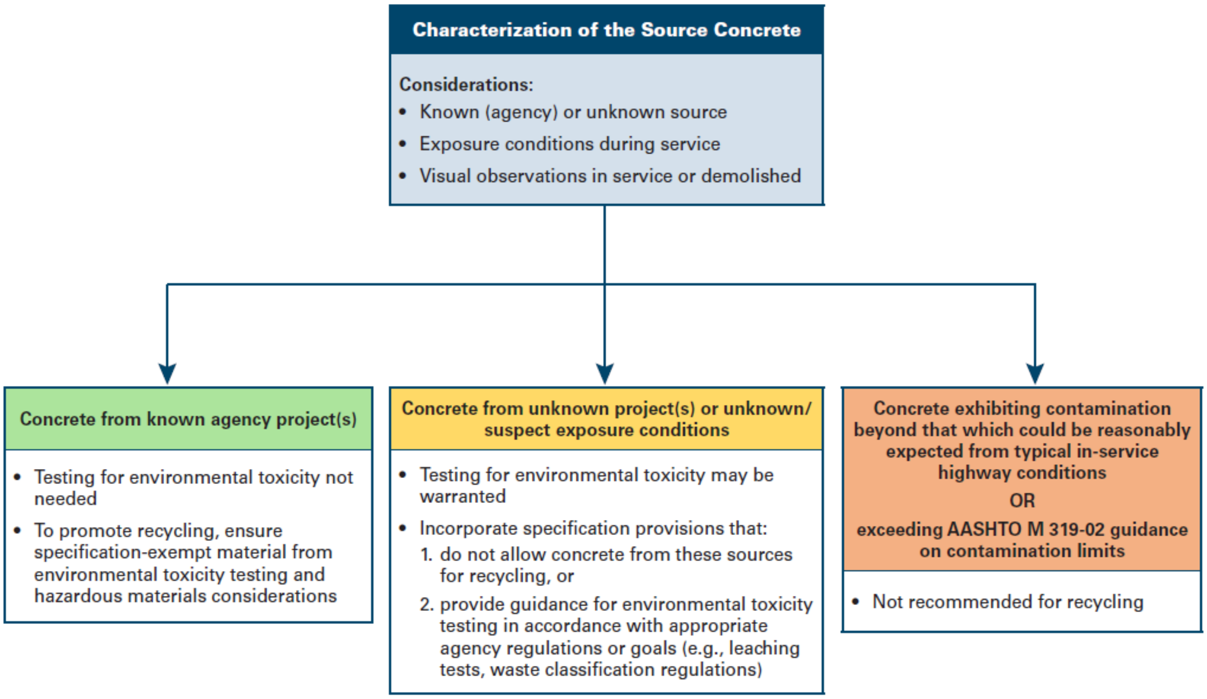


Figure 2.1: Recommended Actions for Qualification of Source Concrete for RCA Usage (Cavalline, 2018a)

Another technical brief was developed for CP Tech Center (Cavalline, 2018b) titled "Protecting the Environment during Construction." This document lists the following Best Management Practices (BMP) and other treatment methods to mitigate potential negative impacts from the use of RCA in pavement layers.

Suspended and dissolved solids from both stockpile runoff and RCA leachate at pavement subdrains can be reduced using bioswales and mechanical catchments (as shown in Figure 2.2), and chemical methods such as floc logs (polyacrylamide products that flocculate/chelate suspended and dissolved solids). The photo in Figure 2.3 shows the installation of floc logs. In general, the available methods of treating runoff to adjust pH include CO_2 bubblers, chemical addition, and products such as pH or "shock" logs.

Figure 2.2: Localized Mitigation of High-pH Leachate from the Drain Near Receiving Waters using pH Log and Bioswale (Cavalline, 2018b)

Figure 2.3: Floc Log Tied to a Wooden Stake in the Outflow Path (Cavalline, 2018b)

2.4 Laboratory Studies

2.4.1 Laboratory Leachate Testing Methods

While there are several proposed laboratory leaching test methods available to characterize the leaching potential from a solid matrix using a leaching fluid, they are broadly categorized as batch leaching and column leaching methods. In the batch leaching method, the sample is placed in a leaching solution for a given amount of time, and leaching potential is measured in predefined time intervals. In the column leaching test, a leaching solution is conveyed through a bed of porous granular material and leaching samples are collected and tested in predefined time intervals. The direction leaching fluid flow can be either down-flow or up-flow. Some of the standard column flow tests are:

1. The Standard Test Method for Leaching Solid Material in a Column Apparatus (ASTM D-4874)
2. The Dutch Standard Column Test (NEN 7343)
3. Nordttest Column Method (NORDTEST, 1995)

2.4.2 Previous Laboratory Studies

A laboratory study to characterize the mechanical properties and environmental suitability of two RCCA samples and blended samples was completed for the Maryland Department of Transportation (Aydilek, 2015). Two (2) RCCA samples, two (2) conventional graded aggregate base (GAB) materials, and one (1) mixture of RCCA-GAB materials were tested to determine the following properties: California Bearing Ratio (CBR), resilient modulus, permanent deformation, durability, and laboratory leaching. Two types of leaching tests were conducted. Batch leaching tests were conducted to determine the effects of curing time, freeze-thaw cycles, liquid to solid ratio, and particle size on leaching of RCCA. The pH-dependent leaching test was conducted to determine the influence of the leaching behavior of metals. Curing of RCCA materials decreased the effluent pH and leached metal concentrations. Effluent pH and leaching of Ca ions decreased with an increase in freeze-thaw cycles. Also, the leached concentrations were generally increased with decreasing particle sizes. The results of pH-dependent leaching tests are shown in the following figure.

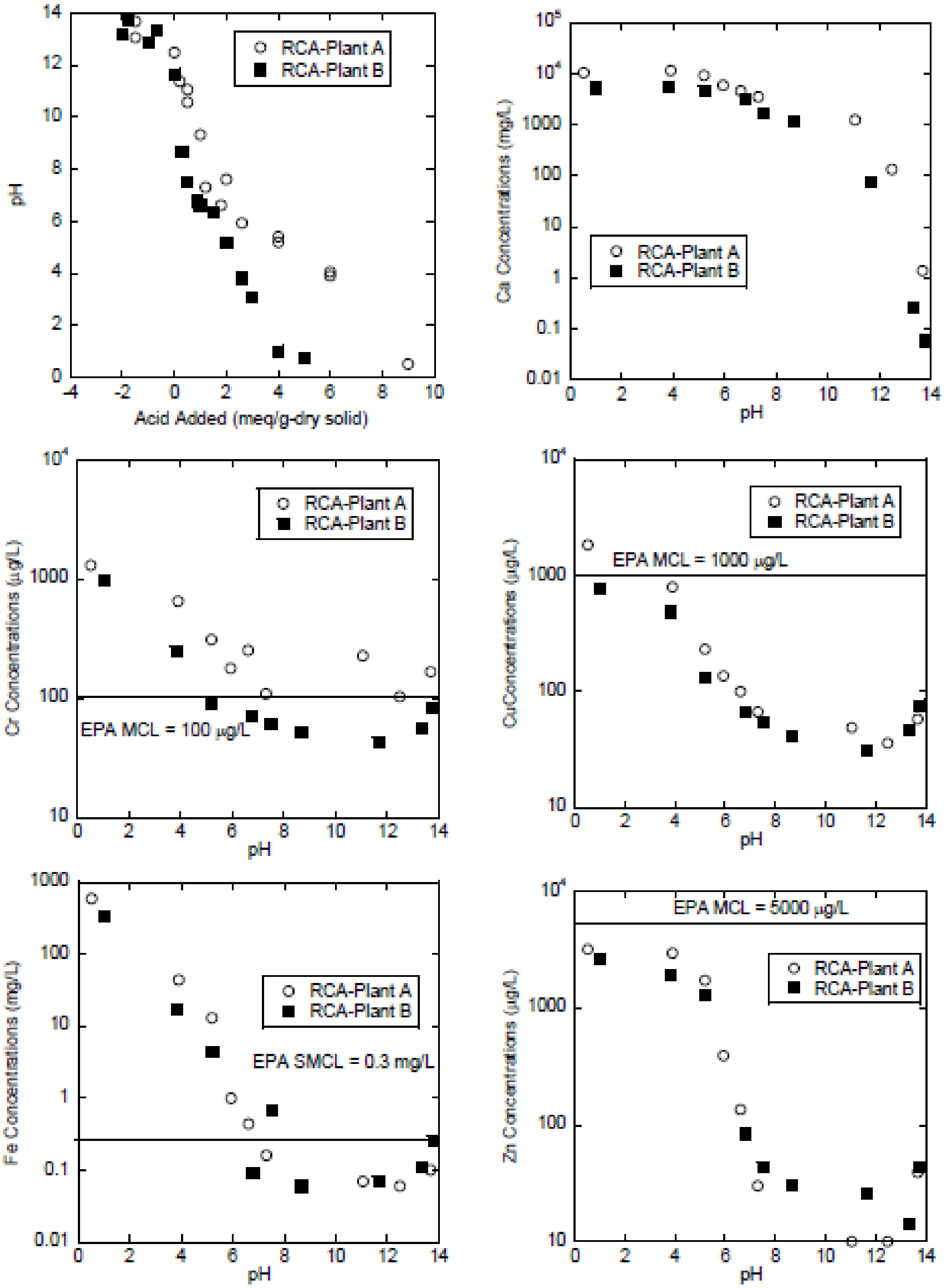


Figure 2.4 Results of pH-Dependent Leaching Tests (Aydilek, 2015)

Leaching of Ca follows a cationic leaching pattern whereas metals show an amphoteric leaching pattern. All metal leaching curves show a U-shaped pattern where the highest leaching observed at acidic solutions and the lowest leaching levels were observed around pH levels of 10 to 11. For

Ca, increasing pH will cause Ca^{2+}ions to precipitate as carbonate while decreasing pH will cause a dissolution of solids.

MDOT studied precipitate from recycled materials in 1987. An in-house research project was conducted to develop a test method for Calcium Carbonate precipitation in aggregate (Muethel, 1987). In this test, a small amount of crushed aggregate is immersed in distilled water in a flat evaporating dish and then exposed to carbon dioxide for 24 hours. This study showed that precipitation is heavily dependent on the pH level of the effluent. The following results were observed during this test.

Table 2.3: Carbonate Precipitate from Aggregate (Muthel, 1987)

Aggregate	Leachate pH	Results of Tests
Steel furnace slag A	11.5	Heavy carbonate deposit
Steel furnace slag B	11.0	Heavy carbonate deposit
Steel furnace slag C	11.5	Heavy carbonate deposit
Steel furnace slag D	11.5	Heavy carbonate deposit
Blast furnace slag A	5.0	No carbonate deposit
Blast furnace slag B	5.5	No carbonate deposit
Blast furnace slag C	5.0	No carbonate deposit
Blast furnace slag D	5.0	No carbonate deposit
PCC A (Gravel)	11.5	Heavy carbonate deposit
PCC B (Gravel)	11.0	Heavy carbonate deposit
PCC C (Gravel)	11.5	Heavy carbonate deposit
PCC D (Gravel)	10.5	Heavy carbonate deposit
PCC E (BF Slag)	11.5	Heavy carbonate deposit
Crushed limestone	5.0	No carbonate deposit
Crushed dolomite	5.0	No carbonate deposit

*carbonate refers to Calcium Carbonate deposits

A study conducted by Hiller et al. (Hiller, 2011) analyzed the leachate from the MDOT laboratory study using a Scanning Electronic Microscope (SEM). The MDOT laboratory study is described in Chapter 3 of this report. The precipitate was analyzed using an SEM equipped with an energy dispersive X-ray analyzer (EDXA), X-ray diffraction (XRD), and weighing of the leachate deposits. This analysis was conducted to determine the chemical composition of leachate from both slag aggregate and RCCA materials. SEM analysis shows the precipitates from slag aggregate and RCCA were products of calcium sulfate hydrate (gypsum) which are not defined as hazardous material. This study also concluded the volume of leachate is lower in coarse and middle graded RCCA compared to fine graded RCCA. The alkalinity of coarse and middle graded RCCA is lower than the maximum threshold level of 12.5 as defined by the EPA Hazard Waste Code for corrosivity.

Another laboratory study conducted by Abbaspour et al. investigated the impact of aging on leachate characteristics of recycled concrete aggregate (Abbaspour, 2016). The effect of aging (stockpiling) was simulated by comparing freshly produced RCCA to aged RCCA in the laboratory and the field. Two types of laboratory leaching tests were conducted on the RCCA samples following batch water leaching tests (WLT) and US Geological Survey leach tests (USGSLT). The results of the study show the pH values were not significantly varied with aging. Also, the potential for precipitate formation was not affected by short term aging (1-year stockpiling).

2.5 Summary of existing knowledge

The following discussion provides a summary of the information collected during the literature review stage of this project. The literature was divided into three categories; general studies, field studies, and laboratory studies.

The general studies provided information related to EPA guidelines on hazardous waste, the chemistry of calcite formation of RCCA base layers, and general guidelines of using RCCA and other recycled materials in roadway base construction. This information was used as the general guide for designing the field sampling plan and the laboratory testing plan in this present study as well as developing potential solutions to reduce pH levels of the effluent and potential for calcite formation at the underdrain outlets.

A review of the field studies provided the information related to the extent of some of the concerns associated with recycled aggregate usage and successful remedial methods used by the other highway agencies. Specifically, specifications related to use of recycled aggregate usage near waterways and some design guidelines were discussed in these publications.

The reported laboratory studies provided a vast amount of knowledge related to the types of available laboratory test methods, their advantages and disadvantages, as well as the types of results to expect. This information informed the laboratory testing program for this present study.

CHAPTER 3 SURVEY OF STATES' DEPARTMENTS OF TRANSPORTATION AND THE HIGHWAY INDUSTRY

3.1 Survey Design

A survey was developed and deployed to assess the usage of recycled aggregate (RA) by highway agencies utilizing "Survey Monkey," an online survey tool. The survey was developed based on discussions with the MDOT Project Management and Research Advisory Panel (RAP) members. The survey consists of nine questions on RA usage and it is included in Appendix A of this report. The survey distribution list included state DOTs, Canadian Provinces, Toll road authorities, and consulting firms.

3.2 Results of the RA Usage Survey

At the end of the survey period, 48 valid survey responses from 37 agencies were received. The following figure shows the highway agencies that participated in the survey. The respondents included thirty-four (34) state DOTs, one (1) Tollroad authority in the US, one (1) consulting firm, and one (1) Canadian province. The map in Figure 3.1 highlights the states and province from which responses were received.

The following section provides the results of the survey where the specific quesiton is followed by the a summary of the responses.

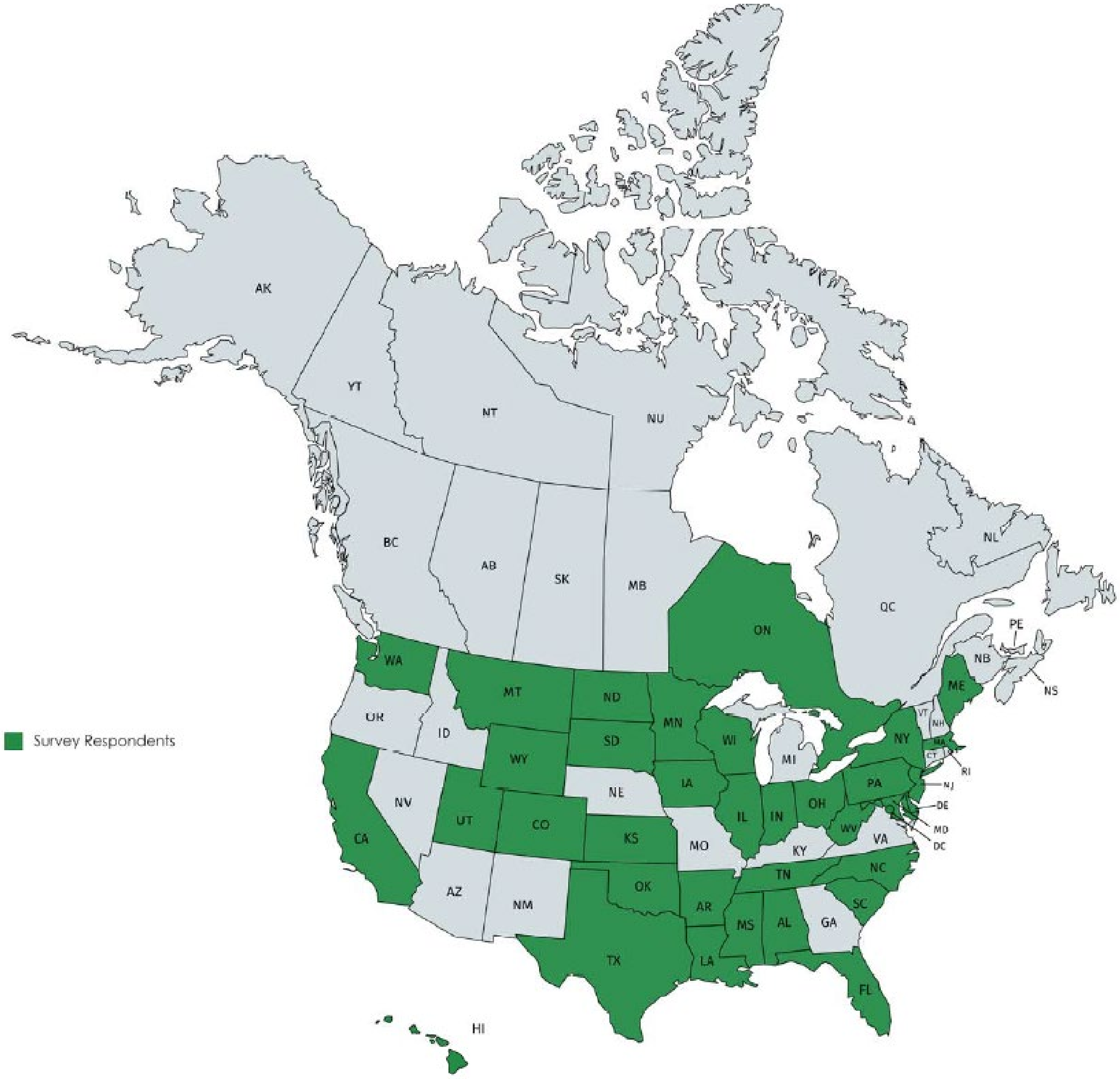
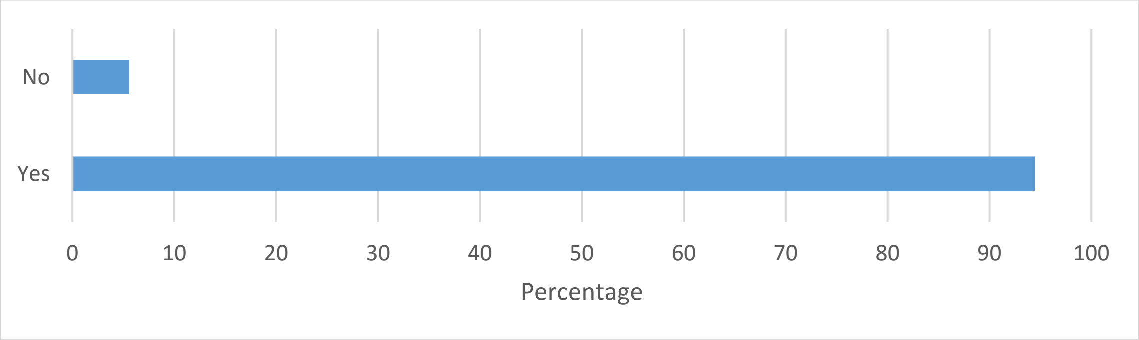


Figure 3.1: Survey Respondents

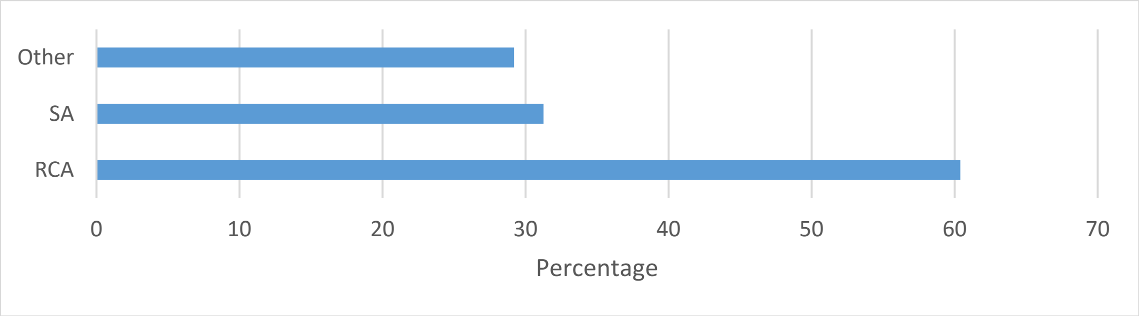
3.2.1 Survey Questions

1. ***Do you permit the use of recycled aggregate (RA) in subbases, bases, shoulders, and erosion control?***



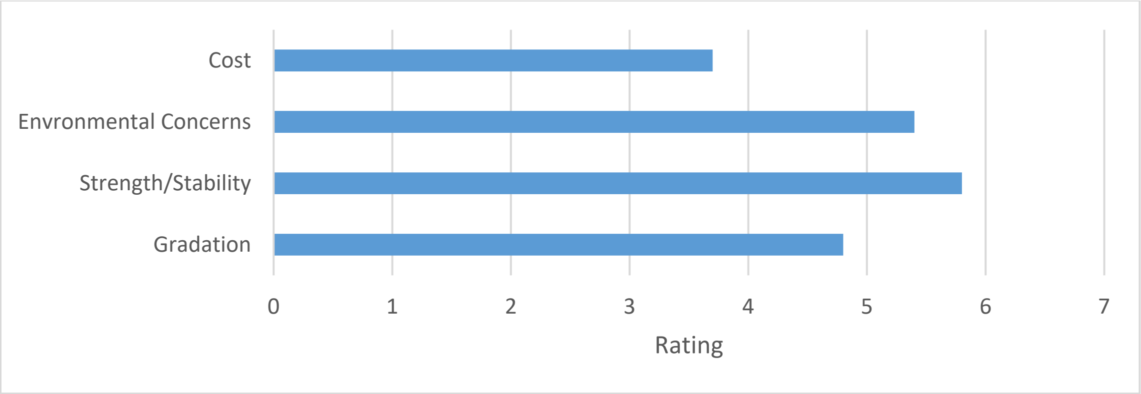
Only Kansas and West Virginia do not permit the use of recycled aggregate (RA) in subbases, bases, shoulders, and erosion control.

2. ***What types of RA do you permit in subbases, bases, shoulders, and erosion control?***
    a. ***Recycled concrete aggregate***
    b. ***Slag aggregate***
    c. ***Other, please list***



Other types: Nickel slag, glass, ceramics, recycled asphalt pavement (RAP)

3. ***Rate the importance (or magnitude) of the following potential barriers within your agency to using RA in pavement foundations. Please rate in a scale from 1 to 10 (10 highest barrier, 1 lowest barrier)***
    a. ***Concerns regarding RA gradation***
    b. ***Concerns regarding RA strength/stability***
    c. ***Environmental concerns (alkalinity runoff, leachate, etc.)***
    d. ***Cost***
    e. ***Other, please specify***



Other barriers: Quality control of mixes, fine aggregate durability, cleanness, debris content (rebar, brick, wood), wear and freeze-thaw soundness, availability of RCA for large projects

4. ***Overall, are environmental concerns cited as barriers to the use of RA in pavement foundation base layers, and/or other areas? Please briefly describe the actual or perceived barriers as related to permitting, mitigation efforts, costs, training, etc.***

Arkansas DOT

- Maintenance issues caused by calcium precipitate are a major concern as well as higher pH effluent from pavement edge drains.

Canada – Ontario Ministry of Transportation

- Although we have strict environmental issues in our Province, the use of the types of RA that I've checked off in question 8 has not been a problem for us so far. We've been more concerned about salt contamination in granular bases and subbases.

Colorado DOT

- One perceived barrier is using RA near a waterway. (Colorado DOT)
- Our environmental unit will not allow RA in "sensitive" areas due to leaching concerns.

Illinois DOT

- IDOT has developed policies and protocols for suppliers of recycled aggregates. This has reduced any barriers in utilizing recycled aggregates.

Illinois Tollway

- Environmental concerns are important, but they haven't been a barrier in our RA usage.

Maryland DOT

- The pH of effluents is of concern but it is not a barrier. RA may require testing and certification to ensure compliance with all state and local applicable and EPA regulations. The required testing may include, but not limited to, EPA Toxicity Characteristic Leaching Procedure or its successor.

Montana DOT

- No. The Montana Department of Environmental Quality allows the beneficial use of recycled asphalt products in base layers provided they are not placed in an aquatic resource or within 100 feet of standing water and groundwater wells. See link for guidance used by MDT: http://deq.mt.gov/Portals/112/Land/SolidWaste/Documents/docs/GuidanceWasteAsphalt.pdf

New Jersey DOT

- For the most part, no with the exception of soil/sediment erosion control issues.

New York DOT

- No, for pavement foundations, but it is no longer allowed in MSES fills (due to pH), nor around any aluminum conduit.

Ohio DOT

- Leachate and runoff are the main concerns. These problems have occurred on a few of our projects.
- Yes - Mitigation of tufa and pH with slag and concrete.

Pennsylvania DOT

- Currently, there are no barriers but we have had issues on jobs. We need to make a decision about continuing the use of these products.

South Carolina DOT

- It certainly limits the available material. We currently only allow RA from singular sources. Stockpiles are approved and not allowed to be further added to. Materials coming from sites with known environmental concerns are not allowed.

Texas DOT

- Recycled materials must meet TxDOT Departmental Material Specification 11000, *Evaluating, and Using Nonhazardous Recyclable Materials Guidelines*. There should be no issues with the above when meeting these specification requirements.

Utah DOT

- No, it's allowed by specification in embankments, borrow and backfill applications.
- Concerns for leachate alkalinity, heavy metals.

Washington State DOT

- Effect on pH of receiving waters.
- Recycled concrete is not allowed in erosion control due to environmental concerns.
- Cost risk associated with environmental compliance.

Wisconsin DOT

- Recycled concrete and asphalt have not had environmental problems. Other materials require certified test results to ensure they do not contain hazardous materials.

5. ***If specific environmental concerns or barriers actually prevented the use of RA in pavement foundation base layers, or other areas in one or more of your projects, what were the reasons?***

Canada – Ontario Ministry of Transportation

- The only issues that we've had are with using mine waste rock containing sulfides, primarily as erosion protection materials. However, to deal with that issue, I've developed a specification containing detailed requirements to deal with such materials when they are being proposed for any aggregate use.

Colorado DOT

- CaOH leaching and pH changes.

Illinois DOT

- The recycled aggregate did not meet IDOT specifications.

Montana DOT

- See linked guidance in the previous answer. Water quality is a concern, but is not a blanket barrier and can be accommodated in many cases.

Ohio DOT

- Tufa clogging of underdrains and the discharge of leachate into receiving waters.
- Certain RAs are not allowed by the specification.

Pennsylvania DOT

- We had a recent project that had tufa coming out of an underdrain. The tufa had to be contained and cleaned up.

Texas DOT

- Recycled materials must meet TxDOT Departmental Material Specification 11000, Evaluating, and Using Nonhazardous Recyclable Materials Guidelines. There should be no issues with the above when meeting these specification requirements.

Washington State DOT

- Recycled concrete aggregate and steel slag are not allowed below the ordinary high water mark of any surface water of the state.
- The primary concern for the use of recycled concrete is the potential for high pH runoff.
- Department of Ecology regulating.

Wisconsin DOT

- The material contains hazardous material.

6. ***If your agency is currently utilizing RA, what measures (if any) do you require to address environmental concerns related to water quality (stockpile management, testing for alkalinity/chemical contaminants, etc.)?***

Arkansas DOT

- Contractors must comply with state regulations.
- None at this time. If a sensitive species were present limitations could be placed on the use of RA.

Colorado DOT

- We recommend that RA not be used within 500 feet of a waterway.
- RA is allowed everywhere except sensitive areas. No extra measures are used in places where RA is used. It is treated as any other aggregate source.

Illinois DOT

- All aggregates must be from an IDOT approved source and follow the Aggregate Gradation Control System (AGCS).

Illinois Tollway

- We don't require anything above and beyond our current environmental policies when using RA.

Louisiana DOT

- Standard SWPPP.

Maryland DOT

- The pH of RC. Currently, RC pH shall be less than 12.4 for all applications. RC usage shall not cause any outfall and infiltration water leaving the site to exceed a pH of 8.5. Acid sulfate, sulfur, or any environmentally safe organic materials may be used to control the pH. We are currently allowing the use of RA derived from state roadway projects only.

Montana DOT

- Distance from aquatic resources and stockpile management. Again, see the linked guidance above.

New Jersey DOT

- Our agency is not responsible for permitting producers of RA. That falls under the jurisdiction of the NJDEP.

New York DOT

- The use of recycled material would not be allowed if it had not been thoroughly vetted by our environmental group. RCA is routinely checked for pH and resistivity.

North Dakota DOT

- Stockpile management.

Ohio DOT

- Aging of stockpiles and chemical testing.
- We allow Recycled Concrete in embankments if blended with 30% natural material.

Pennsylvania DOT

- None at this point but we will be looking at them.

Tennessee DOT

- We require testing and a certification letter stating that the material is free from solid or hazardous waste (e.g. asbestos, mercury, lead). We don't currently have any measures in place to address environmental concerns specific to water quality.

Texas DOT

- Recycled materials must meet TxDOT Departmental Material Specification 11000, *Evaluating, and Using Nonhazardous Recyclable Materials Guidelines*. There should be no issues with the above when meeting these specification requirements.

Utah DOT

- Provide materials free of contamination from chemical or petroleum products for embankment and backfill placements. Materials may include recycled Portland Cement Concrete. Do not include asphalt pavement materials.

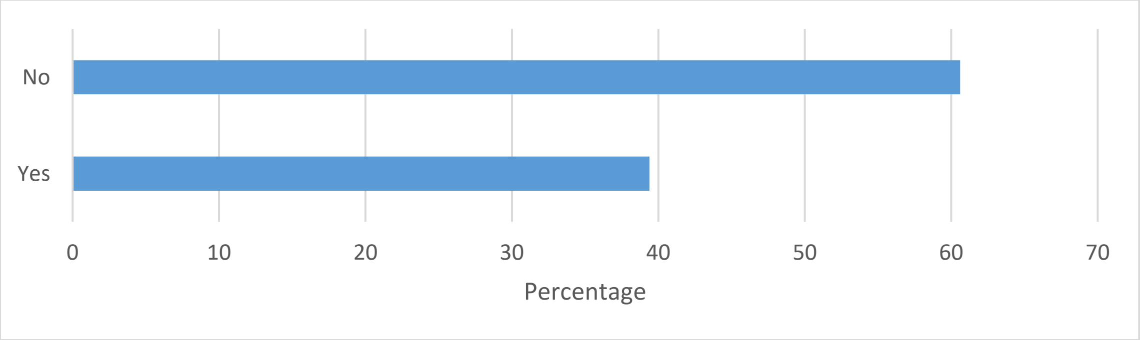
Washington State DOT

- Toxicity testing, stockpile management (and runoff prevention), and pH testing and monitoring in accordance with water quality permits/guidelines.
- Monitor pH.

Wisconsin DOT

- Materials that are not approved in our current specification would require a certified test report listing any hazardous material.

7. Has your agency incorporated strategies in your current specifications, special provisions, or permitting to mitigate environmental impacts associated with RA production?



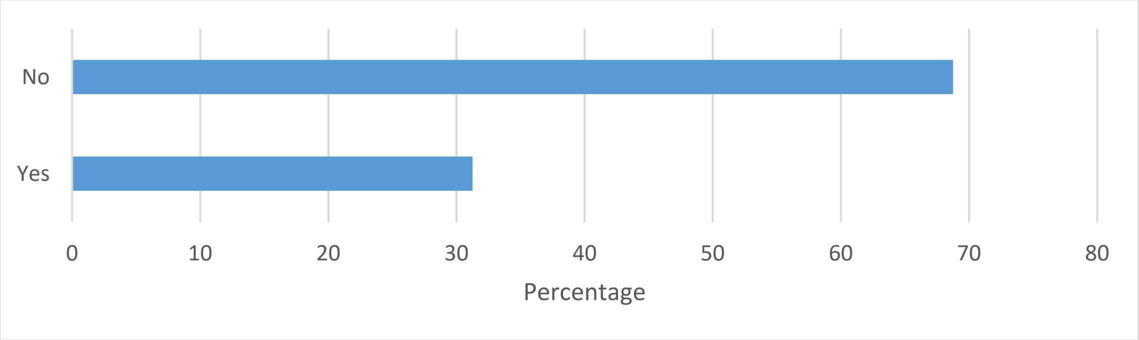
Colorado DOT

- They are not allowed in sensitive areas such as wetlands. We have very few areas where RAs are not allowed, so we don't have a need to change our specs to mitigate these rare instances when they can't be used.

New York DOT

- All recycled materials have gone through the evaluation and BUD process required by the NYS Dept. of Environmental Conservation. Any change in NYSDEC requirements requires reevaluation and modifications of our specs, if necessary. Approx. 10 yrs ago, NYSDOT went through a significant program in cooperation with NYSDEC to eliminate large stockpiles of waste tires (used as embankment fill); once the piles were gone, the program ended.

8. Do you consider potential savings from the use of recycled material in your economic analysis for projects?



The following responses were received from the respondents.

Canada – Ontario Ministry of Transportation

- Since the use of most waste and recycled materials reduces the cost of construction, as long as pavement performance and life are not unduly affected, our Ministry encourages their use as much as possible.

Colorado DOT

- No, we do not. Since it is treated as a virgin aggregate, we cannot determine cost savings when they are used. Contractors build the cost of materials into their bid. We have had adjacent projects bid where one contractor used RAs, while the other didn't. We award on low bid. RAs are not necessarily cheaper than virgin aggregates. Costs of aggregates depend greatly on transportation costs. In some cases, RAs are more expensive than a local virgin aggregate pit.

Florida DOT

- RA is an optional base that the contractor may choose if it is the most economical for the project.

Illinois Tollway

- We evaluate bid prices and use those in our analysis for future projects.

Maryland DOT

- Potential savings may be considered on a case-by-case basis but this will not be at the expense of potential environmental pollution.

Montana DOT

- Contractors are often given the option to use recycled material when it is available, but it is not a requirement and is generally not part of the Engineer's Estimate as it is an unknown.

New Jersey DOT

- RA is 40-50% cheaper in subbase.

New York DOT

- In some areas of the state, the majority of aggregate items are recycled (NYC has no natural aggregate sources) - and this is reflected in both historic and current bid prices. As such, if only natural material was allowed, the cost to transport material from other areas of the state or from neighboring states would be significant.

South Carolina (DOT)

- Generally, potential savings are only considered as part of a project when this is presented as an ATC on design-build projects. We have allowed the use of RA on bid build projects but have never required their use.

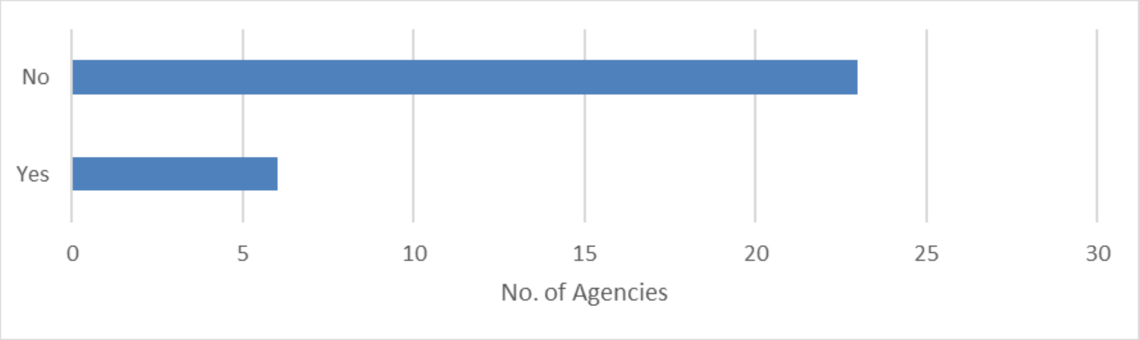
Utah DOT

- It's allowed, and therefore projects can be bid using it to the low bidder. (Utah DOT)
- As recycled concrete is generally allowed if it meets our specifications for virgin aggregate bases, it is considered in the bid prices we use in estimating future project costs.

Wisconsin DOT

- We allow the use of recycled materials and the cost saving is determined in the bidding process.

9. ***Are there any research studies conducted in your state related to environmental concerns/remedial actions of RA? If so please provide where to obtain those research reports.***



Canada – Ontario Ministry of Transportation

- As I said before, we've had more recent issues with mine waste rock which we're dealing with. As far as any research reports go, I'd have to investigate that further. Let me know if you'd like me to do that.

Illinois DOT

- *R27-180 Concrete Pavement Mixtures with High Supplementary Cementitious Materials (SCM) Content*
- *R27-175 Development of Long-Term Aging Protocol for Implementation of the Illinois Flexibility Index Test (I-FIT)*
- *R27-168 Field Performance Evaluations of Sustainable Aggregate By-Product Applications (Phase II)*
- *R27-196HS Rheology-Chemical Based Procedure to Evaluate Additives/Modifiers used in Asphalt Binders for Performance Enhancements (Phase 2)*
- *R27-193-1 Flexible Pavement Recycling Techniques*
- *R27-193-2 Flexible Pavement Design (Full-Depth and Rubblization)*
- All of these can be found at the Illinois Center for Transportation website at http://ict.illinois.edu/.

Illinois Tollway

- https://www.illinoistollway.com/doing-business/construction-engineering/reference-material#Research%20Reports,%20Approved%20Materials%20and%20CCDD%20Facilities%20Lists

Iowa DOT

- https://iowadot.gov/research/reports/Year/2003andolder/fullreports/mlr9604.pdf

Maryland DOT

- Research Report title: *Environmental Suitability of Recycled Concrete Aggregate in Highways* The full report is available at https://www.roads.maryland.gov/OPR_Research/MD-15-SP109B4G-2_RCA-GAB_Report.pdf.

Montana DOT

- https://www.mdt.mt.gov/research/projects/sub_listing.shtml Use the link and look under "Materials" for specific reports.

New York DOT

- I expect that there are - tire shreds from 10+ yrs ago, RCA from perhaps 20 yrs ago. I do not have report locations readily available.

Wisconsin DOT

- *Beneficial Use of Industrial Byproducts: 2000 Usage Summary*, September 2002, Wisconsin Department of Natural Resources Bureau of Waste Management http://worldcat.org/oclc/658210244/viewonline

3.3 Summary

The summary of the survey of State Departments Transportation and the industry is as follows.

1. The survey was well received and 37 agencies (34 state DOTs, 1 Tollway Authority, 1 consultant firm, and 1 Canadian province) responded to the survey.
2. More than 94% of the states responded to the survey allow the use of recycled aggregates in their bases, subbases, shoulders, and for erosion control measures.
3. The main recycled aggregate types used by these agencies include Recycled Concrete Aggregate (RCA) and Slag Aggregate (SA). Other types of recycled aggregates used by these agencies include nickel slag, glass, ceramics, recycled asphalt pavement (RAP).
4. The agencies listed the following barriers for using recycled aggregate in pavement base layers. They are strength/durability, environmental concerns, gradation, and cost.
5. Many respondents have identified high alkalinity and calcite formation as the main concerns when using recycled aggregate as base layers.
6. The majority of the respondents do not consider potential cost savings from recycled material usage in the economic evaluation process.
7. Several specifications and research reports were shared by the survey respondents. These specifications and research reports were reviewed and used in this research when applicable.

CHAPTER 4 REVIEW OF MDOT COLLECTED DATA

4.1 MDOT Laboratory Study

A laboratory study conducted by MDOT investigated the advantages and disadvantages associated with using recycled materials as the Open Graded Drainage Course (OGDC) base material under roadways. RCCA, limestone, natural gravel, and SA base materials were included in the study. Each material was graded into three gradations, near the coarse limit, in the middle and near the fine limit of the MDOT 4G gradation limits. Two sets of samples were prepared where one set was soaked in de-ionized water while the other was soaked in a "simulated acid rain" solution. Each week, pH was measured and 500 milliliters of liquid was removed for leachate analysis. The removed liquid was filtered through a 2.5-micron filter and residue was dried to determine the weight of the leachate. The soaking solution was replaced up to the original amount and soaked for another week. This process was repeated for 12 consecutive weeks. The pH test results and total cumulative precipitate amounts are shown in figures 4.1 and 4.2. The pH chart shows, the pH values for all the base materials are less than the threshold value of 12.5 as defined by hazardous waste by the Michigan Department of Environment, Great Lakes, & Energy (EGLE).

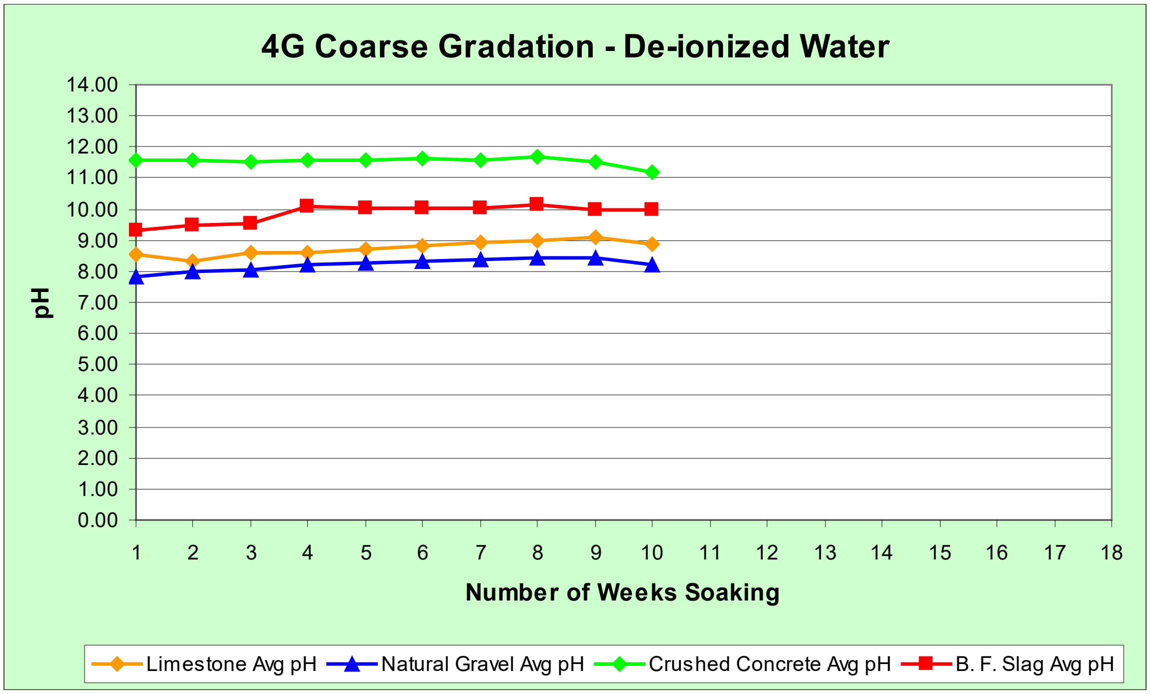


Figure 4.1: pH vs. Number of Weeks of Soaking (MDOT, 2009)

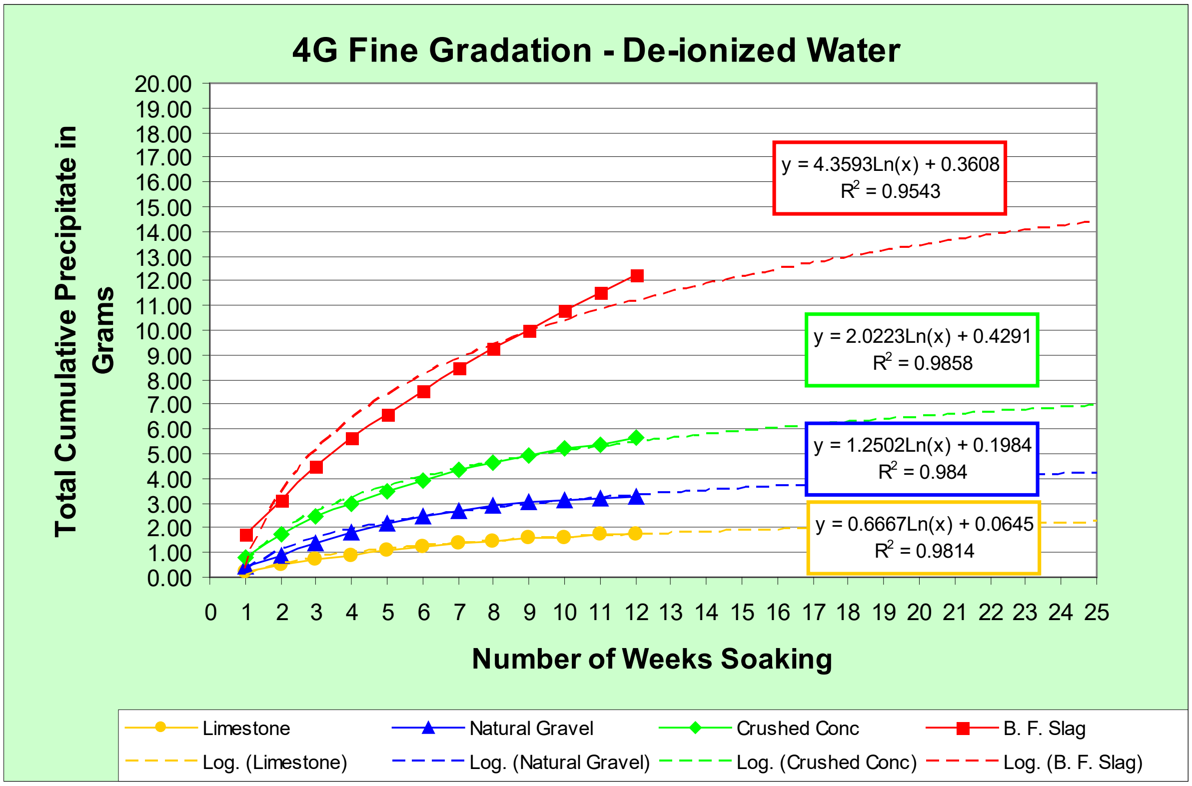


Figure 4.2: Total Cumulative Precipitate Weight vs. Number of Weeks of Soaking (MDOT, 2009)

The above figures show, the highest amount of precipitate was observed for Blast Furnace Slag Aggregates (BFSA) while the highest pH levels were observed for RCCA aggregates.

A limited field investigation was also conducted during this study and typical underdrain outlet condition at BFSA and RCCA sites are shown in figures 4.3 and 4.4.

Figure 4.3: Underdrain Outlet Condition after 2 Years of Service, I-69 East of Flint, BFSA Base (MDOT, 2009)

Figure 4.4: Underdrain Outlet Condition after 1 Year of Service, I-75 near Bridgeport, RCCA Base (MDOT, 2009)

4.2 MDOT Field Study

Michigan Department of Transportation (MDOT) has collected water samples to detect pH and soluble particle content in the underdrain effluent. These data were collected from known sites of a high level of pH in the water discharged from underdrains and a high level of precipitate in the underdrains. The following twelve sites were selected by MDOT and samples were collected in the time period from 2010 to 2018. The site details are shown in Table 4.1.

Table 4.1: MDOT Water Sample Collection Sites

Road Identification	Location	Pavement Type/Geographical Area	Types of Aggregate Used
I-69	Burton	PCC/Urban	Slag Aggregates (SA)
I-69	Davison	PCC/Urban	Limestone/RCCA
I-69	Lapeer	PCC/Urban	RCCA
I-69	Capac	PCC/Rural	Limestone/RCCA
I-94	South of Port Huron	PCC/Rural	RCCA
I-94	South of Port Huron	PCC/Rural	Slag Aggregates (SA)
I-475	Flint	PCC/Urban	RCCA
I-96	Wixom	PCC/Urban	RCCA
I-96	Okemos	PCC/Rural	RCCA
I-96	Lansing	PCC/Urban	Cement Stabilized RCCA
I-75	At Dix/Toledo Highway	PCC/Urban	RCCA
I-94/I-69	Port Huron	PCC/Rural	RCCA

The data collection program consisted of measuring the in-situ pH of the water discharge from the underdrain and collecting 500 ml of discharged water for soluble particle testing in the laboratory. Soluble particle testing was performed by filtering the effluent sample through a filter paper to remove any insoluble particles and then evaporating 500 ml of effluent to measure the weight of soluble particles in the effluent. In the following graph, the soluble particle content is labeled as "tufa" (deposited calcium carbonate) content in grams/500 ml. The summary results of the pH and soluble particle content at all 12 sites are shown in figures 4.5 and 4.6.

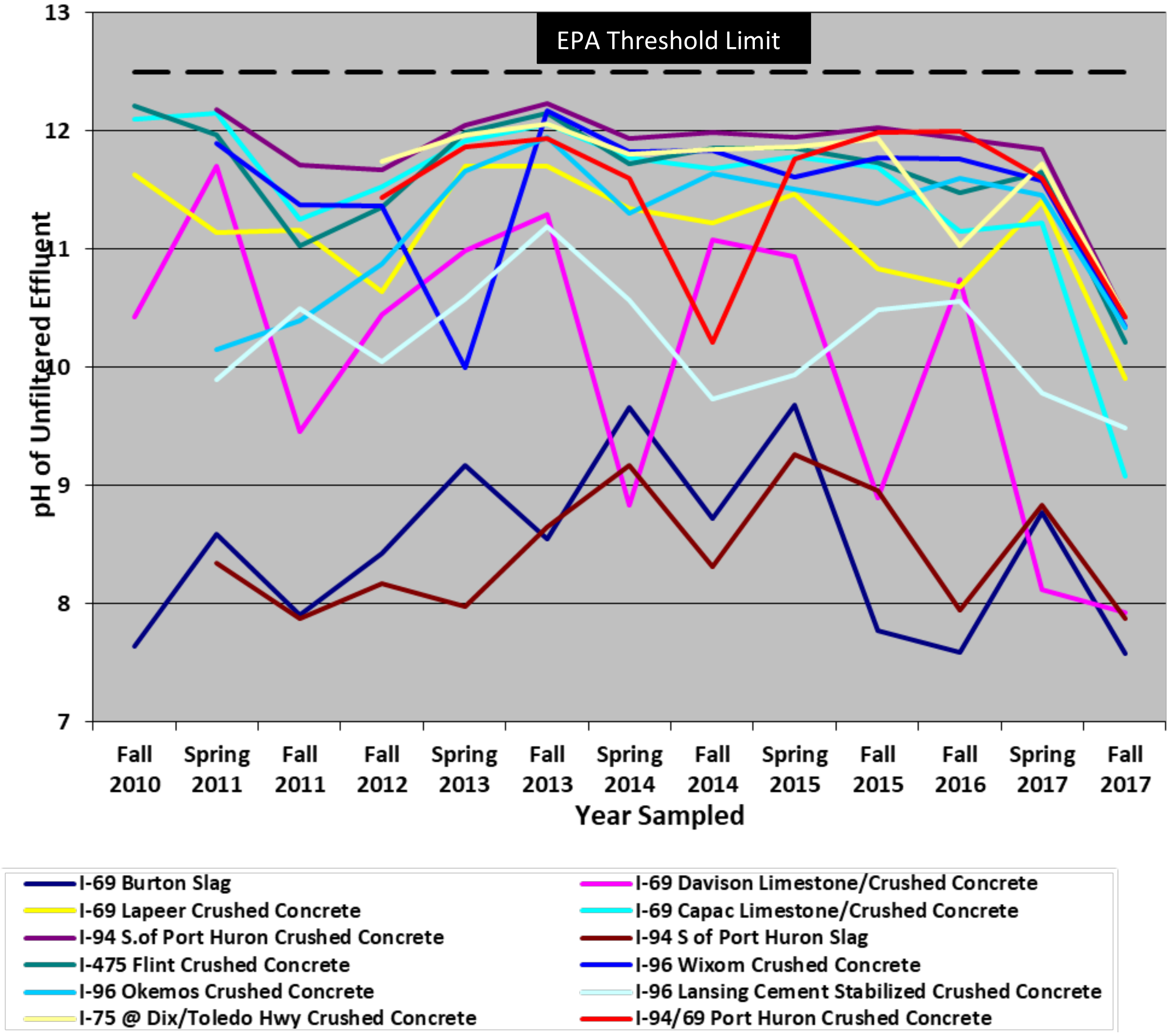


Figure 4.5: pH of the Effluent

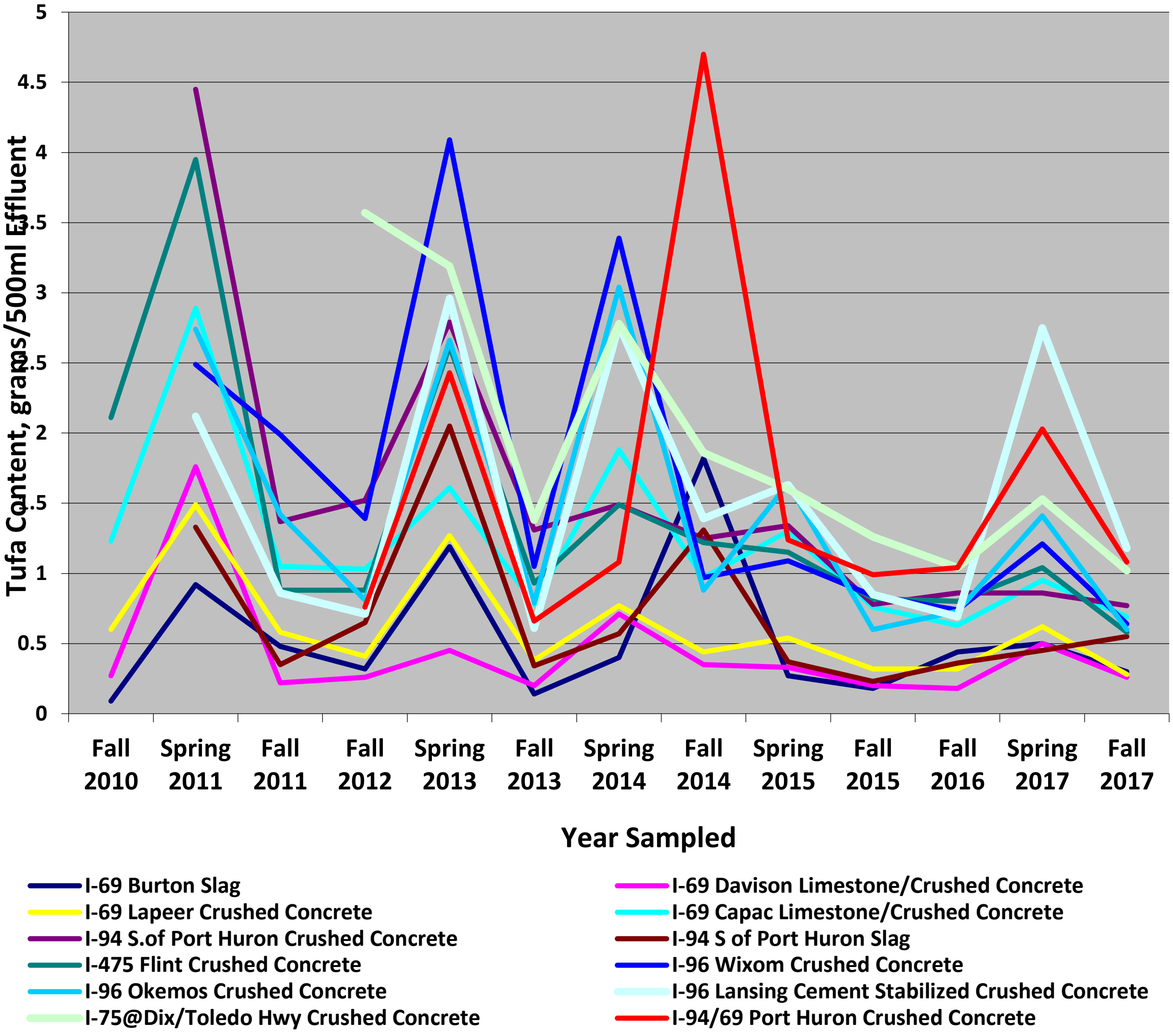


Figure 4.6: Soluble Particle Content of the Effluent

The pH values of the effluent is highest for the bases constructed with crushed concrete (Figure 4.5). These pH values range from 10 to little over 12, however all the observed values were less than EPA's threshold limit of 12.5. The pH of effluent from bases constructed with slag aggregate ranged from approximately 7.5 to 9.5, well below the pH levels of effluent from RCCA bases.

Similar observation can be made for soluble particle content (tufa content) of the effluent from RCCA bases and SA bases, where higher values were observed in RCCA bases compared to SA bases. This observation can be verified in the field by observing the deposited material content of SA bases compared to RCCA bases as shown in Figure 4.6.

It is noted that the effluent from the cement stabilized RCCA base showed pH values in the lower range for RCCA bases however the associated “tufa” production remained on average the same as for other RCCA bases.

A second observation that can be made from the above figures is that pH values and “tufa” content values seem to be higher during the spring time. To evaluate this scenario, Spring and Fall pH and “tufa” content values were plotted separately as shown in the following figures. The “tufa” content was converted to Total Dissolved Solids (TDS) in mg/L (or ppm).

The analysis shows that, at the majority of the locations the pH values in Spring were equal or slightly higher than the Fall values in the same year. In general, however, at most of the locations, the TDS values were significantly higher in the Spring than in the Fall. The reasons for the higher TDS content in the Spring compared to Fall may be due to reasons such as:

1. Use of deicing salt and other chemical compounds during winter storms causing thsese chemicals to seep through cracks and joints into the pavement base layers.

2. Breakdown of materials during freeze-thaw cycles of Michigan’s long winter periods.

The limited MDOT study summarized here was complimented by a comprehensive field study described in Chapter 5 and a laboratory study described in Chapter 6 of this report, respectively.

The research team has also collected field data at some of these original MDOT study sites in the fall of 2018 and the spring of 2019. The new data obtained in this study are added to the MDOT collected data and shown in the following figures.

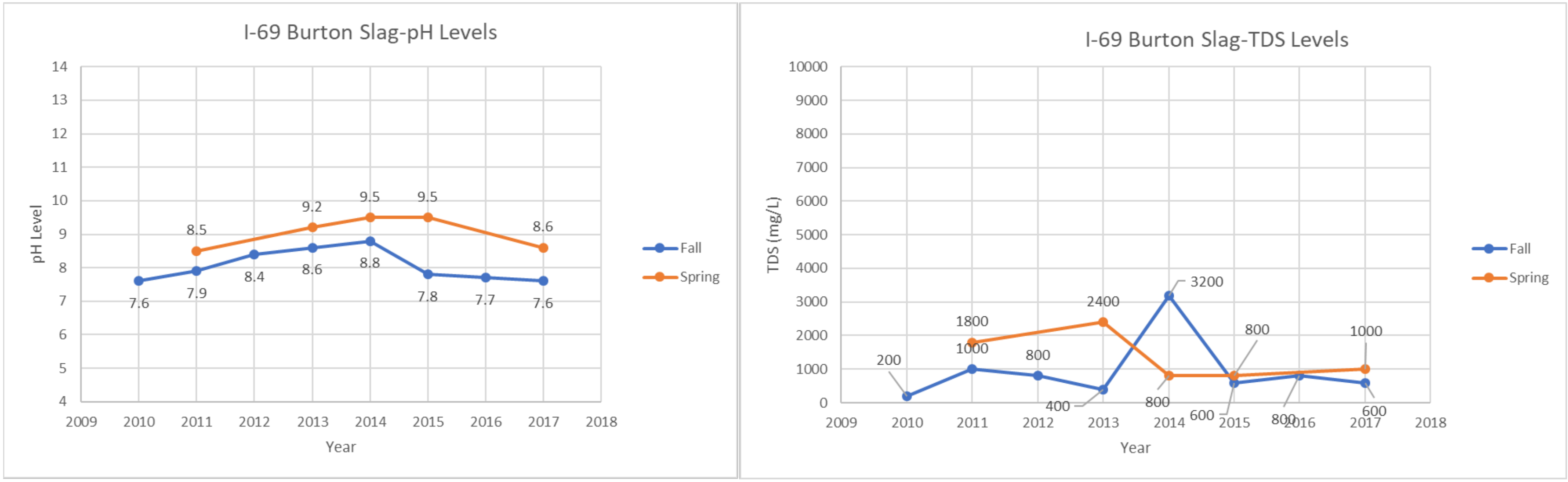


Figure 4.7: pH and TDS Values for Spring and Fall-I-69 Burton Slag

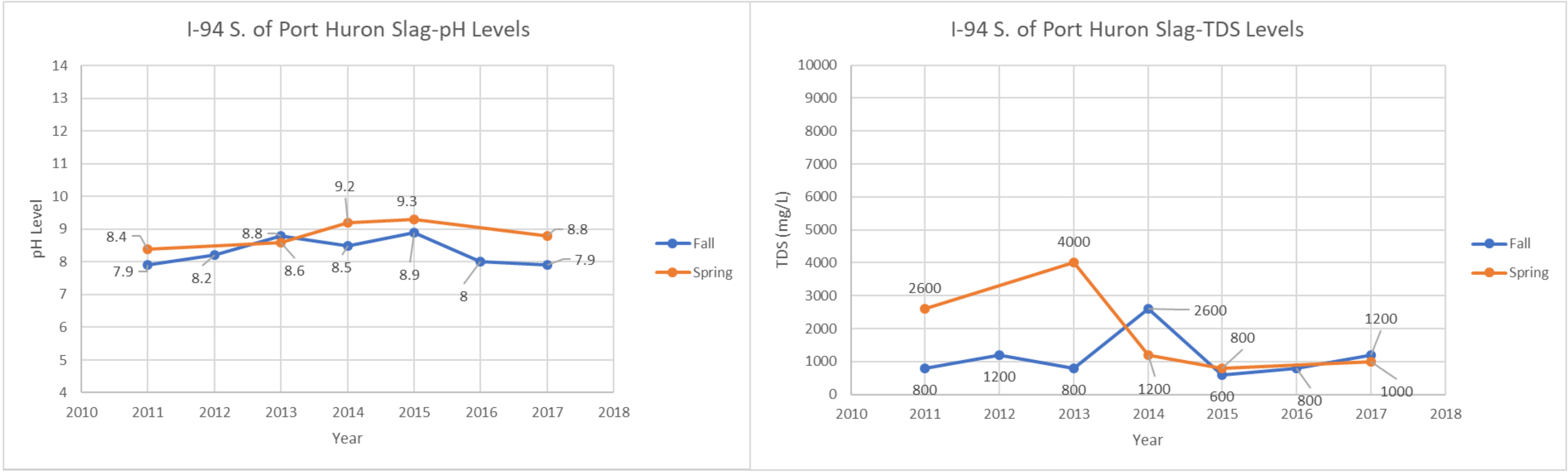


Figure 4.8: pH and TDS Values for Spring and Fall-I-94 S of Port Huron Slag

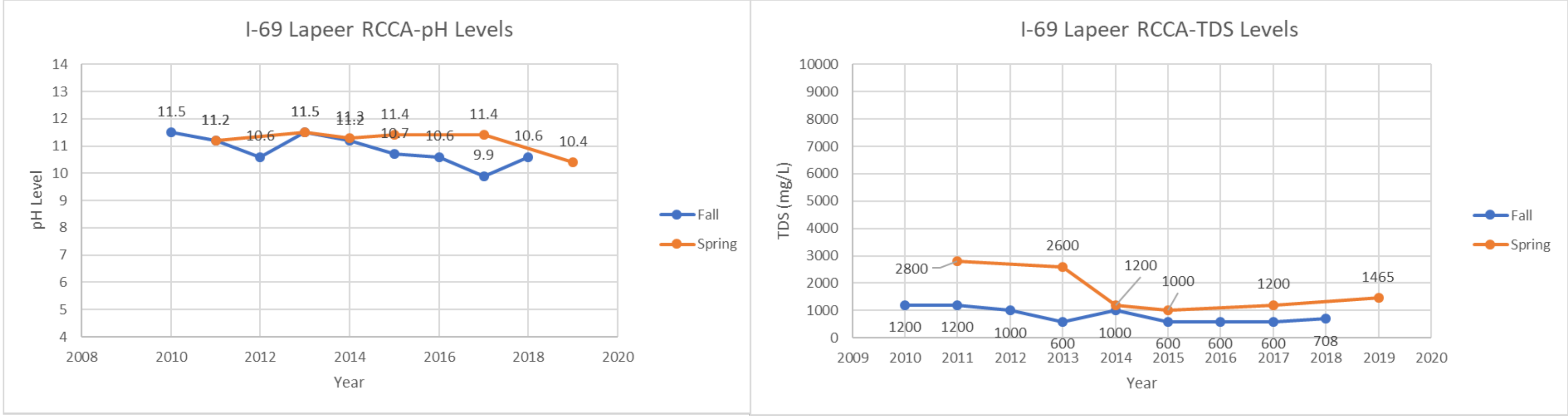


Figure 4.9: pH and TDS Values for Spring and Fall-I-69 Lapeer RCCA

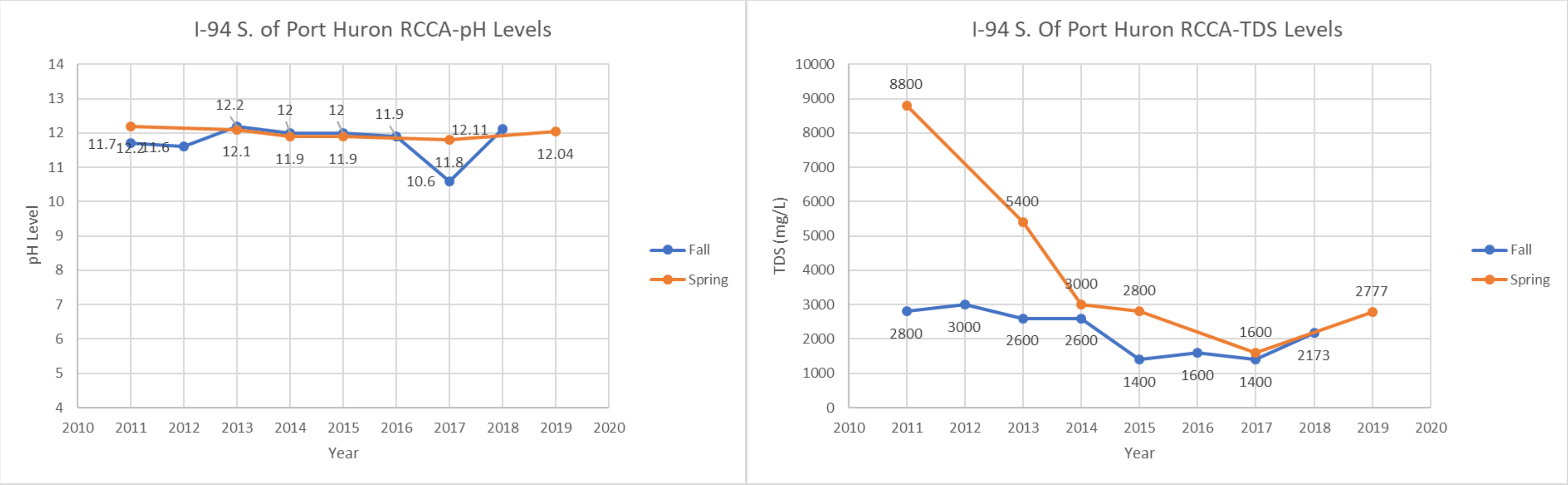


Figure 4.10: pH and TDS Values for Spring and Fall-I-94 S of Port Huron RCCA

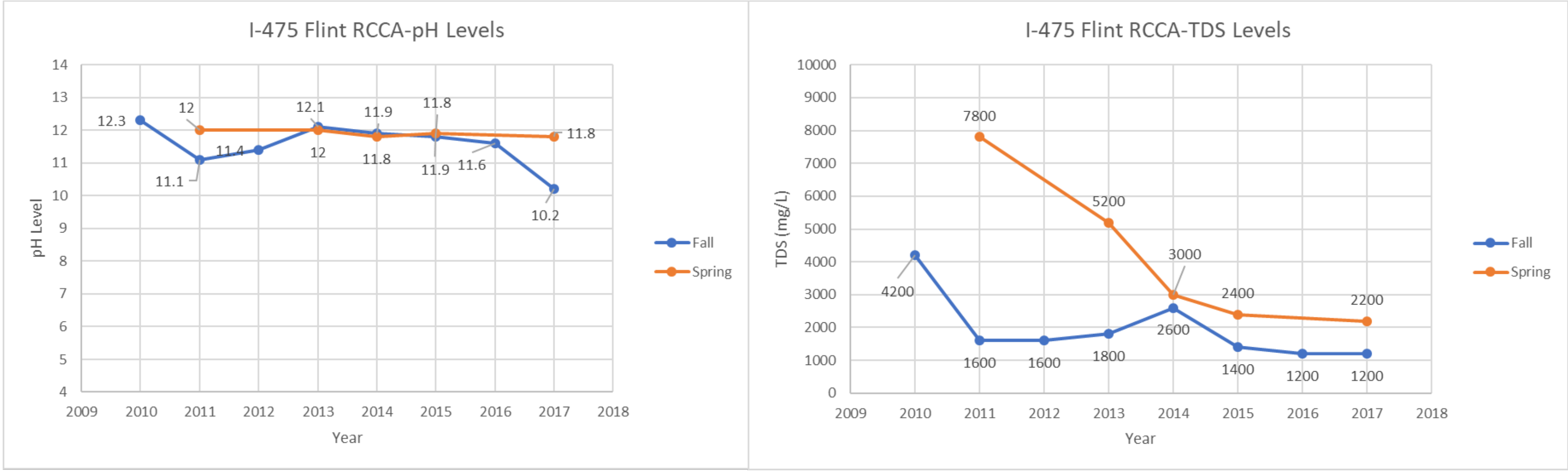


Figure 4.11: pH and TDS Values for Spring and Fall-I-475 Flint RCCA

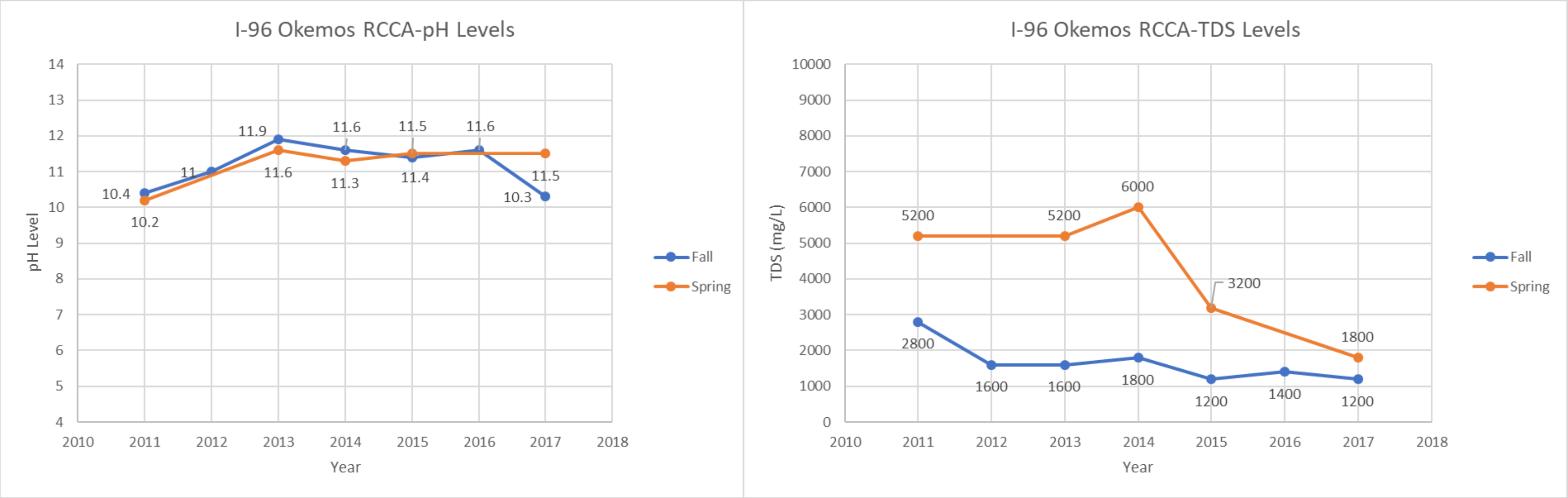


Figure 4.12: pH and TDS Values for Spring and Fall-I-96 Okemos RCCA

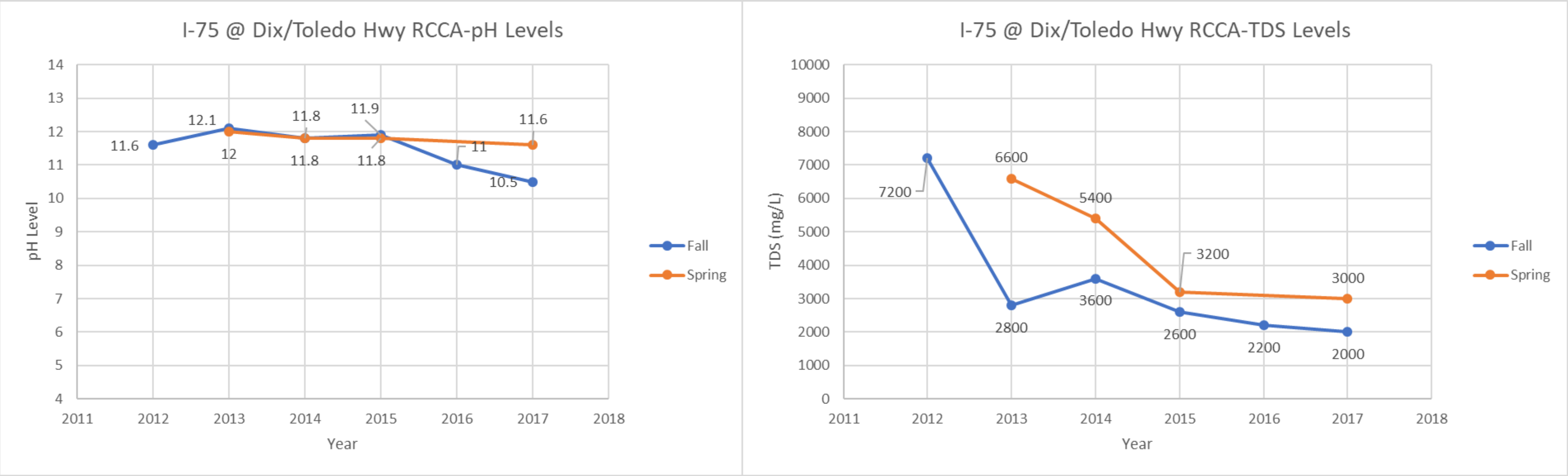


Figure 4.13: pH and TDS Values for Spring and Fall-I-75 at Dix/Toledo Hwy RCCA

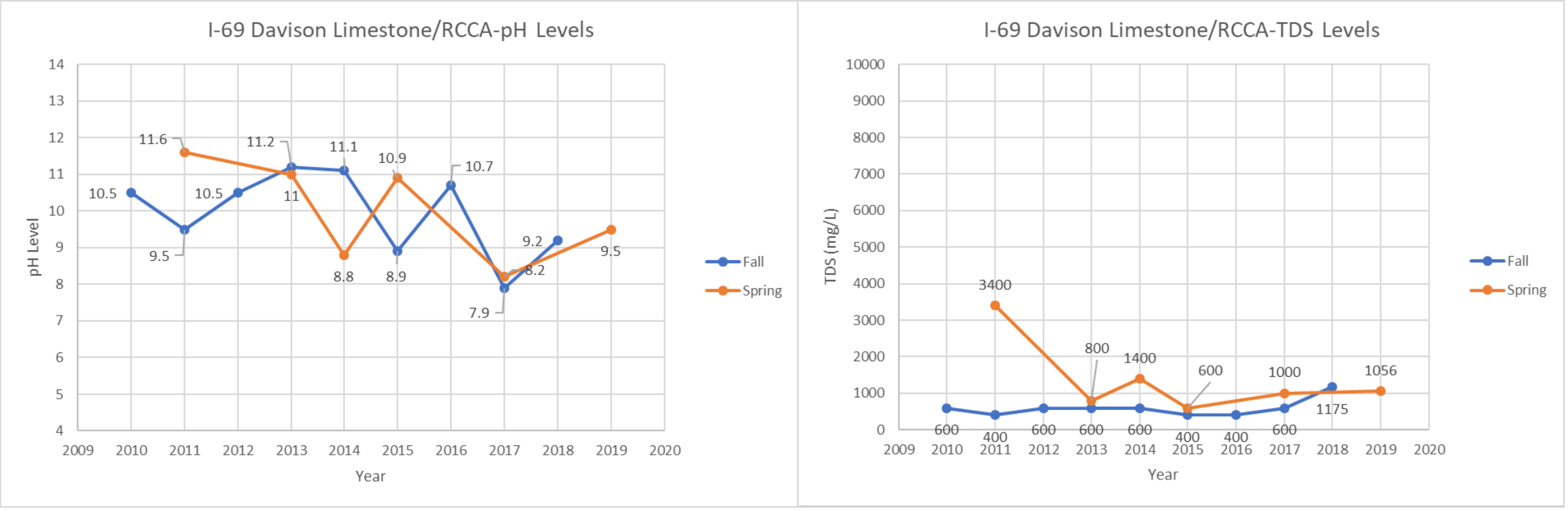


Figure 4.14: pH and TDS Values for Spring and Fall-I-69 Davison Limestone/RCCA

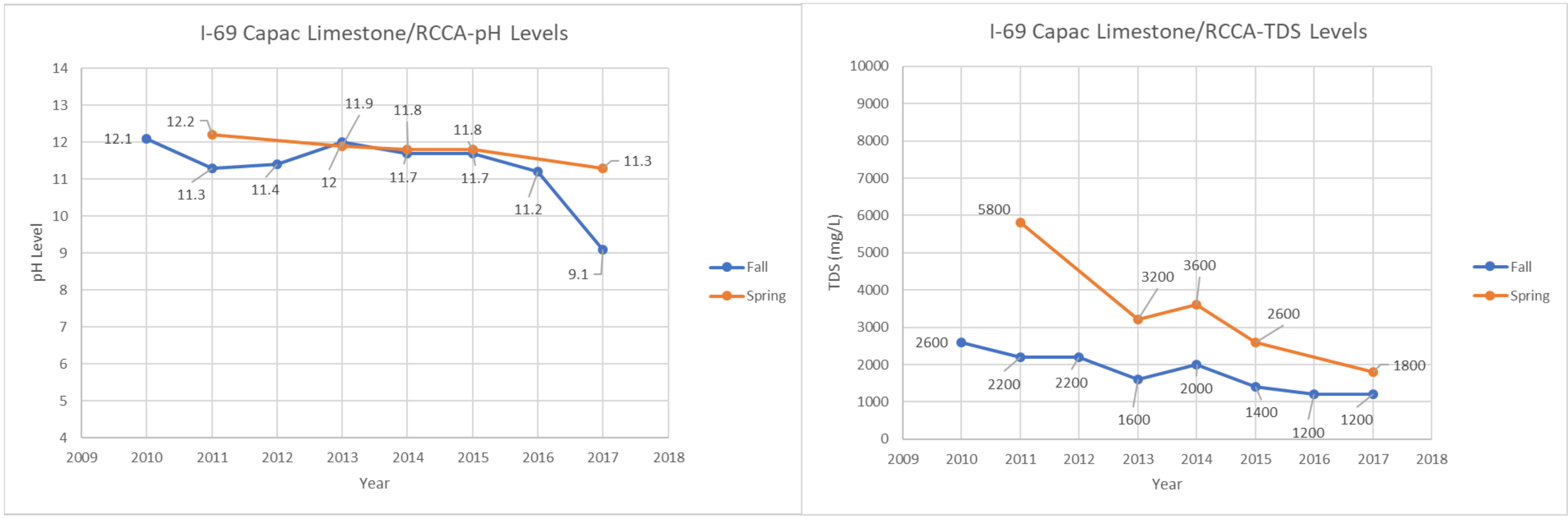


Figure 4.15: pH and TDS Values for Spring and Fall-I-69 Capac Limestone/RCCA

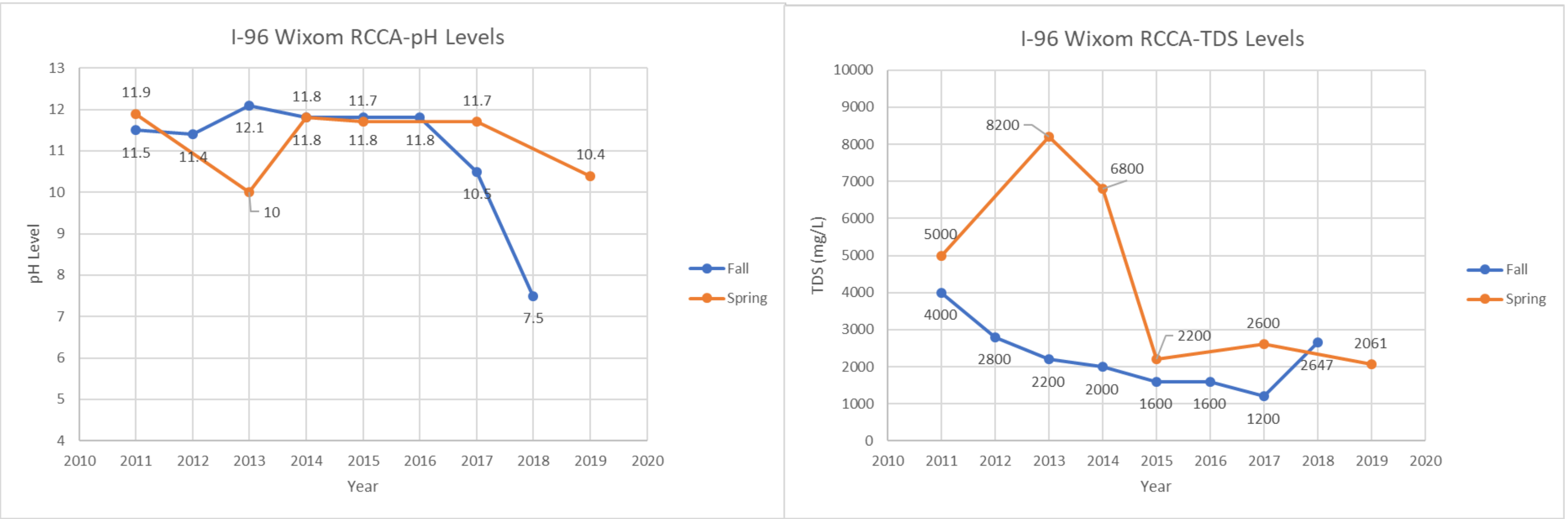


Figure 4.16: pH and TDS Values for Spring and Fall-I-96 Wixom RCCA

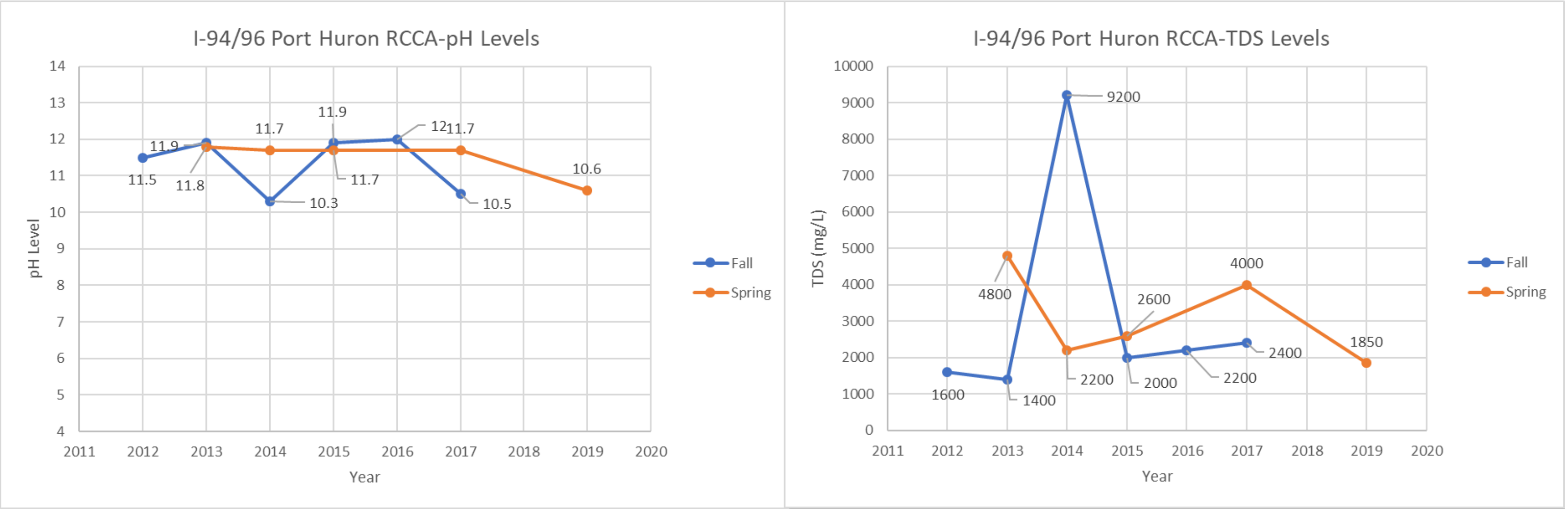


Figure 14.17: pH and TDS Values for Spring and Fall-I-69/I-94 Port Huron RCCA

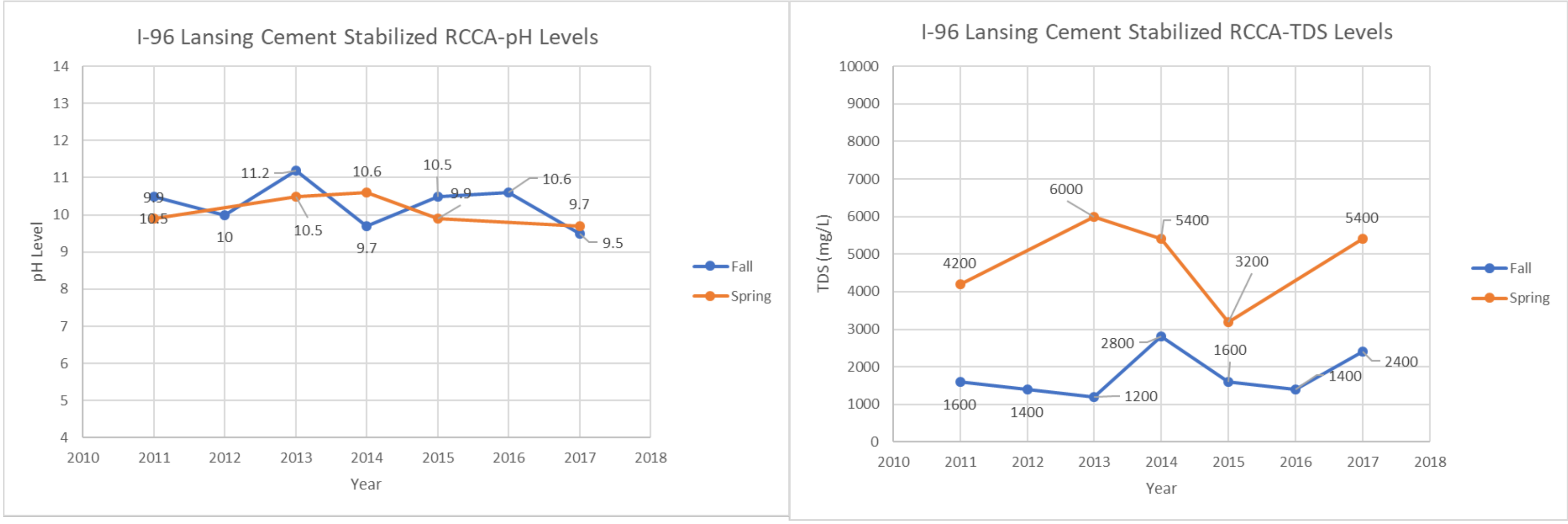


Figure 14.18: pH and TDS Values for Spring and Fall-I-96 Lansing Cement Stabilized RCCA

`CHAPTER 5 FIELD SAMPLING AND TESTING

5 .1 Site Selection

One of the main objectives of this project is to expand the field data collection effort already completed by MDOT and summarized in Chapter 4. Design of a sampling methodology to augment existing MDOT collected data was achieved by considering the variables: type of open-graded base material, age of the pavement (construction year), and the location of the site (urban or rural). Based on discussions with MDOT personnel, including the Research Advisory Panel, pavement engineers and region personnel, the following final sampling plan was adopted for this project.

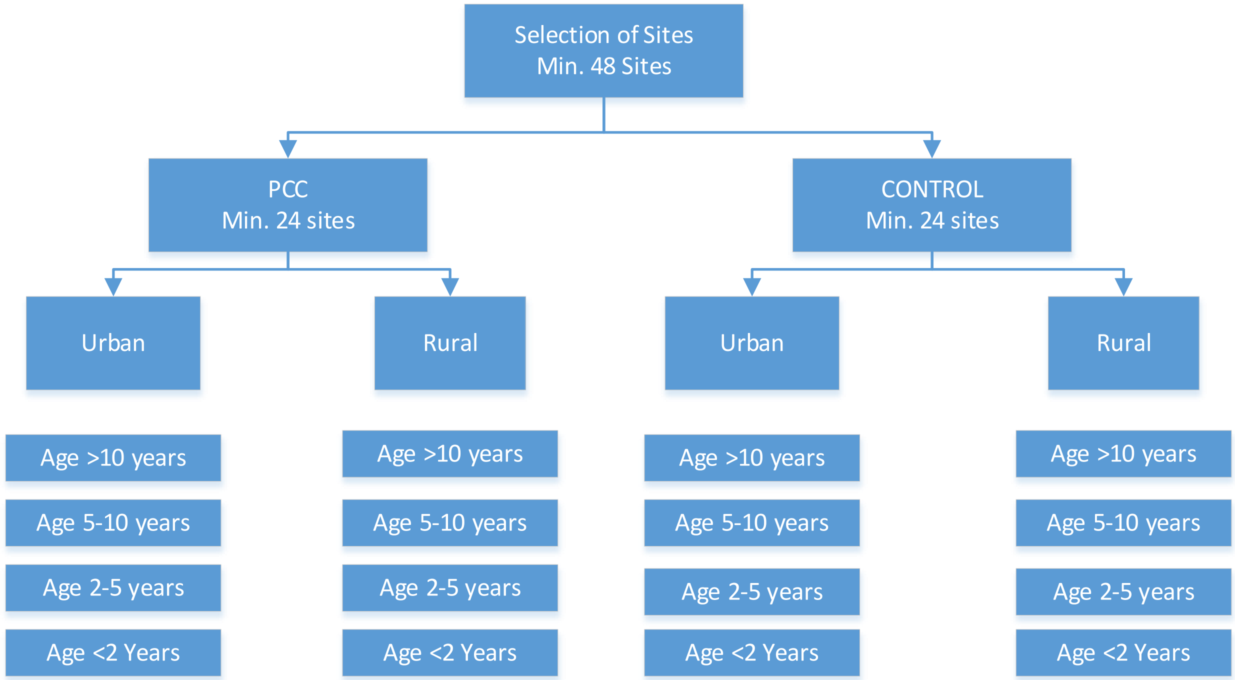


Figure 5.1: Updated Site Selection Criteria

During the 2018-2020 field data collection period, 30 sites were identified to be included in the study. A list of the selected sits is shown in Table 5.1. Each site included one to three underdrain outlet locations, and samples were collected at the outlets and 100-feet downstream of the outlets. Appendix A of this report provides additional information about each selected sampling location.

Table 5.1: Field Sample Collection Sites

Site Identification	Site Location	Site Category	Base Type	Year of Construction	No. of Sample Locations
I275SR-I94	I275 S Ramp to I94	Urban	RCA	2010	2
I69E-DAV	I-69 E Davison	Rural	Limestone	2009	3
I69E-ELB	I-69 E Elba	Rural	Limestone	2009	3
I69E-GOO	I69 E Goodells	Rural	RCA	2015	6
I69E-PH	I69 E Port Huron	Urban	RCA	2011	3
I69W-DAV	I-69 W Davison	Rural	RCA	2010	3
I69W-ELB	I-69 W Elba	Rural	RCA	2010	3
I69W-PH	I69 W Port Huron	Urban	RCA	2011	3
I75NR-Eureka	I75 N Ramp to Eureka Road	Urban	RCA	2013	2
I75NR-sqrlk	I75 North Ramp to Square Lake	Urban	RCA	2017	3
I75NR-Uni	NB I75 to University Drive Ramp	Urban	RCA	2015	2
I75SR-Adams	I75 South Ramp to Adams Road	Urban	SA	2017	3
I75S-Roc	SB I75 Between Gibraltar Road and Huron River Drive	Urban	Limestone	2009	1
I94E-CAS	I-94 E Cass	Rural	RCA	2010	3
I94E-STC	I-94 E St. Clair	Rural	RCA	2010	3
I94W-CAS	I-94 W Cass	Rural	RCA	2010	3
I94WR-I275N	I94 W Ramp to I275 N	Urban	RCA	2010	2
I94W-STC	I-94 W St. Clair	Rural	RCA	2010	3
I96E-Nov	I96 E Novi	Urban	RCA	2010	2
I96ER-I275	I96 E Ramp to I275S	Urban	Limestone	2016	3
I96W-Nov	I96 W Novi	Urban	SA	2010	2
M53N-BRU	M53 N Bruce	Rural	RCA	2013	6
M53S-BRU	M53 S Bruce	Rural	RCA	2013	6
M59ER-Dequ	M59 E Ramp to Dequindre Road	Urban	RCA	2010	1
M59ER-Roch	M59 E Ramp to Rochester Road	Urban	RCA	2010	3
M59E-UTI	M59 E Utica	Urban	RCA	2017	3
M59WR-Dequ	M59 W Ramp to Dequindre Road	Urban	RCA	2010	2
M59W-UTI	M59 W Utica	Urban	RCA	2017	3
M5N-WLk	M5 N Walled Lake	Urban	RCA	1999	3
UniR-I75N	University Drive Ramp to NB I75 Ramp	Urban	RCA	2015	2

The selected sites can be organized per the selection criteria (see Figure 5.1) in a distribution table as shown in Table 5.2. The number of total sites were limited to 30 due to considerations of project duration and logistics in terms of obtaining data from each site immediately following a rain event. Therefore, the project prioritirized selection of 24 sites constructed with RCCA base layers distributed over all the age brackets. Four sites with limestone base layers served as control sites, and two sites with SA base layers were added as reference for recycled materials. Note that sites were not identified for every cell in the distribution table as their characteristic were not found within the Detroit metropolitan area. However, it is the opinion of the research team and the MDOT Research Advisory Panel that the distribution of sites is suffficent to address the study objectives.

Table 5.2: Summary of the Site Distribution

Age (years)	PCC				Control	
	Urban		Rural		Urban	Rural
	RCCA	SA	RCCA	SA	Natural	Natural
>10	1	1	-	-	-	1
5-10	5	-	7	-	-	2
2-5	4	-	4	-	1	-
<2	1	1	-	-	-	-
TOTAL	13	2	11	-	1	3

-Sites not available in this category.

5.2 Field Data Collection Procedure

Field sampling of effluents at the drain outlets was performed according to the following guidelines published by the EPA.

- NPDES Stormwater Sampling Guidance Document (EPA, 1992)
- Industrial Stormwater Monitoring and Sampling Guide (EPA, 2009)

The water sample collection activities were conducted by LTU students and supervised by Dr. Bandara and Dr. Villeneuve. Students were trained on how to collect samples, incorporate quality assurance/quality control techniques (QA/QC), and transport the samples safely back to the laboratory. At the same time, training related to fieldwork activities and personal protection equipment (PPE) were provided to all students before deployment. MDOT permits to work on the road right-of-way were obtained prior to the fieldwork activities.

The sampling process was timed around major rain events throughout the project duration. The research team developed a plan to monitor rain events using weather information sources such as online tools, local news outlets, and airport weather information. Once an event was identified, continuous monitoring of the event was conducted until the event became highly likely (more than 70% chance of rain per online weather tools). At this time, data collection crews were dispatched.

The following in-office preparation activities were performed prior to field sampling: assembling sample gear, preparing sample bottle labels (sample location identifier, initials of sampling personnel, sample type – grab, sample preservation notes, date, and time).

The following sample collection procedure was utilized to obtain an uncontaminated grab:

- Wear disposable powder-free gloves for sampling.
- Fill the sampling label with the required information.
- Fill the sample bottle directly from the discharge/central part of the turbulent flow.
- Place the samples in a sturdy cooler partially filled with ice for transport to the lab.
- If weather permits, use calibrated probes to make on-site measurements of the pH level and TDS of the runoff sample. Otherwise, after returning to the lab, the sample is allowed to return to room temperature, and the pH and TDS values were measured using the calibrated probe. A Hatch Pocket Pro probe was used for field and laboratory pH and TDS measurements.
- Deliver the samples to the lab as soon as possible.
- Preserve the sample using a nitric acid solution for further chemical analysis.

5.2.1 Condition of the Selected Underdrain Outlet Locations

Prior to initiating data collection, a site visit was conducted at each selected site to evaluate the condition of the underdrain outlet and the surrounding area. Some of the underdrains were located in areas with heavy vegetation and some of the underdrain outlets were clogged with calcite buildup. The following pictures in figures 5.2 – 5.6 show the condition of the selected underdrain outlets and surrounding areas for pavements constructed with RCCA bases. In general, the condition of the underdrain outlet and surrounding area depends on several factors including the age of the pavement, amount of precipitate, amount of drainage, etc.

Figure 5.2 Underdrain Outlet I69W-Dav-1 (RCCA Base, Year of Construction 2010, Age 8 Years)

Figure 5.3 Underdrain Outlet at I94W-STC-2 (RCCA Base, Year of Construction 2010, Age 8 Years)

Figure 5.4 Underdrain Outlet at M53N-BRU-4 (RCCA Base, Year of Construction 2013, Age 7 years)

Figure 5.5 Underdrain Outlet at I96E-PH-1 (RCCA Base, Year of Construction 2011, Age 9 Years)

Figure 5.6 Underdrain Outlet at UniR-I75N-1 (RCCA Base, Year of Construction 2015, Age 5 Years)

5.2.2 Chemical Analysis Procedure

Method adapted from EPA SW-846 was used for the chemical analysis procedure (EPA, 2020). All metals were determined on a single sample by a direct-reading emission spectrometric method using an inductively coupled argon plasma as an excitation source.

For the determination of total recoverable elements in aqueous samples, samples are **not** filtered, but acidified with nitric acid to pH <2.

All samples/standards were prepared in 100 ml volumetric flasks and contained an internal standard. Water samples were digested by refluxing with hot dilute mineral acid(s) as specified in the EPA method SW-846. Each sample had a laboratory fortified sample prepared containing an aliquot of the environmental sample to which known quantities of the method analytes(metals) are added in the laboratory. The Laboratory Fortified Sample Matrix (LFM) is analyzed exactly like a sample, and its purpose is to determine whether the sample matrix contributes bias to the analytical results.

Also, a method blank was prepared in the same manner as the samples and carried through the complete procedure and contain the same acid concentration in the final solution as the sample solution used for analysis. All samples were prepared to contain **5% HCl-1% HNO3** prior to analysis on the Inductively Coupled Plasma (ICP).

Standards for the interested metals were used to create calibration curves for the ICP before the samples were analyzed. An Initial Calibration Verification (ICV) standard was analyzed to verify the ICP measured at correct concentrations of analytes. Also, a Continuing Calibration Verification (CCV) standard was run as a check every 8-10 samples to verify ICP signal was still within the calibration.

5.3 Summary of Collected Data

5.3.1 Summary of pH and TDS Results

Water samples from underdrains and downstream locations were collected during multiple rain events thru the time frame from 2018 to 2020. A total of 411 individual samples were collected and a summary of the collected data is shown in Table 5.3.

Table 5.3 Summary of Collected Field Data

Site	Age (Years)	Outlet (O)/Down Stream (D)	Base Type	Average pH	Std. Dev. pH	TDS (ppm)	Std. Dev. TDS (ppm)
M5N-WLk	19.0	O	RCCA	7.26	1.36	1224.9	406.5
M5N-WLk	19.5	O	RCCA	8.24	0.56	1291.8	896.4
M5N-WLk	19.0	D	RCCA	7.24	1.04	1026.9	397.6
M5N-WLk	19.5	D	RCCA	8.49	0.56	965.2	614.4
I69E-Dav	9.0	O	LS	9.20	0.83	1092.4	650.7
I69E-Dav	9.5	O	LS	9.00	1.13	1093.3	736.8
I69E-Dav	9.0	D	LS	8.08	0.09	366.7	31.3
I69E-Dav	9.5	D	LS	8.25	0.48	710.0	272.9
I69E-Elb	9.0	O	LS	9.25	1.06	1175.3	829.7
I69E-Elb	9.5	O	LS	9.53	1.25	1056.5	742.5
I69E-Elb	9.0	D	LS	8.24	0.11	427.0	28.8
I69E-Elb	9.5	D	LS	8.78	0.38	1149.4	860.0
I96E-Nov	8.0	O	RCCA	7.50	2.07	2647.1	692.8
I96E-Nov	8.5	O	RCCA	10.40	2.18	2061.5	1201.5
I96E-Nov	8.0	D	RCCA	6.63	1.45	1330.5	477.8
I96E-Nov	8.5	D	RCCA	8.85	0.79	1621.4	653.1
I96W-Nov	8.0	O	SA	7.51	1.63	1463.4	602.8
I96W-Nov	8.5	O	SA	9.58	1.29	1995.7	748.0
I96W-Nov	8.0	D	SA	7.39	1.40	1370.2	642.9
I96W-Nov	8.5	D	SA	8.57	0.51	1344.0	465.5
I275SR-I94	8.0	O	RCCA	8.10	2.21	1963.3	859.2
I275SR-I94	8.5	O	RCCA	11.67	2.21	180.5	70.0
I275SR-I94	8.0	D	RCCA	9.07	1.73	1223.5	744.6
I275SR-I94	8.5	D	RCCA	9.56	1.22	970.0	834.4
I94WR-I275N	8.0	O	RCCA	8.87	1.23	1630.0	515.6
I94WR-I275N	8.5	O	RCCA	10.31	0.27	1210.0	693.0
I94WR-I275N	8.0	D	RCCA	7.82	0.50	1183.3	76.4
I94WR-I275N	8.5	D	RCCA	8.51	0.84	1029.5	621.8
I69W-Dav	8.0	O	RCCA	10.05	0.26	731.0	318.1
I69W-Dav	8.5	O	RCCA	9.78	0.55	1010.8	418.4
I69W-Dav	8.0	D	RCCA	7.57	0.14	506.7	128.3

Site	Age (Years)	Outlet (O)/Down Stream (D)	Base Type	Average pH	Std. Dev. pH	TDS (ppm)	Std. Dev. TDS (ppm)
I69W-Dav	8.5	D	RCCA	9.01	0.66	1036.9	263.4
I69W-Elb	8.0	O	RCCA	10.58	1.46	2096.8	1902.1
I69W-Elb	8.5	O	RCCA	10.43	1.39	1465.7	567.7
I69W-Elb	8.0	D	RCCA	8.54	0.86	387.0	234.7
I69W-Elb	8.5	D	RCCA	8.17	0.19	886.3	238.9
I94E-Cas	8.0	O	RCCA	11.21	1.49	1768.2	831.9
I94E-Cas	8.5	O	RCCA	11.91	0.16	2206.3	512.6
I94E-Cas	8.0	D	RCCA	9.80	0.45	613.0	91.8
I94E-Cas	8.5	D	RCCA	10.75	0.64	966.7	77.7
I94W-Cas	8.5	O	RCCA	11.84	0.84	1363.1	587.0
I94W-Cas	8.0	O	RCCA	11.85	0.09	1560.0	167.0
I94W-Cas	8.5	D	RCCA	8.36	0.74	561.0	223.7
I94W-Cas	8.0	D	RCCA	10.66	2.27	807.0	423.1
I94E-Stc	8.5	O	RCCA	12.06	0.47	1738.2	595.3
I94E-Stc	8.0	O	RCCA	12.07	0.25	2549.5	1715.9
I94E-Stc	8.5	D	RCCA	9.87	0.54	329.5	191.6
I94E-Stc	8.0	D	RCCA	9.78	-	959.0	-
I94W-Stc	8.0	O	RCCA	12.14	0.29	2609.5	1120.2
I94W-Stc	8.5	O	RCCA	12.01	0.08	2960.0	879.6
I94W-Stc	8.0	D	RCCA	10.04	1.30	456.2	153.8
I94W-Stc	8.5	D	RCCA	9.48	1.07	1753.7	1679.3
I69E-Ph	7.5	O	RCCA	10.64	2.05	1849.7	2149.4
I69E-Ph	7.5	D	RCCA	8.10	0.13	772.3	82.0
M53S-Bru	5.5	O	RCCA	8.54	0.75	576.8	370.7
I69E-Goo	3.5	O	RCCA	9.80	1.89	1153.7	1013.3
I69E-Goo	3.5	D	RCCA	9.97	2.81	1362.0	1156.8
I75SR-Adams	1.0	O	SA	8.01	0.26	400.4	557.6
I75SR-Adams	1.5	O	SA	8.49	0.92	1099.4	1748.8
I75SR-Adams	1.0	D	SA	8.60	1.39	125.9	79.8
I75SR-Adams	1.5	D	SA	8.27	-	132.0	-
I75NR-Sqrlk	1.0	O	RCCA	10.72	1.88	2406.1	1030.6
I75NR-Sqrlk	1.5	O	RCCA	10.62	2.16	1761.5	1514.6
I75NR-Sqrlk	1.0	D	RCCA	9.97	2.47	383.5	44.5
I75NR-Sqrlk	1.5	D	RCCA	9.57	1.48	243.3	154.6

5.4 Statistical Analysis of Collected Data

Statistical analysis of collected field data was conducted to determine if there is a significant difference in recorded pH and TDS levels when the following variables are considered: season (fall versus spring), pavement age, pavement base type, and the location of sample collection (at outlet and downstream).

5.4.1 Effect of Season on pH and TDS values

Statistical analysis was conducted to determine if there is a significant difference in pH and TDS levels depending on the season that the samples are collected. The statistical comparisons were conducted using the probability associated with a two-sample t-test for difference in means. In general terms, the aim is to determine if the average value of sample series A, μ_A, is equal to the average value of sample series B, μ_B. Sample series A and B represents samples taking in the fall and spring, respectively.

Assume: significance level, $\alpha = 0.05$, Null Hypothesis, $H_0 = \mu_A = \mu_B$, Alternate Hypothesis $H_a = \mu_A \neq \mu_B$

Then, the test statistic $t = \frac{\overline{\mu_A} - \overline{\mu_B}}{\sqrt{\frac{S_A^2}{n_A} + \frac{S_B^2}{n_B}}}$

Where, $\overline{\mu_A} = Mean\ of\ the\ sample\ A$

$\overline{\mu_B} = Mean\ of\ the\ sample\ B$

$S_A = Standard\ Deviation\ of\ sample\ A$

$S_B = Standard\ Deviation\ of\ sample\ B$

$n_A = Sample\ size\ of\ sample\ A$

$n_B = Sample\ size\ of\ sample\ B$

Then the probability (*p*-value) of two sample means are equal can be calculated as follows.

$$p = prob(T \geq |t|)$$

where T = tabulated t distribution which depends on the degree of freedom, f, which refers to the number of independent pieces of data that form the distribution

$$f = n_A + n_B - 2$$

If the $p\text{-}value < \alpha$, then the Null Hypothesis can be rejected.

The above statistical comparison was made using the t-test function provided in MS Excel. The MS Excel t-test function returns the probability associated with a Student's t-Test. This probability can be used to determine whether two samples are likely to have come from the same two underlying populations that have the same mean.

Table 5.4 Statistical Analysis of pH and TDS Values Based on the Season of Sample Collection

Sampling Location	**Number of samples showing the means are statistically different**	
	pH	TDS
At the Outlet	3 (9%)	0 (0%)
Downstream	4 (12%)	4 (12%)

As seen from the above table, at the majority of the locations there is no statistically significant difference in the pH and TDS values collected in the Spring and Fall.

5.4.2 Location of Sample Collection

Statistical analysis was conducted to determine whether there is a statistical difference in pH and TDS values between the samples collected at the underdrain outlet and 100 feet away from the (downstream) outlet. The statistical comparison was completed using the t-test function provided in MS Excel as described in the previous section. The results are shown below.

Table 5.5 Statistical Analysis of pH and TDS Values Based on the Location of Sample Collection

Measure	Number of samples showing the means are statistically different
pH	9 (50%)
TDS	8 (44%)

Approximately, 50-percent of the locations, there is a statistically significant difference in the pH values of the samples collected at the outlet and 100-ft away from the outlet.

5.4.3 Age and Base Type

The differences in pH values of the leachate based on the age of the pavement and base type were analyzed using regression, trendline, analysis. All MDOT collected data and the data collected during this study at the underdrain outlet endings are included in the analysis.

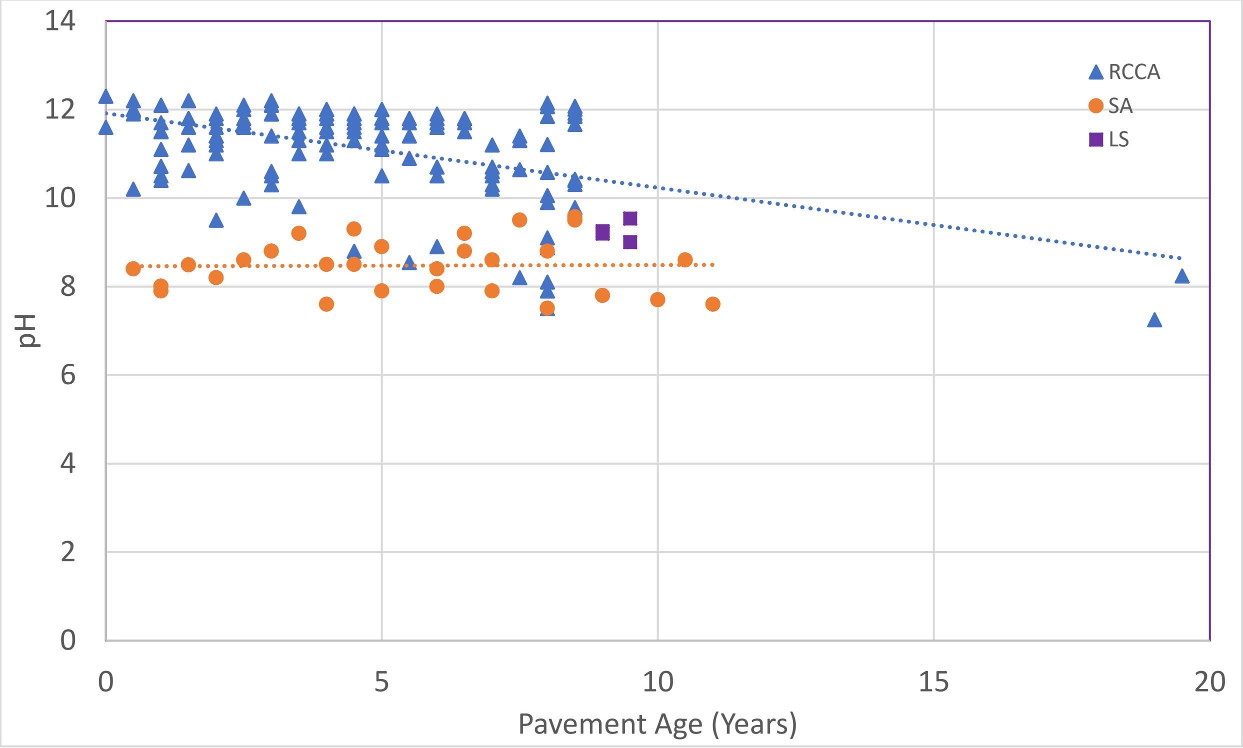


Figure 5.7 Trend Between pH and Age for Different Base Types

As shown in the Figure 5.7, the pH values of the leachate from slag aggregate (SA) bases remained constant throughout the pavement life included in the study period. The mean value of the pH was approximately 8.5.

There is an insufficient number of data points for limestone bases (LS) to identify a trend. However, the average leachate pH value from the limestone bases was approximately 9.2. This value falls within the expected range of pH values based on studies reported in the literature (see Chapter 2).

The highest number of data points were available for the pH values of the leachate from the recycled crushed concrete aggregate (RCCA) bases. The regression line shows a downward trend with an average pH value of 11.9 within a year of construction and an average pH value of 8.0 when the pavement age approaches 20 years.

The observed relationship between the TDS of the leachate from different types of bases as a function of the pavement age is shown in Figure 5.8.

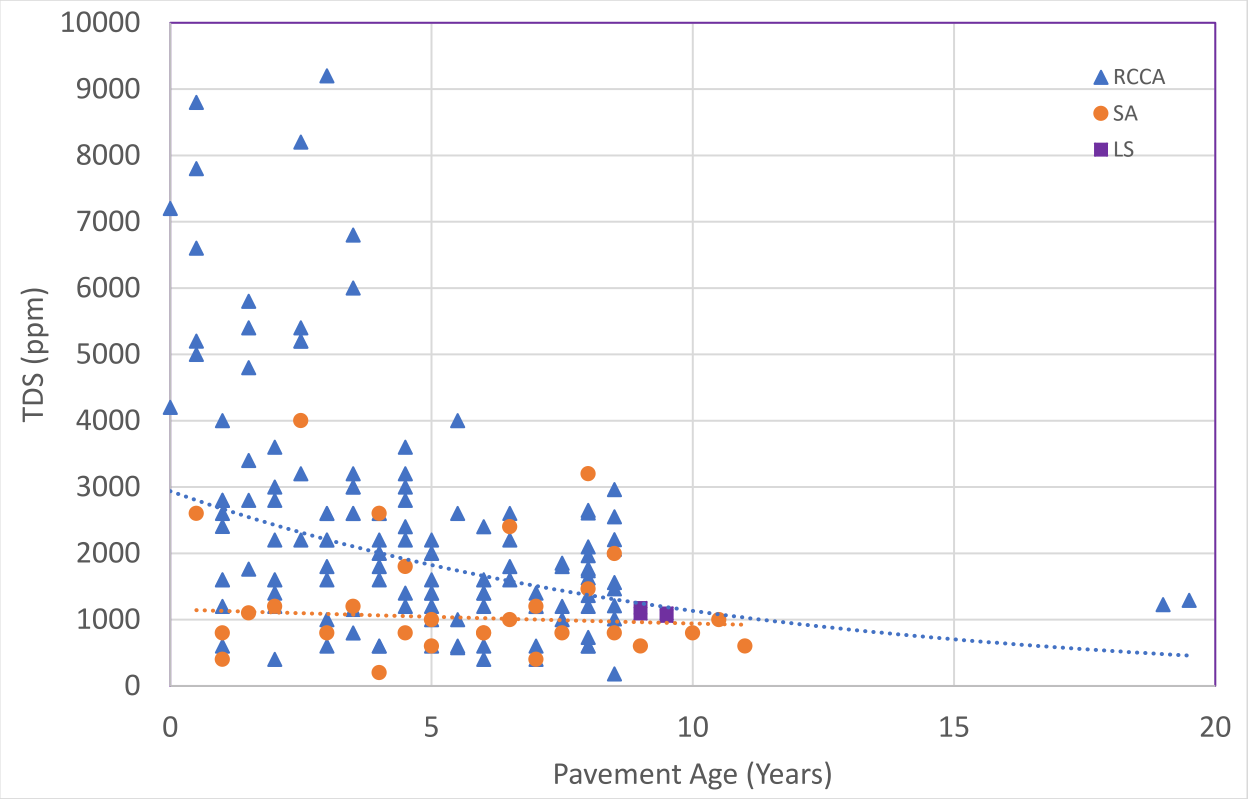


Figure 5.8 Relationship Between TDS and Age for Different Base Types

The TDS values of the leachate for SA and RCCA bases show a decreasing exponential trend with increasing pavement age. High TDS values were observed during the early years of the pavement life. This is similar to the observations reported in the literature where higher pH values of the leachate were observed when the soluble content was high.

5.4.4 Results of the Chemical Analysis

Table 5.6 contains the results of the chemical analysis of the collected leachate samples of all field samples. The results of the leachate samples from the laboratory testing are shown in Table 5.7. These tables list the average, maximum, and standard deviation of all tested heavy metals and their applicable EPA limit, when available from EPA wastewater guidelines (EPA, 2005).

Table 5.6 Results of the Chemical Analysis of Field Samples

Heavy Metal	Average (ppm)	Maximum (ppm)	Standard Deviation (ppm)	EPA Allowable Limit (ppm)
Arsenic (As)	0.00928	0.4473	0.0045	5.0
Cadmium (Cd)	0.00122	0.0269	0.0005	1.0
Chromium (Cr)	0.00713	0.0352	0.0083	5.0
Cobalt (Co)	0.00264	0.0462	0.0054	
Copper (Cu)	0.02443	0.1457	0.0249	
Lead (Pb)	0.00819	0.1914	0.0014	5.0
Manganese (Mn)	0.12203	3.58	0.0019	
Nickel (Ni)	0.04959	0.157	0.01348	
Selenium (Se)	0.00354	0.0333	0.0668	1.0
Zinc (Zn)	0.31275	20.677	0.0097	

Table 5.7 Results of the Chemical Analysis of Laboratory Samples

Heavy Metal	Average (ppm)	Maximum (ppm)	Standard Deviation (ppm)	EPA Allowable Limit (ppm)
Arsenic (As)	0.00292	0.1884	0.0152	5.0
Cadmium (Cd)	0.00211	0.2059	0.0166	1.0
Chromium (Cr)	0.00273	0.2040	0.0164	5.0
Cobalt (Co)	0.00228	0.2128	0.0171	
Copper (Cu)	0.00777	0.1887	0.0160	
Lead (Pb)	0.00246	0.1983	0.0160	5.0
Manganese (Mn)	0.00335	0.0851	0.0072	
Nickel (Ni)	0.00222	0.2024	0.0163	
Selenium (Se)	0.00316	0.1924	0.0155	1.0
Zinc (Zn)	0.00825	0.2924	0.0289	

As shown in the above tables, the observed heavy metals from leachate from both field and laboratory samples were at minimum levels and none of the values were exceeded the EPA allowable limits.

5.5 Summary and Discussion of Field Sampling and Testing

The following is a summary and discussion of the findings from the field and associated laboratory testing employed during this project. The sampling plan was developed to supplement MDOT collected field leachate samples from RCCA, SA, and LS bases. From the 30 selected sites, a total of 411 leachate samples were collected.

1. Based on the MDOT collected data, there was a hypothesis that there may be a difference between the pH and TDS values of the samples collected in the fall and the spring, as discussed in Chapter 4. This hypothesis was further tested during the latest field sampling activities. The results of the analysis show that there is no statistically significant difference in the average pH and TDS values of the samples collected during the spring and fall rain events.
2. For approximately 50-percent of the locations, there is a statistically significant difference in pH and TDS values of the leachate collected at the underdrain pipe outlets and 100-feet away from the outlet. Diluting of the leachate with the runoff rainwater is likely the reason for this difference. Therefore, it can be assumed that the pH and the TDS of the leachate are not detrimental to the environment beyond a few hundred feet from the underdrain outlet. However, plants and other aquatic lives may be unable to thrive in the immediate vicinity of the underdrain outlets due to the high alkalinity of the leachate as evidenced during site visits.
3. The relationships between pH, TDS, and age of the pavement for the different RCCA, SA, and LS bases were evaluated. In general, the average pH values of leachate from slag aggregate (SA) bases are lower than the leachate from limestone (LS) bases. The pH of the leachate from SA bases showed the pH values remained constant with increasing pavement age. The leachate from RCCA showed that the pH values were decreased with a linear trend with increasing pavement age. Analysis of the TDS in the leachate for RCCA and SA bases show a decreasing exponential trend with increasing pavement age. The number of LS aggregate bases were limited, hence, a trendline was not established.
4. Chemical analysis of the leachate showed minimum heavy metal concentrations well below the EPA wastewater guidelines.

CHAPTER 6: EXPERIMENTAL SIMULATION OF DRAINAGE SYSTEM - PAVEMENTS WITH OPEN GRADED BASES

6.1 Introduction to Laboratory Study

The field data obtained in this study as well as earlier MDOT data were obtained at discrete points in time, and therefore making it challenging to describe adequately the effect of time and accumulative rain events on the pH and TDS levels in the pavement drainage discharge. To study these characteristics over time, a laboratory testing plan was designed to obtain data that supplement the field data collection effort. The laboratory testing plan consists of a modified column leaching procedure based on the Dutch Standard Column Test (NEN 7343) (NEN, 1995). This procedure simulates water entering the pavement cracks and joints and then leaches into the base and then to the underdrain system. A review of MDOT construction practices documented the following variations of open graded underdrain designs per the MDOT Standard R80 Series (MDOT, 2012).

1. Standard open-graded underdrain trench with 6-inches of 4G open-graded drainage course with 20-inches of 34R open-graded aggregate. This type of design is used in all road construction with open-graded base courses located outside of the Metro Detroit area.
2. Open-graded drainage course modified special provision with 16-inches of 4G open-graded drainage course with 10-inches of 34R open-graded aggregate (Figure 6.1). This type of design is used in all road construction with open-graded base courses in the Metro Detroit area.

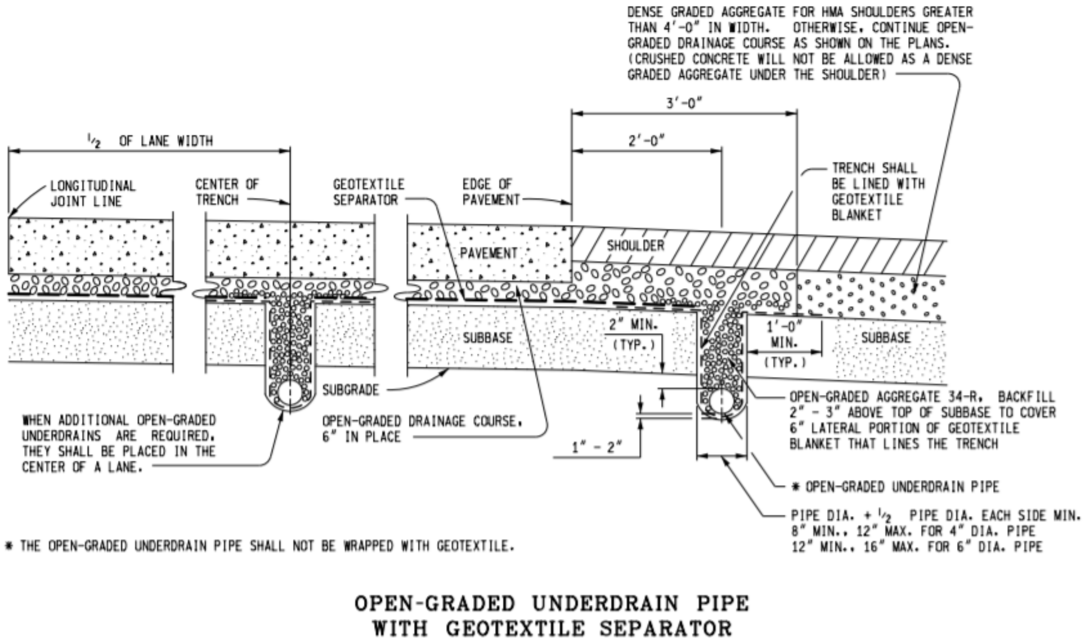


Figure 6.1: MDOT Open Graded Underdrain Detail, MDOT Standard Plan R80 Series (MDOT, 2012)

6.2 Laboratory Program Design

6.2.1 Rainfall Data

In order to determine the amount of water entering into the pavement base through surface cracks and joints, rainfall data was needed to quantify the rain events. Since all of the field-testing sites were located in the Metro Detroit/Southeastern (SE) Michigan area, rainfall data from Detroit Metropolitan Airport (DTW) were considered representative for this region (NOAA, 2019). The annual rainfall data in terms of the accumulative number of rain days and rainfall amounts for years 2009 to 2019 for SE Michigan are shown in Table 6.1.

Table 6.1: Annual Average Rainfall Data for SE Michigan (NOAA, 2019)

Year	Number of Rain Days	Total Yearly Rainfall (inches)
2009	41	21.82
2010	42	22.51
2011	53	50.56
2012	36	13.71
2013	45	25.70
2014	49	26.15
2015	48	20.62
2016	40	21.03
2017	42	19.01
2018	49	28.06
2019	31	21.82
Average	**44.5**	**24.90**

The frequency of rainfall events as function of the total daily rainfall amount is shown in Figure 6.*2*. and Table 6.2 contains daily rainfall statistics. The frequency of rainfall events as function of the hourly rainfall amount is shown in Figure 6.*3*. The hourly rainfall statistics are summarized in Table 6.3. All data were based on years 2009 to 2019 for the SE Michigan area.

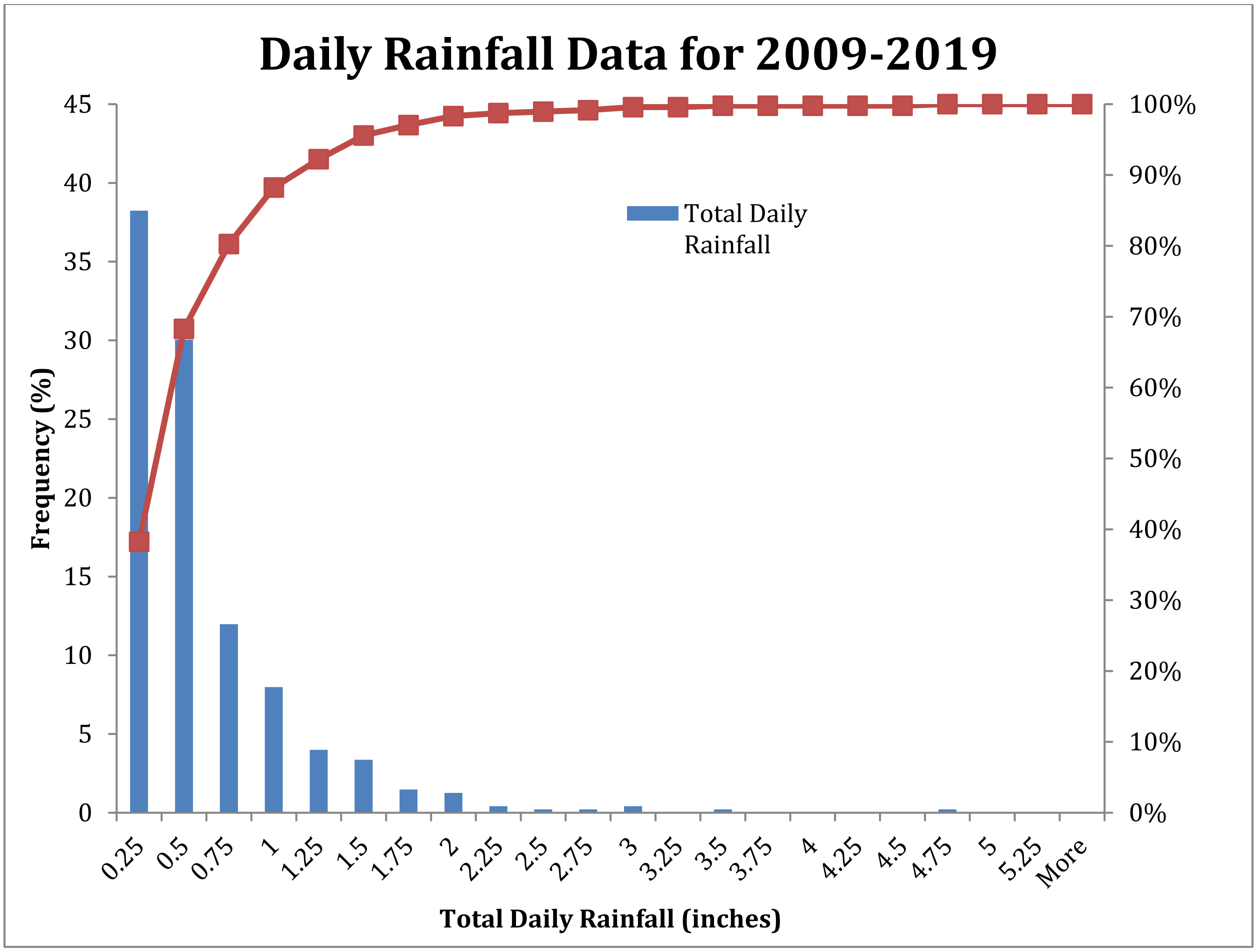


Figure 6.2: Total Daily Rainfall Data for Years 2009-2019 (NOAA, 2019)

Table 6.2: Summary Statistics of the Daily Rainfall Data for Years 2009-2019 (NOAA, 2019)

Statistic	Value
Average daily rainfall (inches)	0.50
Maximum daily rainfall (inches)	4.57
The standard deviation of daily rainfall (inches)	0.50
Median of daily rainfall (inches)	0.33
90th percentile of daily rainfall (inches)	1.09
The average number of rain days per year	44.5
Average rain duration per day (hours)	2.2

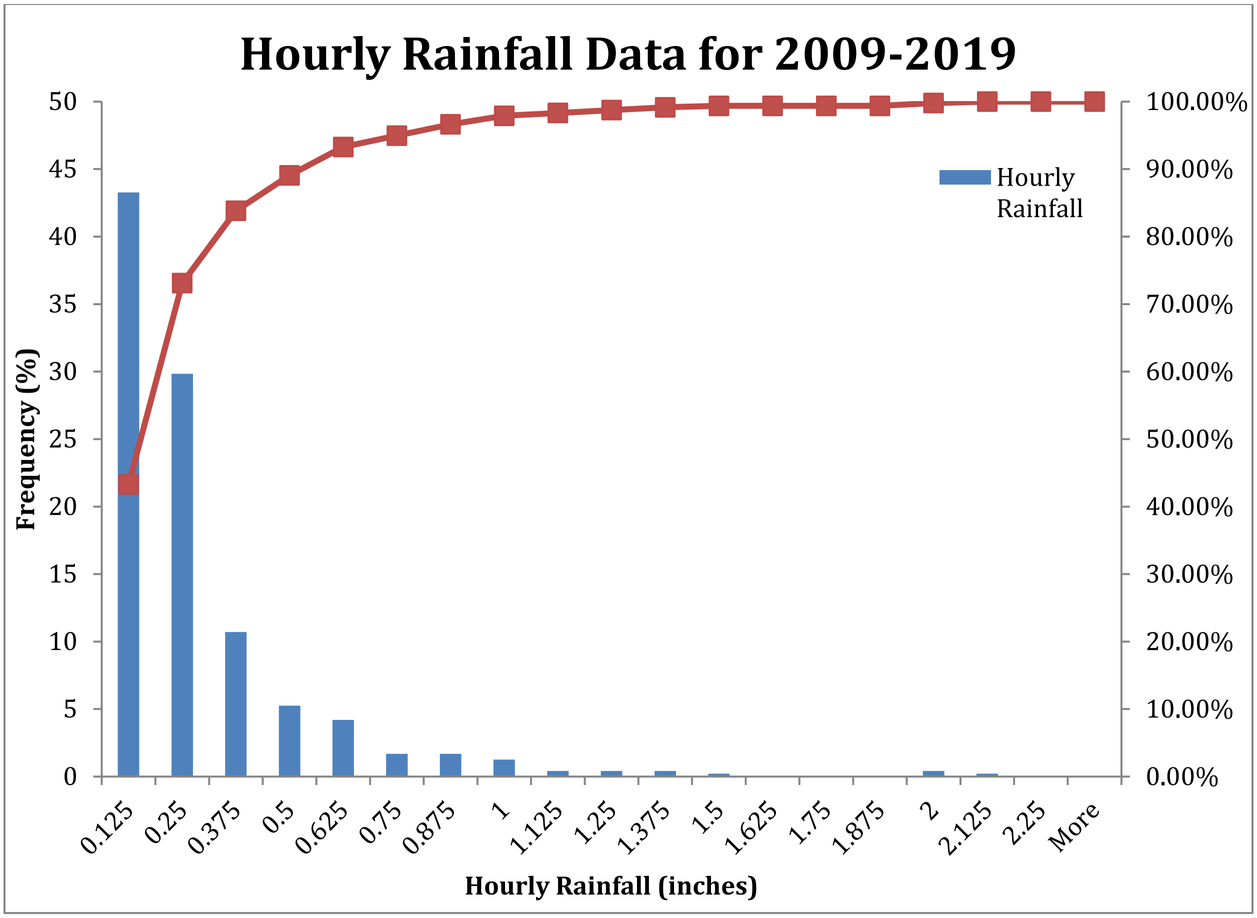


Figure 6.3: Total Hourly Rainfall Data for Years 2009-2019 (NOAA, 2019)

Table 6.3: Summary Statistics of Hourly Rainfall Data for Years 2009-2019 (NOAA, 2019)

Statistic	Value
Average hourly rainfall (inches)	0.23
Maximum hourly rainfall (inches)	2.06
The standard deviation of hourly rainfall (inches)	0.26
Median of hourly rainfall (inches)	0.14
90th percentile of hourly rainfall (inches)	0.53

The above data show that an average rainfall of 0.23 inches per hour (Table 6.3) lasts for approximately 2 hours (Table 6.2. These rainfall events occur approximately 44.5 days per year (Table 6.2) in SE Michigan. Therefore, 0.23 inches per hour of rain for 89 hours represents a typical year. Using these results, 1,335 hours or 55.6 days are required to represent 15 years of typical rainfall events. Previous research and field data collected during this research suggest that in 10-15 years, the pH levels of the leachate levels off to an acceptable level. Therefore, a testing period of 15 years was selected for the laboratory testing program. To accelerate the experimental process, 1 inch per hour of rainfall (90th percentile rainfall) was used in the experiment. These variables assume an average yearly rainfall of 25 inches. This rainfall amount will result in 25 hours of leachate testing to represent 1 year of rainfall or 375 hours of testing to represent 15 years rainfall. Samples were collected and analyzed every 12.5 hours, representing leaching of rainwater at six-month intervals.

6.2.2 Testing Setup

Based on the MDOT underdrain outlet details provided in the Standard Plan R-80 Series (MDOT, 2012), a pavement section was modeled with 300 feet of underdrain outlet spacing as shown in Figure 6.*4*. Assuming a 6-inch diameter column leaching test setup, the rainwater seeping rate through an equivalent 6-inch diameter pavement base area was calculated using the following assumptions:

- Underdrain outlet spacing = 300 ft
- Lane width = 12 ft
- Number of lanes = 3
- Percentage of total runoff seeping through joints and cracks = 15%
- $Total\ water\ volume\ passing\ through\ a\ 6-inch\ diameter\ area = 6{,}368\ ml/hr$ $(388.8\ in^3/hr)$

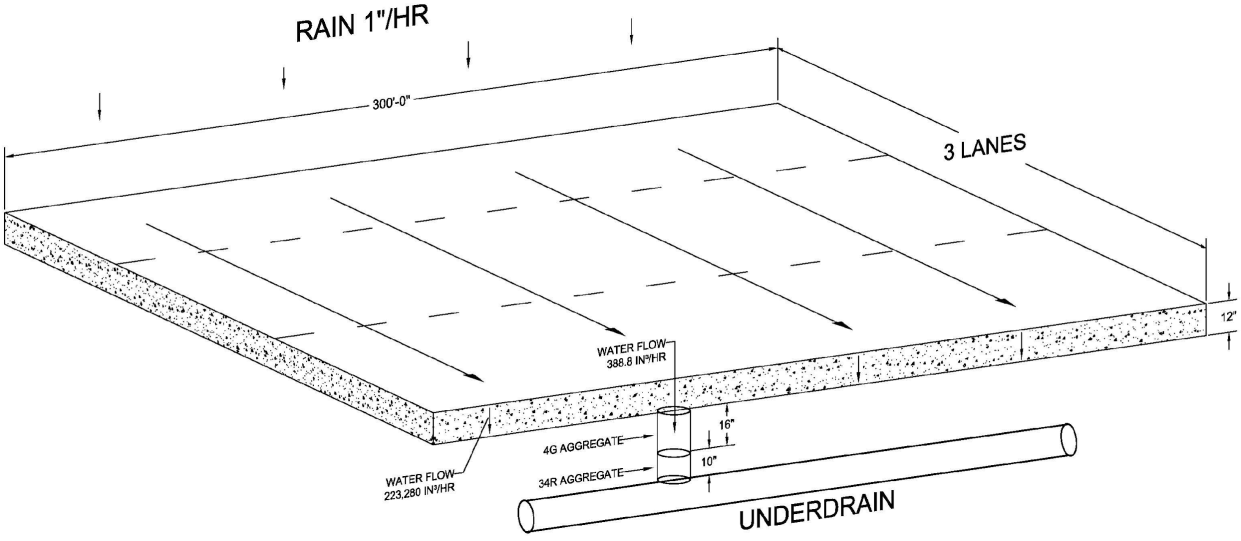


Figure 6.4: Modeled Pavement Section

The experimental setup consists of a uniform flow water supply, a water spray system to simulate water seeping through cracks and joints, and a 6-inch diameter tube filled with 4G open graded aggregate followed by 34R open-graded aggregate. The designed experimental setup is shown in Figure 6.*5* Deionized water was used as the leaching solution.

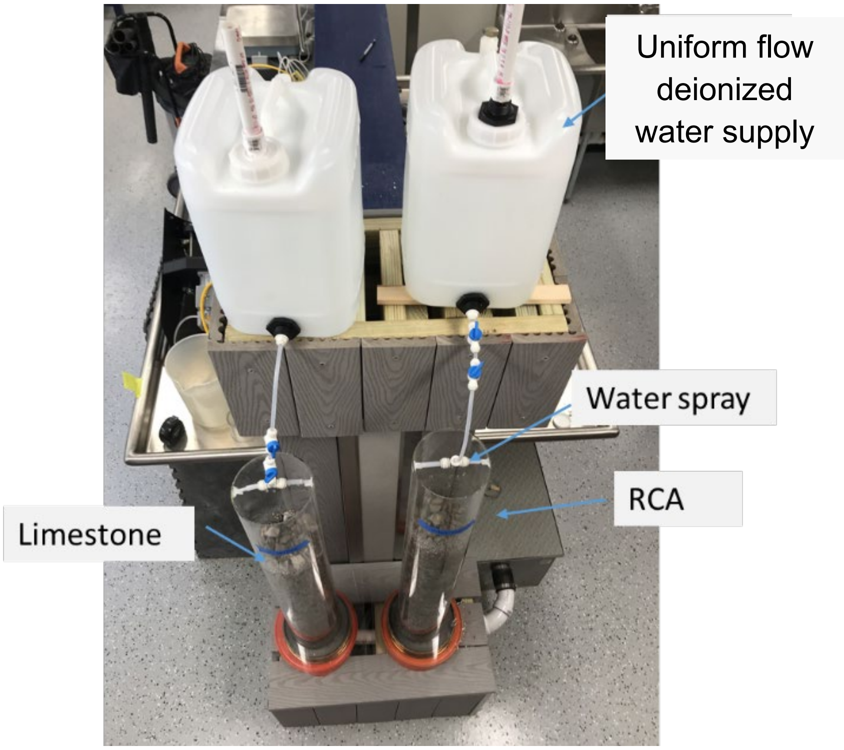


Figure 6.5: Overview of the Experimental Setup

The above setup was modified to run six samples concurrently as shown in Figure 6.*6*.

Figure 6.6: Duplicate Experimental Setup with 6-inch Diameter PVC Tubes

The laboratory test matrix is shown in the following table. The selected material specifications and pavement base thicknesses represent typical MDOT open-graded base sections (MDOT, 2012), as well as potential solutions to lower pH levels of the leachate as described in Section 2.2 of this report.

Table 6.4: Laboratory Test Matrix (Assume 375 hours of testing, equivalent to 15 years)

Test Setup*	Base Type	Base Thickness (inches)		Notes
		4G	34R	
LS1	Limestone	16	10	
RCCA1	Crushed Concrete	16	10	
SA1	Slag Aggregate	16	10	
LS2	Limestone	6	20	
RCCA2	Crushed Concrete	6	20	
SA2	Slag Aggregate	6	20	
RCCA-Wash1	Washed Crushed Concrete	16	10	RCCA washed for 15 minutes in a mechanical washer
RCCA-Wash2	Washed Crushed Concrete	6	20	RCCA washed for 15 minutes in a mechanical washer
RCCA+LS1	Crushed Concrete+ Limestone	16	10	50/50 blend of RCCA and LS
RCCA+LS2	Crushed Concrete+ Limestone	6	20	50/50 blend of RCCA and LS
RCCA+SA1	Crushed Concrete+ Slag Aggregate	16	10	50/50 blend of RCCA and SA
RCCA+SA2	Crushed Concrete+ Slag Aggregate	6	20	50/50 blend of RCCA and SA
Baseline RCCA	Crushed Concrete	16	N/A	16” inches of RCCA tested for 125 hours (equivalent to 5 years)
Baseline 34R	34R limestone aggregate	N/A	10	10” of 34R aggregate tested for 125 hours (equivalent to 5 years)

Key

LS1 - 16-inch limestone open-graded base
RCCA1 - 16-inch crushed concrete open-graded base
SA1 - 16-inch slag aggregate open-graded base
LS2 - 6-inch limestone open-graded base
RCCA2 - 6-inch crushed concrete open-graded base
SA2 - 6-inch slag aggregate open-graded base
RCCA-Wash1 - 16-inch washed crushed aggregate base
RCCA-Wash2 - 6-inch washed crushed aggregate base
RCCA+LS1 - 16-inch crushed concrete and limestone blend
RCCA+LS2 - 6-inch crushed concrete and limestone blend
RCCA+SA1 - 16-inch crushed concrete and slag aggregate blend
RCCA+SA2 - 6-inch crushed concrete and slag aggregate blend

Baseline RCCA- 16-inches of crushed concrete open-graded base only
Baseline 34R - 10-inches of 34R limestone aggregate only

6.3 Laboratory Test Results

Specimen samples were collected in triplicate after every 12.5 hours of simulated rainfall (equivalent to 6 months of rainwater seeping through the pavement system). The characteristics of effluent pH and total dissolved solids (TDS) were obtained using a Hatch Pocket Pro+ and reported as an average value. The TDS readings were measured in parts per million (ppm). Sampling continued until 375 hours of simulated rainfall (equivalent to 15 years of service life) was reached. The Hatch Pocket Pro+ probe was calibrated as per manufacture's guidelines using the buffer solutions obtained from the manufacturer. The results attained from the column tests are presented and discussed in the subsequent sections. The sections are labeled according to the nomenclature set forth in Table 6.4.

After 25 hours of simulated rainfall, a 500-mL sample was collected and preserved for chemical analysis.

6.3.1 Limestone 1 (LS1)

The Limestone 1 test tube contained 16 inches of 4G limestone aggregate over 10 inches of 34R open-graded aggregate. The pH values ranged from 7.0 to 9.3. Although variations are observed, the linear regression trend line has a slight negative slope with a mean pH value of 8.65. The slight alkaline nature is due to release of Ca^{2+}ions from the limestone leaching into water. Since limestone will release Ca^{2+}ions whenever water is seeping through the pavement base, this alkaline nature is expected to last throughout the life of the pavement or until Ca^{2+}ions are no longer available.

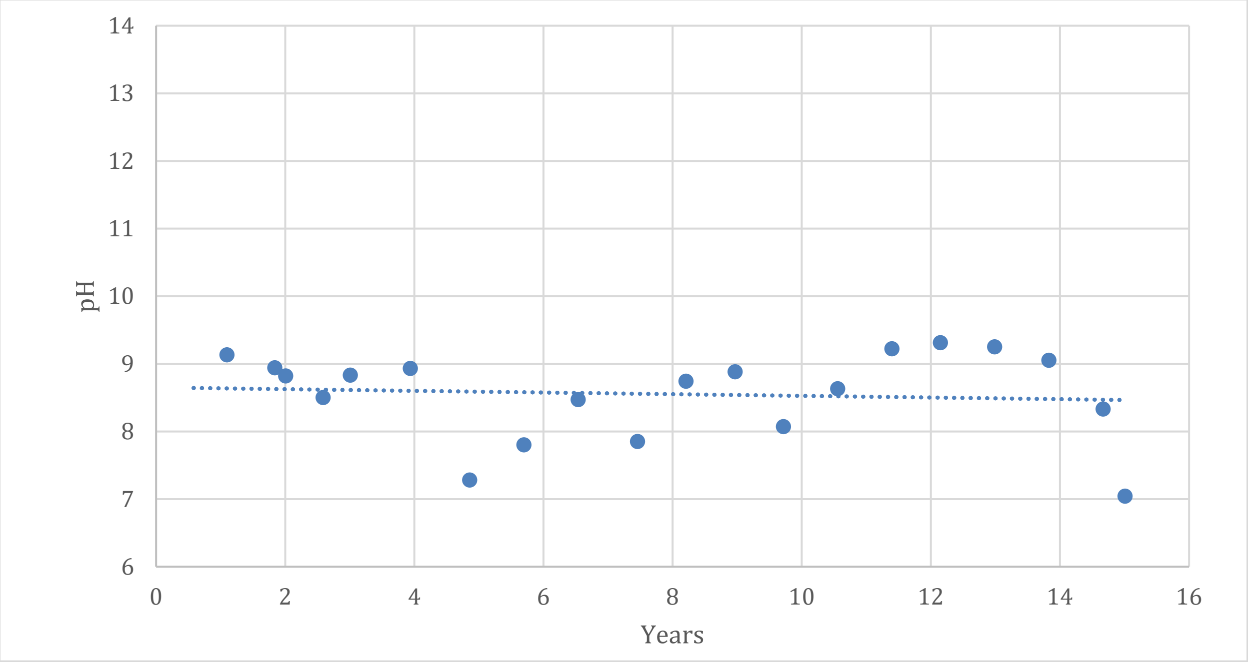


Figure 6.7: Limestone 1 (LS1) pH Values

The TDS values varied from 18 ppm to 65 ppm and show a slight negative correlation with time (Figure 6.*8*). Early TDS test results are higher and show considerable variability. However, after 8 years, the data points followed a narrow band. The early variability may be due to the release of dust particles attached to aggregates.

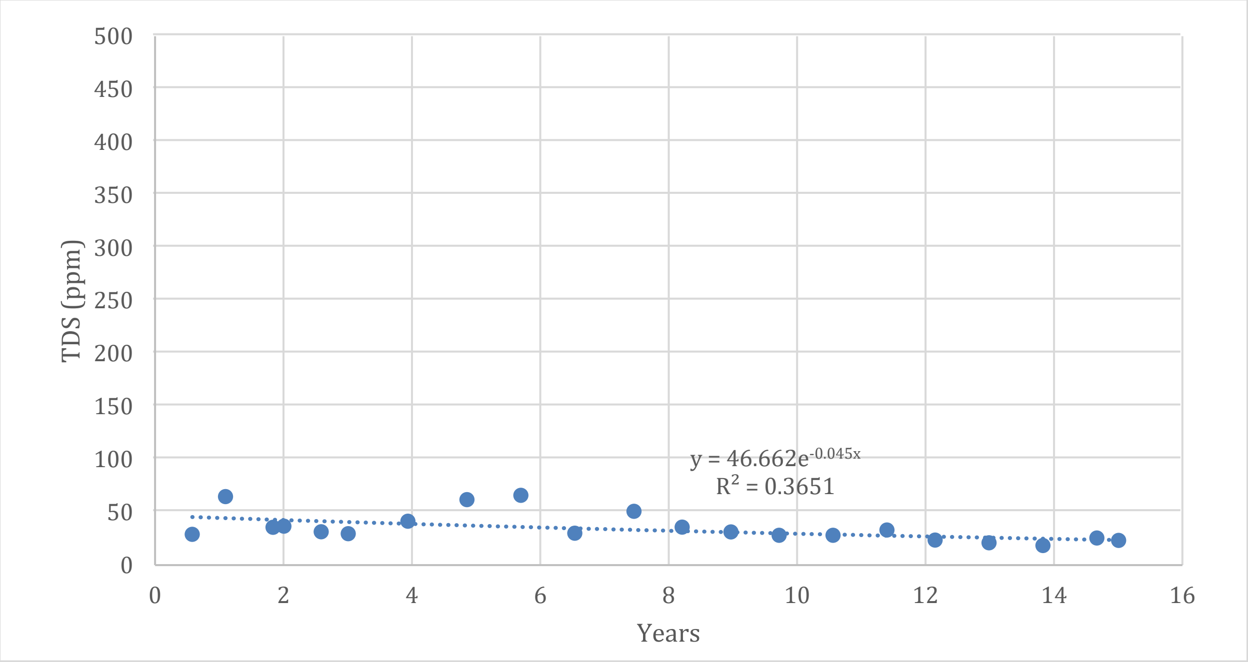


Figure 6.8: Limestone 1 (LS1) TDS Values

6.3.2 Recycled Crushed Concrete Aggregate 1 (RCCA1)

The RCCA1 test tube contained 16 inches of 4G recycled crushed concrete aggregate over 10 inches of 34R aggregate.

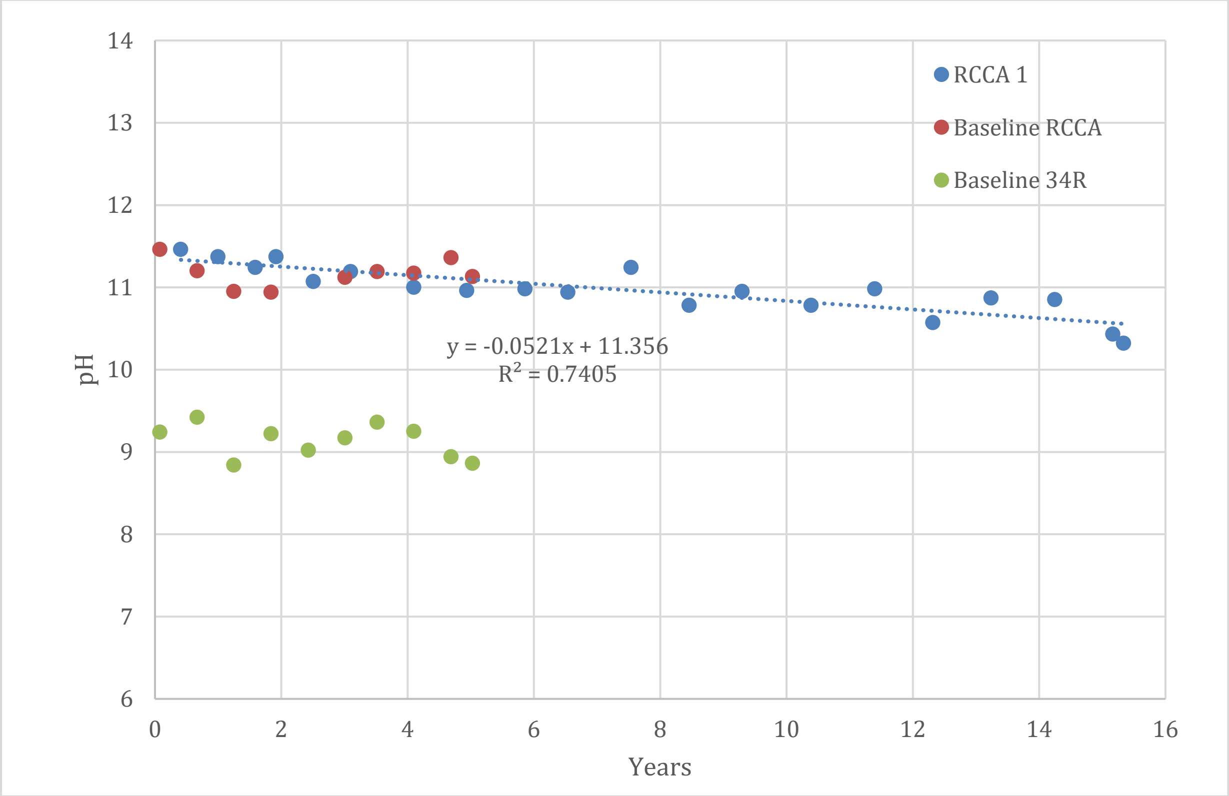


Figure 6.9: Recycled Crushed Concrete Aggregate 1 (RCCA1) pH Values

Figure 6.*9* show a linearly decreasing relationship with respect to time. The pH values of RCCA1 setup slowly decreased from 11.5 to 10.3 in 15 years. Baseline RCCA pH values are very similar to RCCA1 values indicating RCCA material dominates the pH influence of RCCA1 setup. The pH of Baseline 34R is very similar to Limestone pH values. Leaching of Ca^{2+}ions from the Portlandite within the RCCA particles is the main reason for higher pH values as compared to the limestone base discussed above.

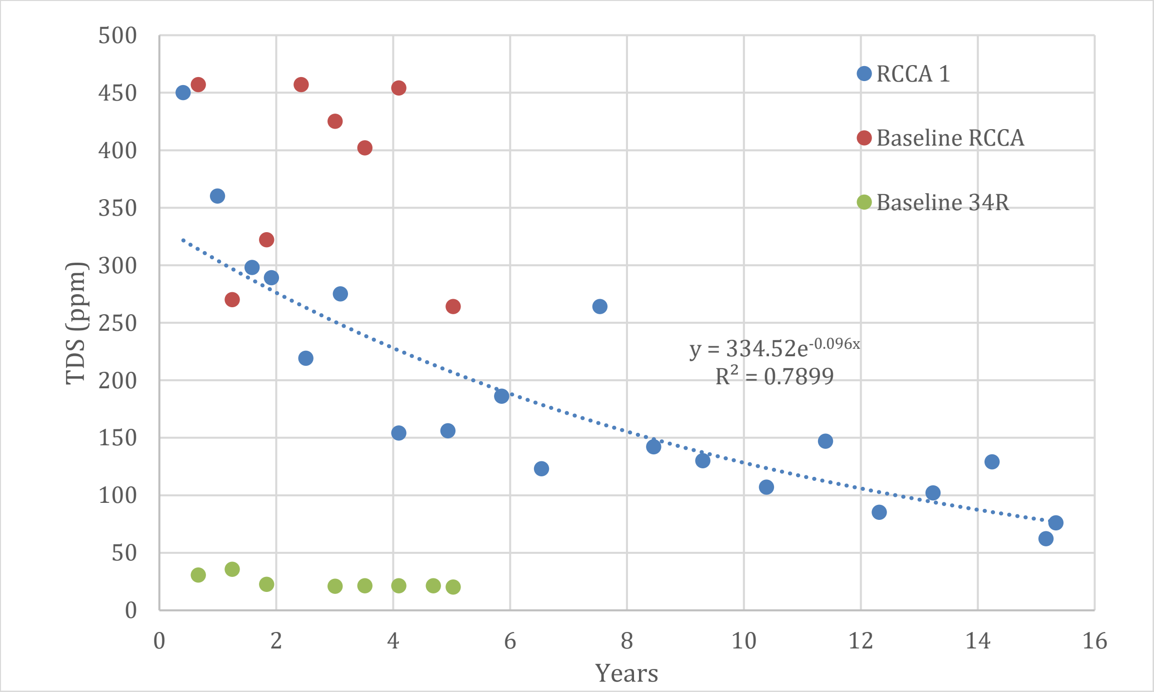


Figure 6.10: Recycled Crushed Concrete Aggregate 1 (RCCA1) TDS Values

TDS values for the RCCA1 material show a strong negative exponential trend (Table 6.10). The range of TDS values decreased from 450 ppm to 62 ppm in 15 years. When compared to LS1, the initial TDS levels of the RCCA1 materials were 7 times higher. TDS values of Baseline RCCA is slightly higher than RCCA1 setup and the TDS values of the Baseline 34R aggregate is negligible.

A relationship between the pH and TDS values was plotted (Figure 6.*11*). This relationship shows there is an exponential growth of TDS with increasing pH values of the leachate in the RCCA1 test. One important observation derived from this relationship is that when the pH increases above 10 - 11, more calcite deposits (directly proportional to TDS) can be expected in underdrain outlet endings.

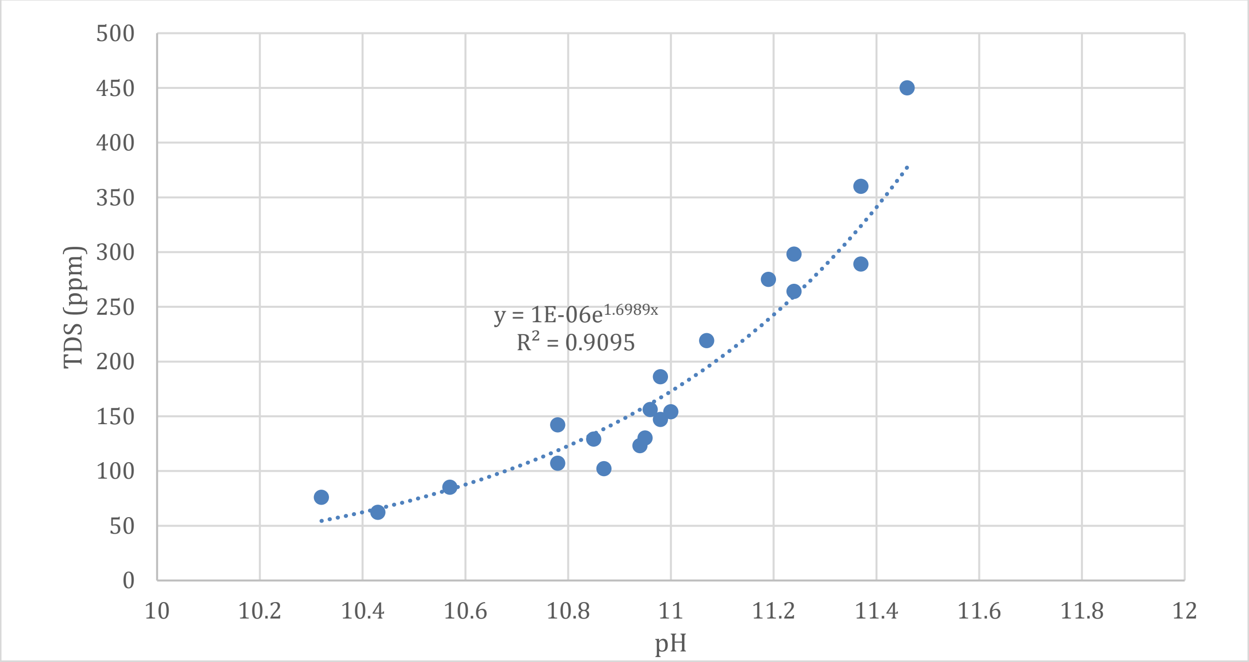


Figure 6.11: Relationship of pH and TDS for RCCA1

6.3.3 Slag 1 (SA1)

The Slag 1 (SA1) test tube contained 16 inches of 4G slag aggregate over 10 inches of 34R aggregate. See Appendix B Figures B.5 and B.6 for the pH and TDS graphs.

Blast furnace slag exhibits a pH in the leachate solution in the range of 7.6 to 9.67. Further, the trend line shows a slightly upward relationship. However, it can be concluded the pH values were within a narrow band with a mean value of 8.9.

The TDS values for SA1 test setup varied and decreased from a high of 125 ppm to a low of 22 ppm. Higher variability of TDS values was observed during the first 8 years of the testing after which most of the data followed a negative exponential trend line. When compared to the RCCA1 test setup, the SA1 TDS results were approximately 50% lower throughout the testing duration of 15 years.

6.3.4 Limestone 2 (LS2)

The Limestone 2 test tube contained 6 inches of 4G limestone aggregate over 20 inches of 34R aggregate. See Appendix B Figures B.7 and B.8 for the pH and TDS graphs.

The pH values for the LS2 test setup decreased from 10.1 to 7.8. As with the LS1 test setup, these pH values can be considered fairly uniform throughout the testing period of 15 years. The mean pH of the LS2 results was 9.4, slightly higher than the mean pH of the LS1 which was 8.6. The increased pH is attributed to the thicker layer of 34R material of 20 inches in LS2 versus 10 inches in LS1.

The TDS values for the LS2 test setup varied and decreased from a high of 77 ppm to a low of 13.2 ppm, showing a negative exponential relationship. These values were similar to the LS1 test results.

6.3.5 Recycled Crushed Concrete Aggregate 2 (RCCA2)

The RCCA 2 test tube contained 6 inches of 4G recycled crushed concrete aggregate over 20 inches of 34R aggregate. See Appendix B Figures B.9 and B.10 for the pH and TDS graphs.

The pH values for the RCCA2 test setup varied from 8.2 to 9.7 and showed a slightly upward linear relationship. These pH values were noticeably lower than the RCCA1 values. These results indicate that the 6-inch RCCA open-graded base course is performing better than the 16-inch RCCA open-graded base course in terms of alkaline nature of the leachate (Figure 6.*12*).

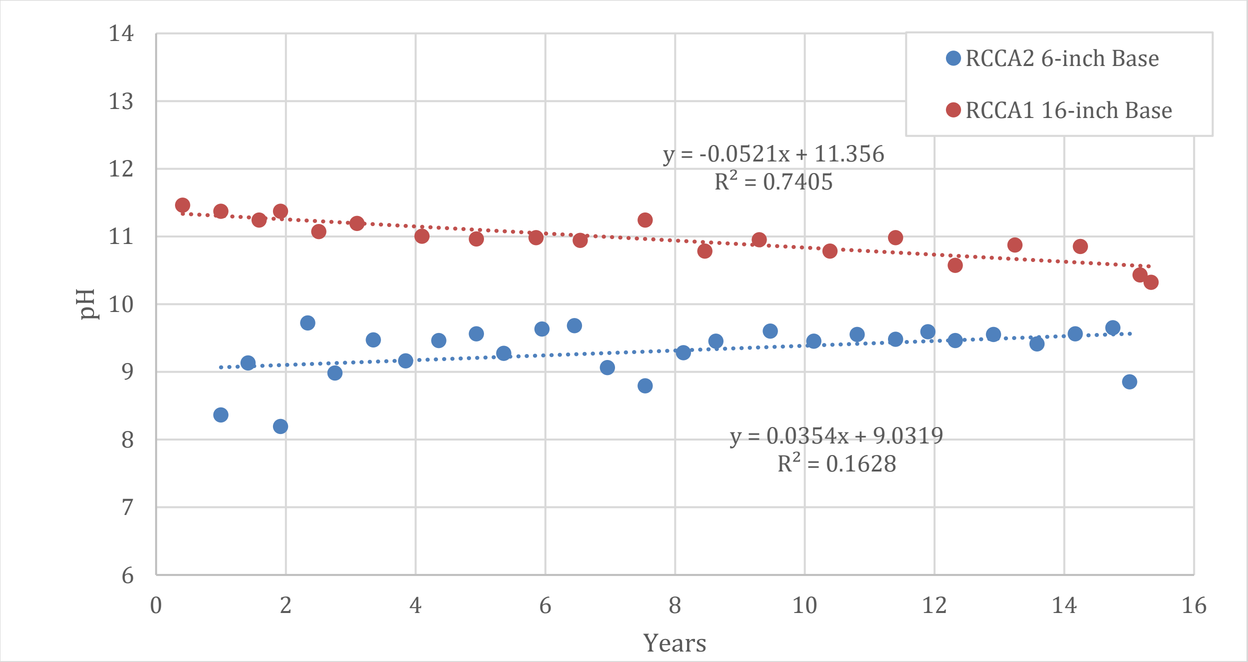


Figure 6.12: Comparison of pH Values of RCCA1 and RCCA2

The TDS values for the RCCA2 also show similar benefits of using the 6-inch RCCA open-graded base course when compared to the 16-inch RCCA open-graded base course. The TDS values ranged from a high of 54 ppm to a low of 26 ppm with a negative exponential trend. This shows a possible reduction of TDS by 80-90% when using the 6-inch base compared to the 16-inch base.

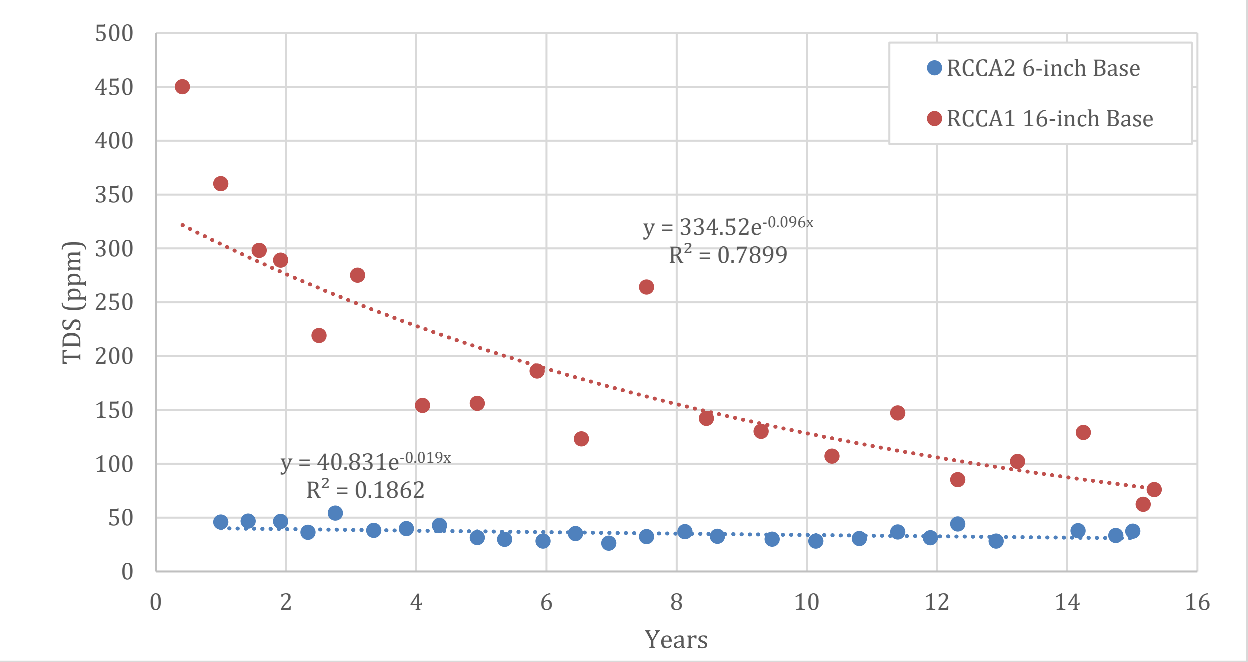


Figure 6.13: Comparison of TDS Values of RCCA1 and RCCA2

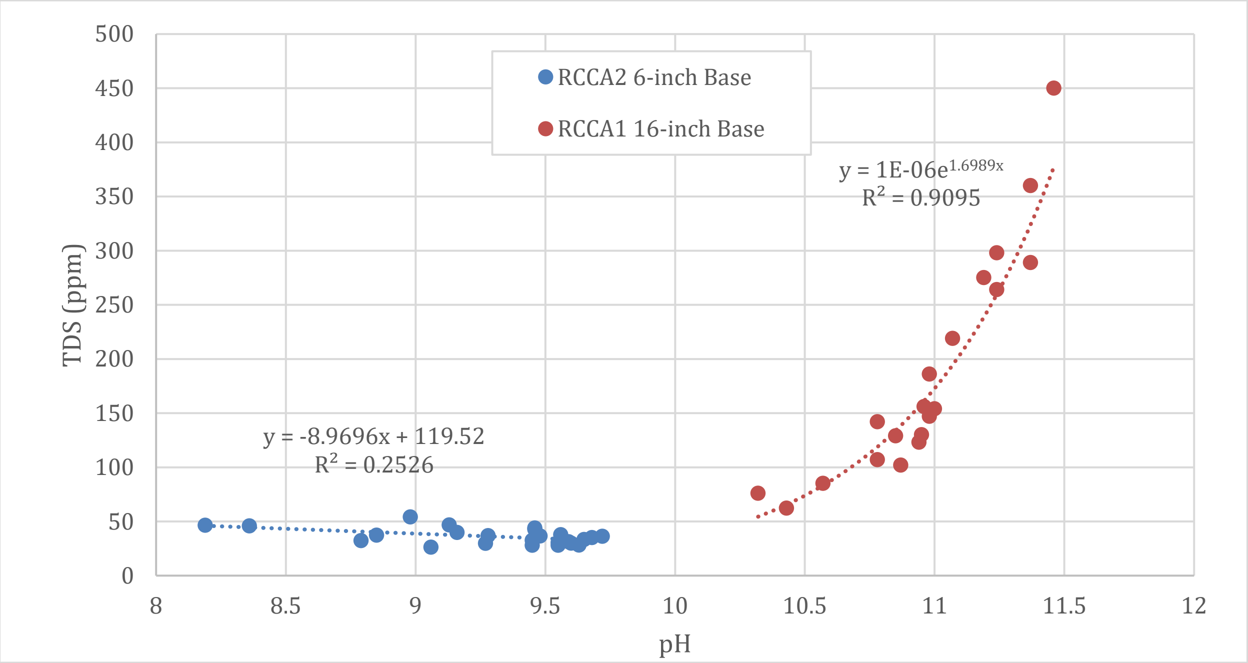


Figure 6.14: Relationship of TDS vs. pH for RCCA1 and RCCA2

Plotting the TDS results versus pH results for both RCCA1 and RCCA2 on the same figure clearly show how the TDS values influence the pH values of the leachate (Figure 6.14). When the pH value exceeds about 10, the data indicate that the TDS release change from a nearly constant to a rapidly increasing behavior. An increase in TDS values is an indicator of increased precipitate potential at the underdrain endings.

6.3.6 Slag 2 (SA2)

The Slag 2 test tube contained 6 inches of 4G slag aggregate over 20 inches of 34R aggregate. See Appendix B Figures B.11 and B.12 for the pH and TDS graphs.

The pH values for the SA2 test setup varied from 7.4 to 9.6 and showed slightly upward linear trend, similar to the SA1 test setup. The average pH was 8.8, similar to the average pH of SA1 which was 8.9.

The TDS values of the SA2 test setup decrease from a high of 60 ppm to a low of 29 ppm with a negative trend. The TDS results of SA,2during the early years, is about half of the TDS results of the SA1 test setup.

6.3.7 Recycled Crushed Concrete Aggregate + Limestone 1 (RCCA+LS1)

The RCCA+LS1 test tube contained 16 inches of a 50/50 blend of 4G recycled crushed concrete and limestone aggregate over 10 inches of 34R aggregate. See Appendix B Figures B.13 and B.14 for these pH and TDS graphs.

The pH values of RCCA+LS1 decreased from a high of 10.8 to a low of 9.6 with a downward linear trend. Inclusion of 50% limestone aggregate lowered the pH values by approximately 1.0, showing a similar downward linear trend as RCCA1. The combined pH graphs for RCCA1 and RCCA+LS1 are shown in Figure 6.*15*.

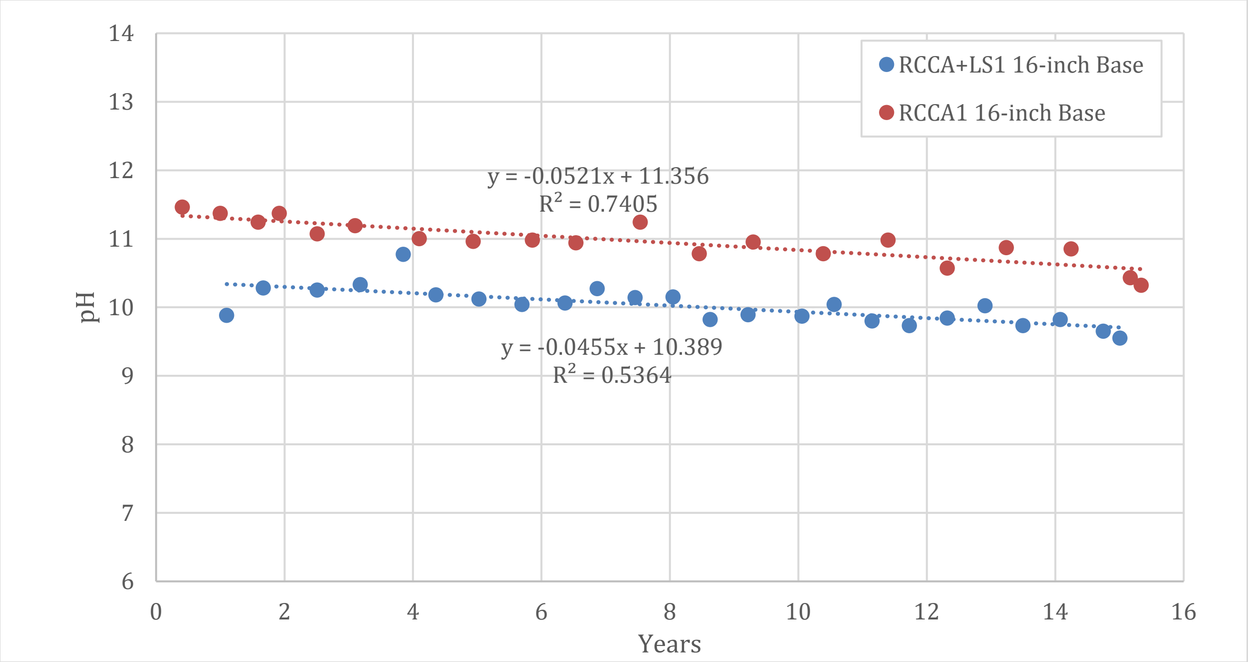


Figure 6.15: Comparison of pH values for RCCA1 and RCCA+LS1

This relationship shows the benefit of using a 50/50 combination of RCCA and LS than using RCCA alone as the open-graded base material.

The TDS values of the RCCA+LS1 blend decreased from a high of 148 ppm to a low of 42 ppm with a negative exponential trend. As shown in Figure 6.*16*, the TDS values were much lower for the RCCA+LS1 blend than when using RCCA only.

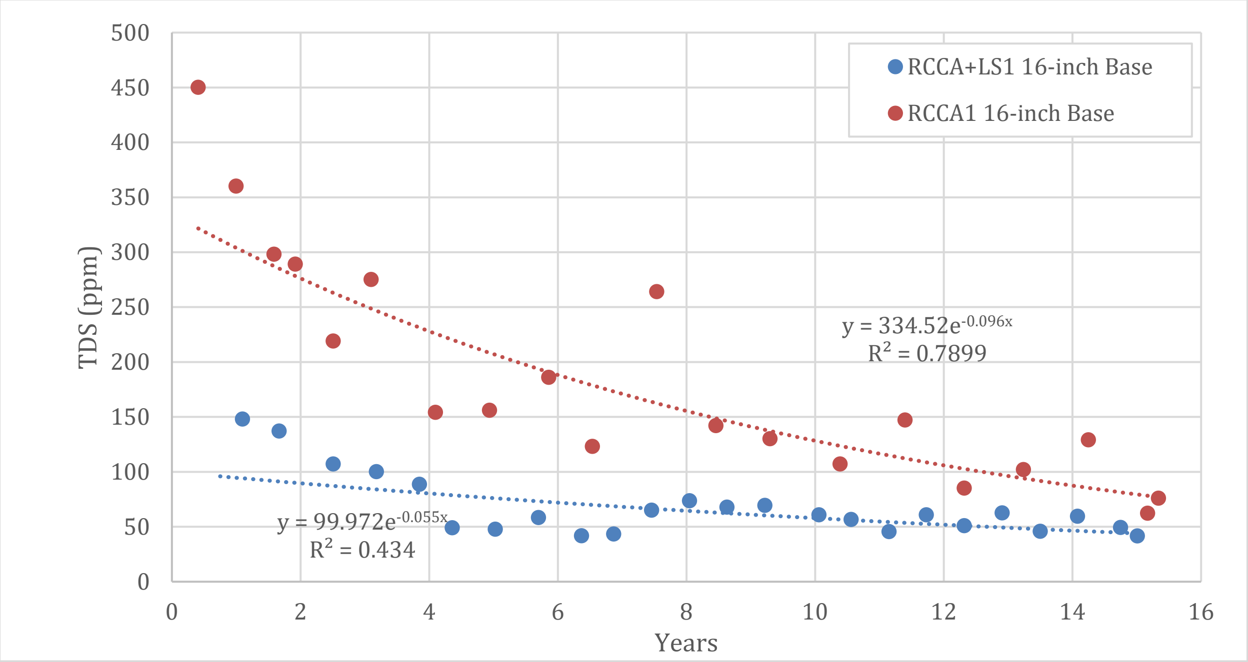


Figure 6.16: Comparison of TDS Values for RCCA1 and RCCA+LS1

6.3.8 Recycled Crushed Concrete Aggregate + Limestone 2 (RCCA+LS2)

The RCCA+LS2 test tube contained 6 inches of a 50/50 blend of RCCA and LS aggregate over 20 inches of 34R open-graded aggregate. See Appendix B Figures B.15 and B.16 for these pH and TDS graphs.

The pH values of the RCCA+LS2 test setup decreased from a high value of 10.4 to a low value 8.5, similar to RCCA2 test setup. Similar observations can be made in TDS for the RCCA+LS2 base where no significant difference was observed when compared to 6-inch thick RCCA only base. Therefore, it can be concluded that using a blend of RCCA+LS in 6-inch base is not advantageous when compared to 6-inch thick RCCA only base.

6.3.9 Recycled Crushed Concrete Aggregate + Slag 1 (RCCA+SA1)

The RCCA+SA1 test tube contained 16 inches of a 50/50 blend of 4G recycled crushed concrete and slag aggregate over 10 inches of 34R aggregate. See Appendix B Figures B.17 and B.18 for the pH and TDS graphs.

The pH values of RCCA+SA1 varied and decreased from a high of 11.5 to a low of 10.2 with a downward linear trend. Inclusion of 50-percent slag aggregate lowered the pH values by approximately 0.3 at the beginning. However, the difference increased to 0.6 in 10 years. Overall, the inclusion of 50-percent slag aggregate in the RCCA base slightly decreased the pH of the leachate.

Similar observations can be made for TDS graphs. Inclusion of slag aggregate in the RCCA base has slightly decreased the TDS values of the leachate.

6.3.10 Recycled Crushed Concrete Aggregate + Slag 2 (RCCA+SA2)

The RCCA+SA2 test tube contained 6 inches of a 50/50 blend of 4G recycled crushed concrete and slag aggregate over 20 inches of 34R aggregate. See Appendix B Figures B.19 and B.20 for the pH and TDS graphs.

The pH values decreased from a high of 11.0 to a low of 9.0 after 15 years of rainfall simulation. However, RCCA2 (6-inches of RCCA over 20-inches of 34R open-graded aggregate) pH values were lower than the combination of RCCA and SA indicating that there is no benefit of including a 50/50 blend of RCCA and SA in terms of reducing pH of the leachate.

Similar observations can be made for TDS graphs. Inclusion of slag aggregate in the RCCA base has slightly increased the TDS values of the leachate. Therefore, no benefit can be obtained by adding SA to the RCCA when a 6-inch base is used for construction.

6.3.11 Washed Recycled Crushed Concrete 1 (RCCA-Wash1)

The RCCA-Wash1 test tube contained 16 inches of washed 4G recycled crushed concrete aggregate over 10 inches of 34R aggregate. See Appendix B Figures B.21 and B.22 for the pH and TDS graphs.

As shown in Figure 6.*17*, an approximate 0.50 reduction in pH value was observed when washed RCCA was used in the 16-inch open-graded base course.

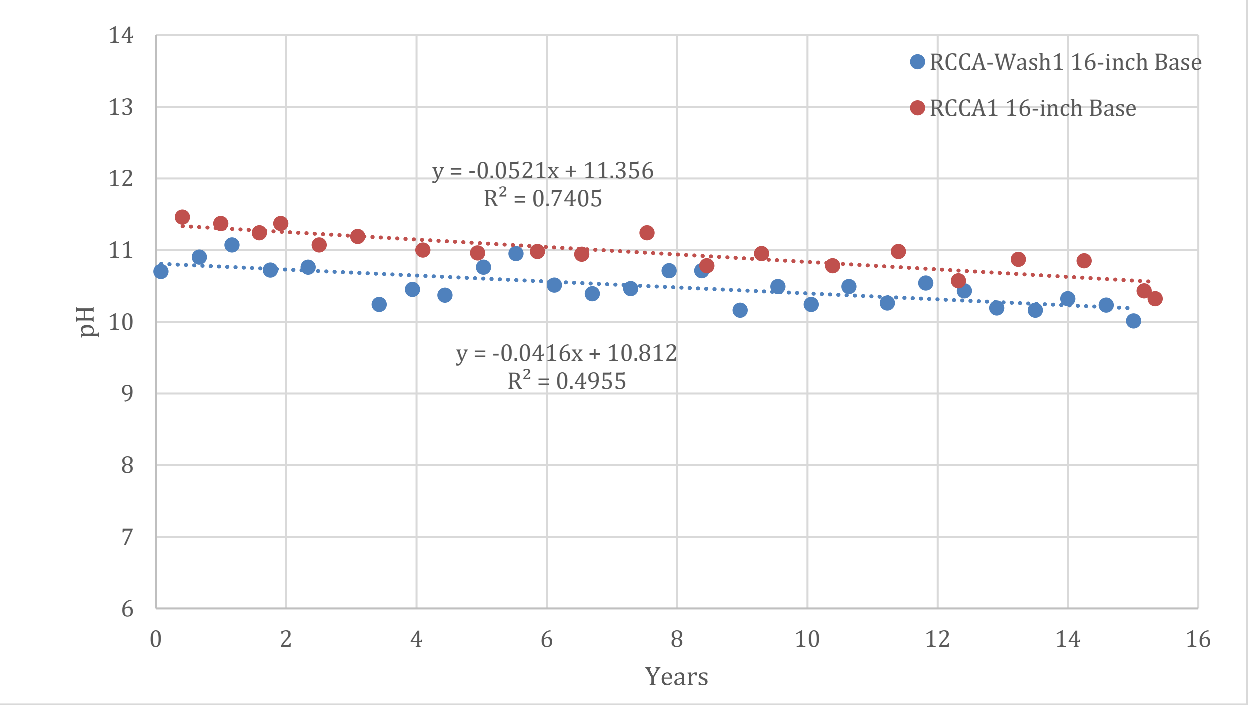


Figure 6.17: Comparison of pH Values for RCCA1 and RCCA-Wash1

A similar observation was made for the TDS values when compared to RCCA1 test setup. A decrease of approximately 50 ppm of TDS was observed in the early years when washed aggregates were used in the 16-inch open-graded base course.

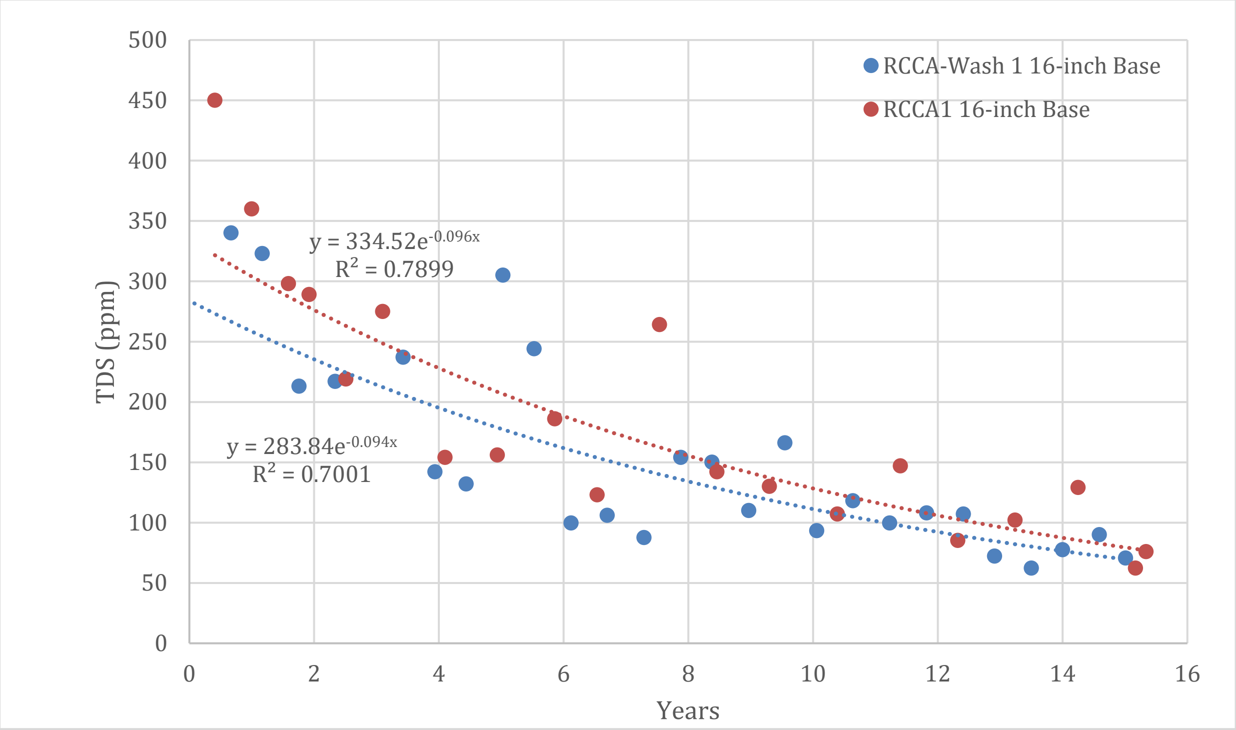


Figure 6.18: Comparison of pH Values for RCCA1 and RCCA-Wash1

6.3.12 Washed Recycled Crushed Concrete 2 (RCCA-Wash2)

The RCCA-Wash 2 test tube contained 6 inches of washed 4G recycled crushed concrete aggregate over 20 inches of 34R aggregate. See Appendix B Figures B.23 and B.24 for the pH and TDS graphs.

The pH values of the RCCA2 test setup were slightly lower than the washed RCCA2 test setup in the first few years and then the data of both bases fell on the same line. This indicates that for the RCCA stockpile used in this study, that there is no benefit of washing aggregate in terms of reducing pH of the leachate when 6 inches of open-graded base course is used.

Similar observations can be made for TDS graphs. Therefore, no real benefit can be obtained by washing the RCCA used in this study, in terms of TDS values, when a 6-inch base is used for construction.

6.3.13 Combined Results

Below are the plotted comparative TDS and pH values for the completed tests.

Over the duration of the testing period, RCCA1 consistently exhibited higher pH values than the other profiles (Figure 6.*19*). These profiles show that mixing RCCA with LS and SA consistently lowers the pH values of the leachate when compared to RCCA alone. Similarly, washing RCCA also shows a benefit in reducing pH values of the leachate. SA and LS base courses exhibit the lowest pH values when compared to RCCA combinations.

The variations of pH values of 6-inch base layers over the testing period of 15 years are shown in Figure 6.*20*. During the early years, higher pH values were observed for the RCCA+LS2 test setup. The lowest pH values were observed with the SA2 test setup. However, all the pH values settled at about 9.5 after 10 years of simulated rainfall.

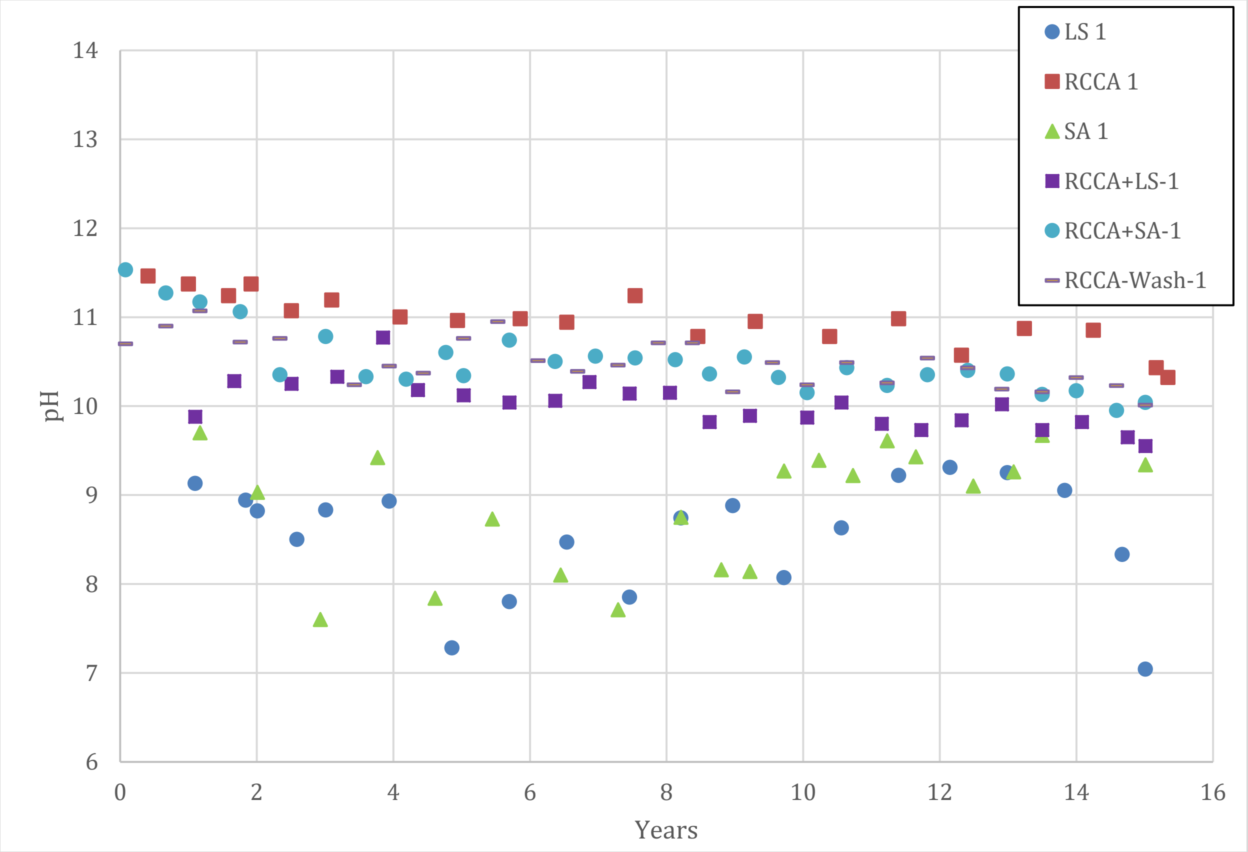


Figure 6.19: Comparative pH Values for 16 inches of 4G Aggregate Base over 10 inches of 34R Aggregate

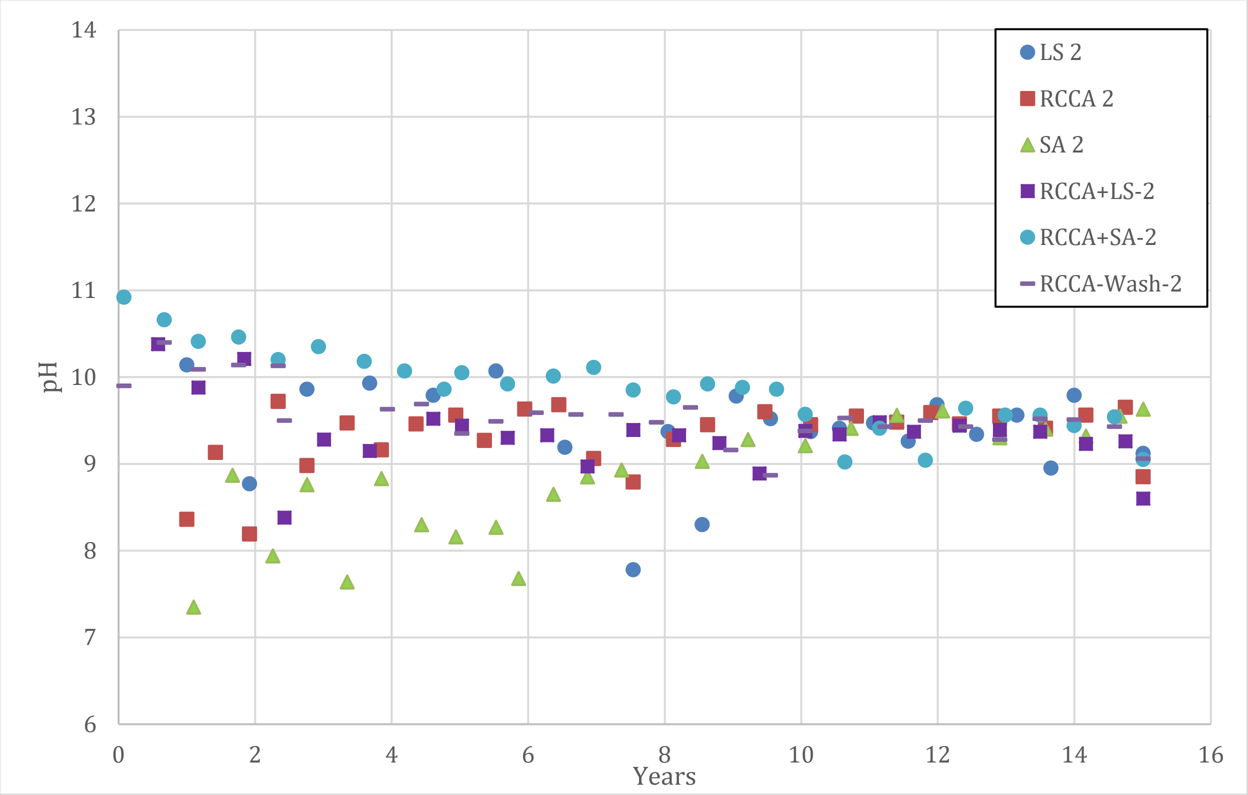


Figure 6.20: Comparative pH Values for 6 inches of 4G Aggregate Base Over 20 inches of 34R Aggregate

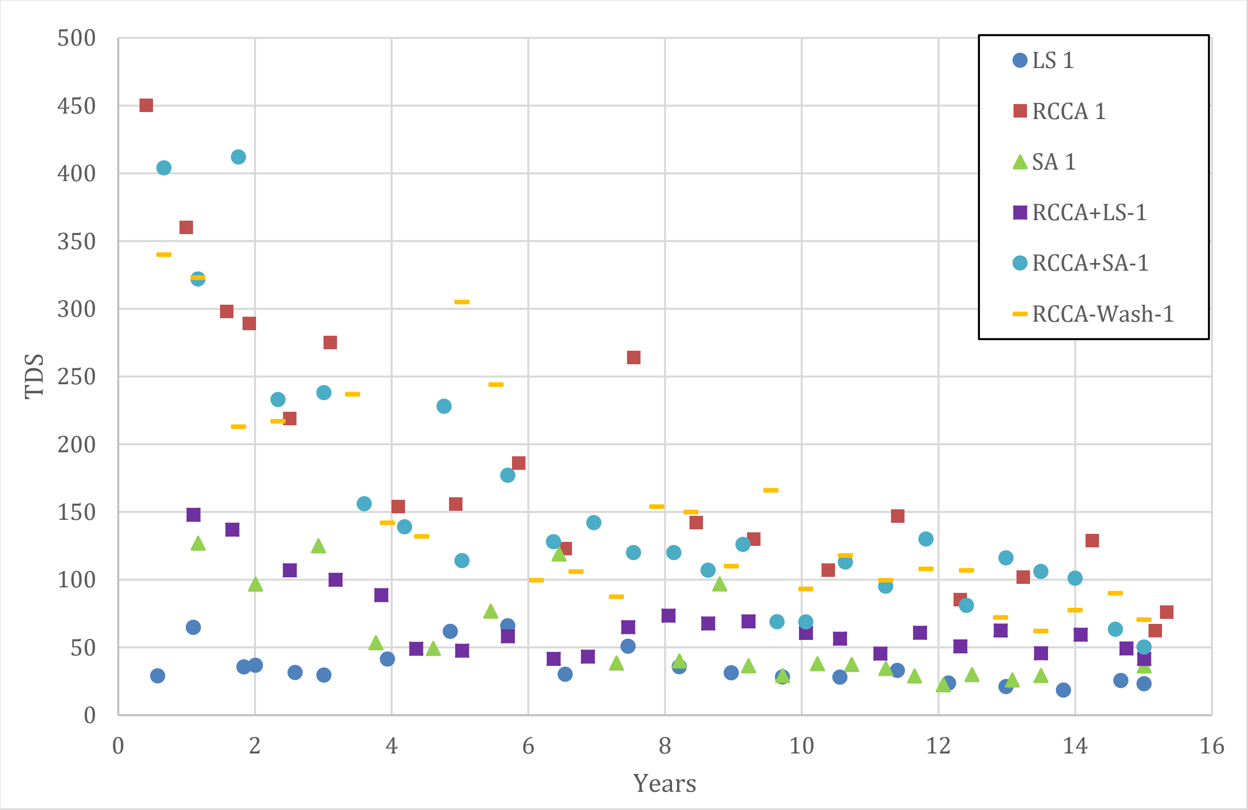


Figure 6.21: Comparative TDS Values for 16 inches of 4G Aggregate Base over 10 inches of 34R Aggregate

In terms of TDS, a decrease in TDS values is observed for all 16-inches base (see Figure 6.*21*). Again, recycled crushed concrete aggregate (RCCA1) produced the highest TDS results and limestone (LS1) produced the lowest TDS results. Combining RCCA with LS decreased the TDS values significantly when compared to other treatments.

The variations of the TDS values for all the 6-inch base courses (Test Setup 2) over the 15-year testing period are shown in Figure 6*.22*. Similar values of TDS were observed for all test combinations except when RCCA+SA2 base layer was used.

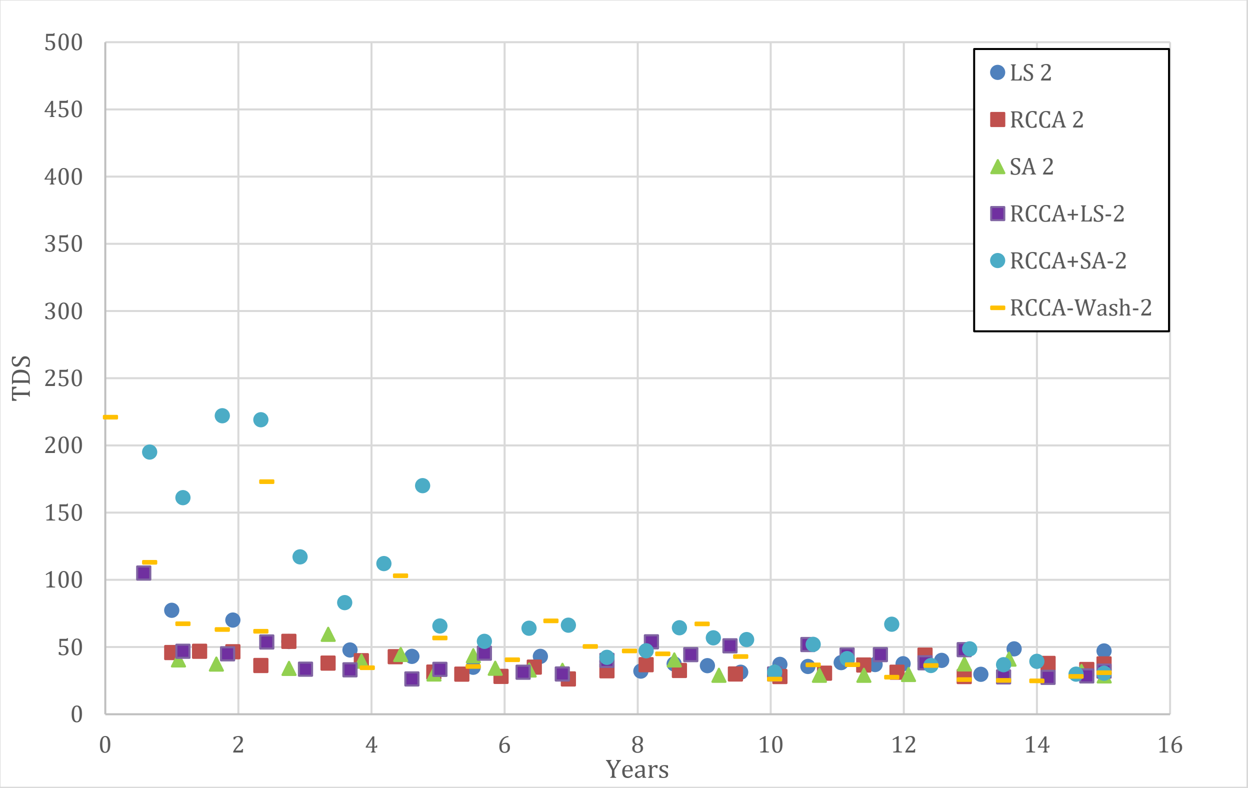


Figure 6.22: Comparative TDS Values for 6 inches of 4G Aggregate Base over 20 inches of 34R Aggregate

6.4 Summary of the Laboratory Program

The following summary of results were developed to highlight the main points derived from the laboratory testing program. This laboratory program consisted of several standard pavement base construction details used by MDOT as shown in Table 6.4. Some of the proposed solutions reported in the literature to limit high pH and soluble content in the effluent were also included the laboratory program. The proposed solutions include:

a. Blending RCCA and LS in 50/50 proportions
b. Blending RCCA and SA in 50/50 proportions
c. Washing RCCA prior to use in the experiment

The findings of the laboratory investigation are:

1. Slightly alkaline leachate and low levels of soluble particles (measured by TDS) were observed in all limestone and slag aggregate bases.
2. Highly alkaline leachate and higher levels of soluble particles in the effluent were observed for RCCA base with 16-inch thickness during the first 8-10 years of service life.

3. A relationship was developed as shown in Figure 6.23 with the pH and TDS values to determine that the pH level is associated with higher levels of soluble particles which can generate calcite deposits at the underdrain outlet endings.

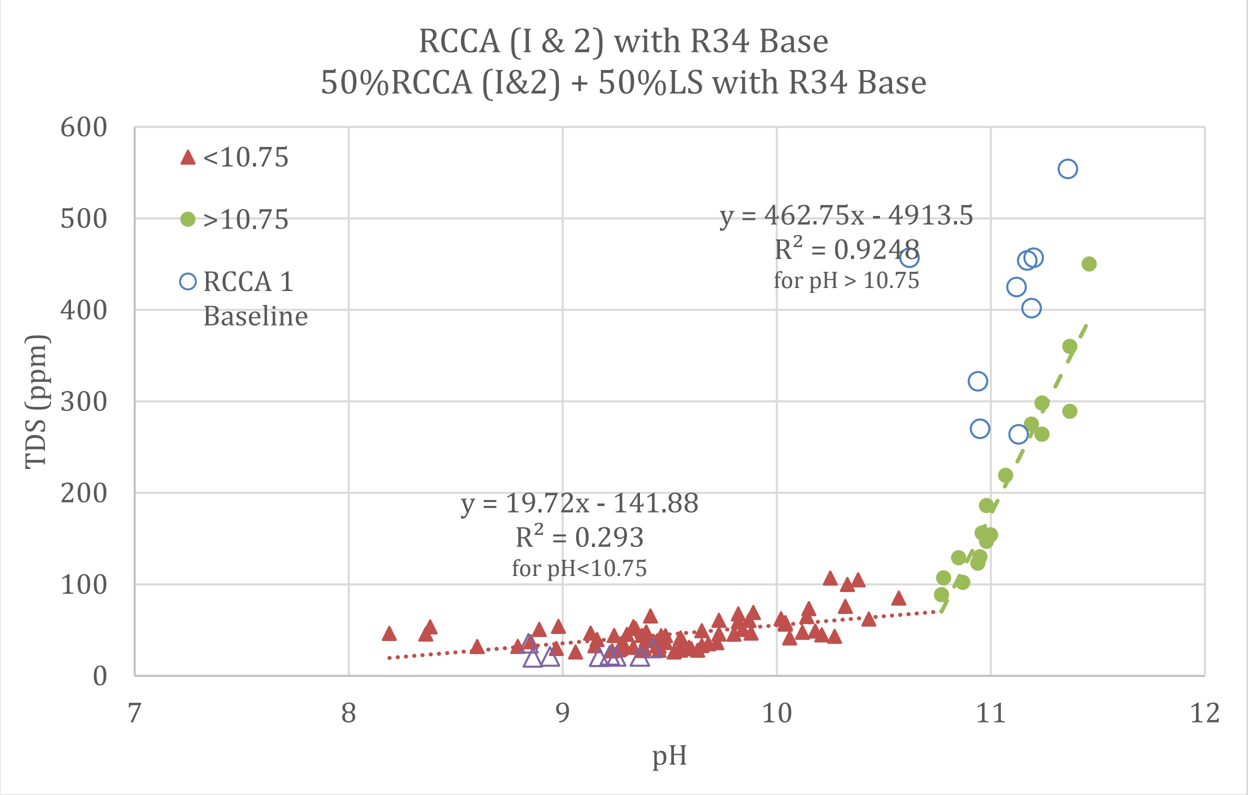


Figure 6.23: pH vs. TDS Relationship for All RCCA Aggregates

4. Slightly alkaline leachate and low levels of soluble particles in the effluent were observed in RCCA base with 6-inch thickness.
5. Based on the TDS and pH relationships of all RCCA materials (16-inch base and 6-inch base), it can be concluded when the pH level is higher than 10.75, higher levels, > 100, of soluble particles can be expected in the leachate. This can lead to high levels of precipitate at the underdrain outlet endings.
6. The laboratory investigation supports the following recommendations for 16-inch RCCA bases:
    a. Use a 50/50 blend of RCCA and LS
    b. Use a 50/50 blend of RCCA and SA
    c. Wash RCCA prior to use in the construction. The effect of washing is shown in figure 6.24. When washed RCCA is used in the 16-inch base a measurable reduction of pH (<10.75) and TDS approaching 150-200 ppm within 5 years can be observed.

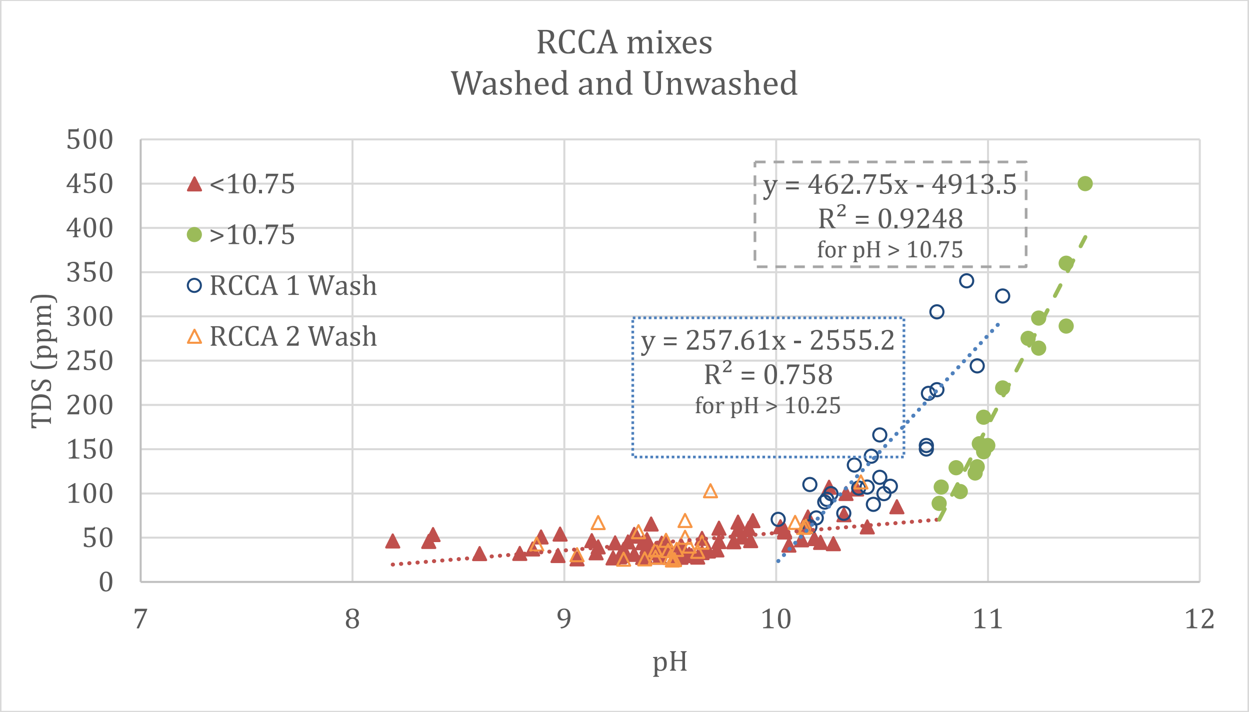


Figure 6.24: Effect of Washing of RCCA Aggregates

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Based on the data and results presented in previous chapters the following conclusions and recommendations are developed.

7.1 Conclusions

1. The literature review and survey of several states' Departments of Transportation and other highway agencies revealed that use of recycled aggregates is common in a variety of highway applications including pavement base/sub-base construction. The majority of the highway agencies have recognized the value of using recycled aggregates in base/sub-base construction; however, several adverse effects on the pavement drainage system have been identified such as:
    a. high alkalinity of the leachate from the recycled crushed concrete aggregate (RCCA) bases. The high alkalinity of water can destroy the vegetation and other aquatic life. The high alkalinity of water can also rust the rodent screens of the drainage outlets.
    b. clogging of drainage features such as filter fabrics, pipes, and outlets due to calcite formation and other soluble/suspended particle deposits. Clogging can increase moisture levels within the pavement base causing premature pavement failure.
    c. increase of hazardous materials in the leachate water. Studies have shown minor increases in heavy metals leached from recycled crushed concrete aggregate bases.
2. MDOT conducted a limited laboratory and field investigation of recycled aggregate base materials and found increased levels of soluble particles and pH levels of the leachate and deposit formation at the drainage outlets. High alkalinity and deposits caused damage to the vegetation around the underdrain outlets.
3. During this study, additional field sites with different types of base materials were selected for sampling to supplement MDOT's collected data. Leachate water samples from the underdrain outlets and 100-feet from the outlets were collected during several rainfall events. The pH and Total Dissolved Solids (TDS) of the leachate were measured at the site and samples were preserved for further chemical testing. These field and associated laboratory testing, conducted in this study, have confirmed some of the observations made by the earlier MDOT study. Chemical analysis of leachate showed a minimum amount of heavy metals in the leachate and their levels were well below the EPA limits for wastewater standards.
4. A laboratory investigation was conducted in this study to supplement the discrete data points observed during field sampling and testing. A column leachate testing procedure based on the Dutch Standard Column test (NEN 7343), NEN, 1995) was used in the laboratory study. Fifteen (15) years of rainfall was simulated to drain through the pavement bases constructed from different base materials (LS, SA, RCCA, and combinations of these materials). Based on the results, several relationships were realized for the variables pH,

TDS, and pavement age for each base type. The leachate from limestone and slag aggregate bases exhibit somewhat constant pH values throughout the pavement life. As expected, the leachate from RCCA bases showed initial high values of pH and TDS followed by decreasing trends. A linear relationship between pH and pavement age as well as a decreasing exponential relationship between TDS and pavement age were observed. A new relationship between TDS and pH was developed for RCCA materials that clearly shows the critical pH value beyond which calcite formation at the underdrain outlets rapidly increases. Based on results from this study, the critical pH value for the accelerated onset of calcite formation is about 10.50 - 10.75.

5. Several treatment solutions to decrease the pH of leachate and soluble particles were evaluated in the laboratory study including the blending of RCCA with LS and SA and washing RCCA prior to use in the base. While all treatments solutions were effective, some solutions were more successful than others. Blending LS and SA in a 50/50 ratio with RCCA materials produced lower soluble particles and pH values for 16-inch base layers. Washing of the RCCA aggregates, prior to construction, has also yielded lower amounts of soluble particles and pH values for 16-inch base layers. Both of these treatment solutions did not yield any improvements for 6-inch base layers.
6. MDOT's standard base design of 6-inch open-graded drainage layer with RCCA yields lower pH and TDS values compared to the 16-inch modified base with RCCA used in the Metro region. Lower soluble particles and lower pH values were observed in the leachate from 6-inch thick RCCA base layers.

7.2 Recommendations and Proven Techniques

The following recommendations and proven techniques were derived from the results of the literature review as well as field and laboratory investigations completed in this study. Some of the environmental concerns of using recycled aggregate have shown to be mitigated through planning and design considerations, use of conventional Best Management Practices (BMPs), and implementable construction controls (Snyder et al, 2018).

Table 7.1 Recommendations and Proven Techniques

Consideration	Recommendations for Mitigation/Proven Techniques	Supporting Evidence
	Project Planning Considerations	
Contamination and pollutants from the source concrete	Use of concrete from known agency sources. *MDOT is already following this recommendation. MDOT 2012 Standard Specification for Construction states "use department-owned concrete" (MDOT, 2012).*	Cavalline (2018)
	Prequalification of the source material. *MDOT currently uses department-owned concrete as aggregate, only.*	Cavalline (2018)
High pH Leachate	Place drainage outlets at least 100 feet away from receiving waters.	Cavalline (2018)

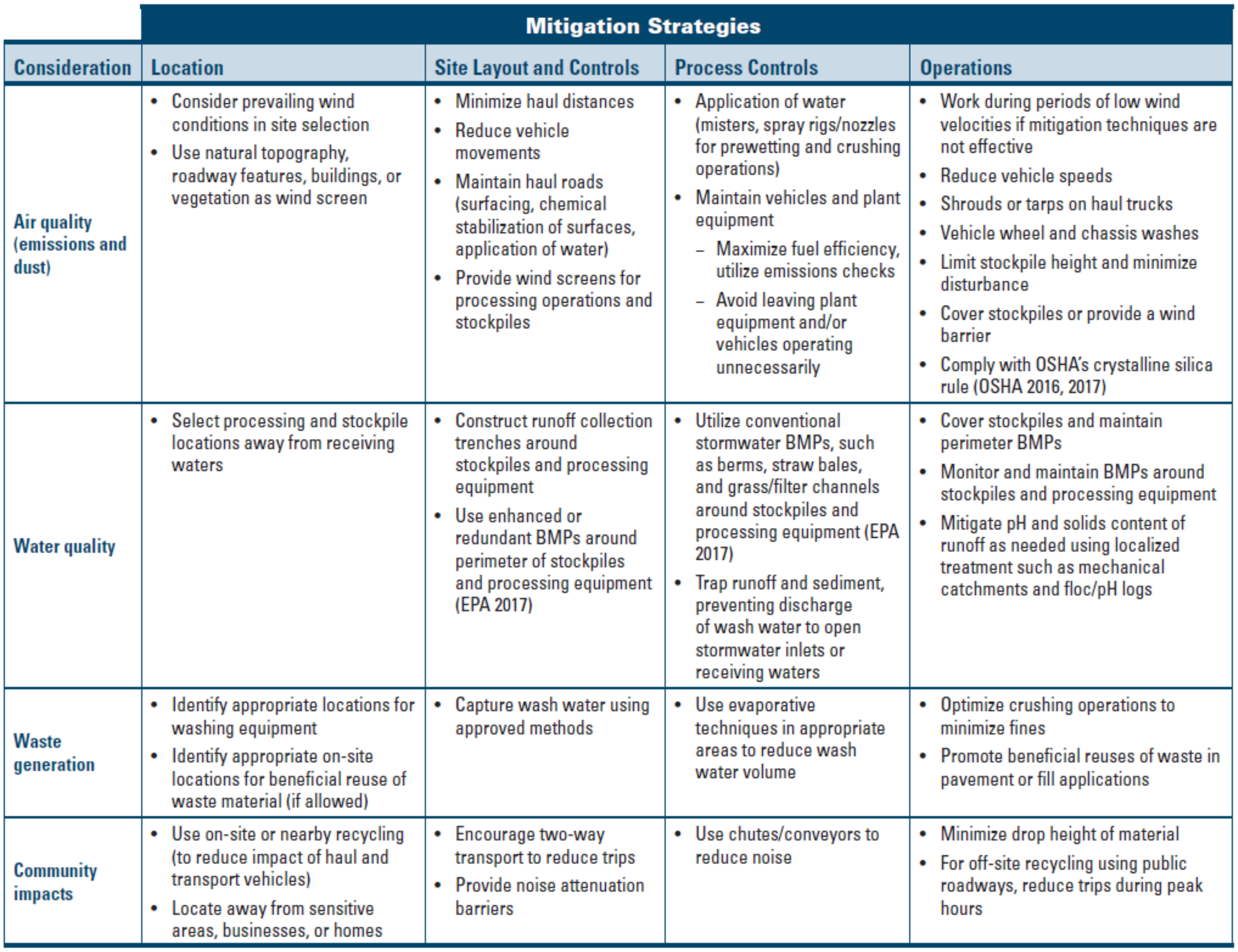
Consideration	Recommendations for Mitigation/Proven Techniques	Supporting Evidence
	Project Planning Considerations	
	MDOT currently limits the use of crushed concrete within 100 feet from the water sources. (MDOT Special Provision 12SP902-C)	
	Use hardy vegetation and bioswales near drain outlets. *Recommend MDOT to use hardy vegetation in bioswales.*	Cavalline (2018)
	Consider temporary use of pH adjustment products, such as pH ("shock") logs, at potentially problematic locations (after construction. *Recommend MDOT to use pH logs. One example of commercially available pH logs includes Applied Polymer Systems, APS 700 Series Floc Logs. Installation guidelines and other details are provided by the manufacturer.*	Cavalline (2018)
Pollutants in Leachate	Construct drains away from receiving waters. *MDOT currently limits the use of crushed concrete within 100 feet from the water sources.*	Cavalline (2018)
	Utilize bioswales or mechanical sediment traps. *MDOT currently employs bioswales to contain leachate.*	Cavalline (2018)
Sediments and Solid Precipitate	Use daylighted bases. *Recommend MDOT to construct daylighted bases where practical. Federal Highway Administration has developed a Technical Brief on daylighted permeable bases. (FHWA,CPTP Tech Brief, 2009)*	Cavalline (2018) *FHWA, CPTP Tech Brief, 2009*
	Prequalify geotextile fabric per AASHTO M319. *MDOT, currently, uses ASTM standards to prequalify geotextile fabrics.*	Cavalline (2018)
	Wrap trench (rather than the pipe) in geotextile fabric. *MDOT currently follows this practice.*	Cavalline (2018)
	Consider eliminating rodent screens. *MDOT is currently considering eliminating rodent screens.*	Cavalline (2018)
	Consider blending RCCA with natural aggregate or slag aggregate. *Recommend MDOT to consider blending RCCA with natural or slag aggregates in 50/50 proportions.*	This study. Cavalline (2018)
	Utilize mechanical sediment trap at the outlet structure. *More research is needed.*	Cavalline (2018)
	Utilize chemical coagulant products, such as "floc" logs, at local problematic locations (after construction) *Recommend MDOT to consider employing chemical coagulant products*	Cavalline (2018)
	Use 6-inch open-graded base course instead of 16-inch base course.	This study.

Consideration	Recommendations for Mitigation/Proven Techniques	Supporting Evidence
Project Planning Considerations		
	Recommend MDOT to consider using 6-inch open graded base course.	
	Wash RCCA aggregates prior to use in construction. *Recommend MDOT to initiate provisions for washing or air blasting of RCCA after crushing operations to remove dust particles.*	This study. Snyder (2018).
	Eliminate RCCA passing #4 sieve and replaced with natural or slag aggregates. *Recommend MDOT to include this provision in the MDOT standard specification for construction.*	This study. Snyder (2018)
	Stabilize RCCA open-graded bases *Recommend MDOT to initiate further research studies to consider stabilizing RCCA bases with cement or asphalt emulsions.*	This study. Snyder (2018).
Construction Considerations		
Construction practices	Avoid or minimize using RCCA bases as haul roads. *Recommend MDOT to limit the use of exposed open-graded base layers as haul routes*	This study. Snyder (2018).
	Use bio-swales and chemical methods during construction. *Recommend MDOT use bio-swales and chemical methods during construction.*	This study. Snyder (2018)

7.2.1 Recommendations for Construction with RCCA

These recommendations to mitigate environmental concerns arising from using RCCA in pavement base layers are similar to those used in day-to-day highway construction activities without using recycled aggregates. However, some specific recommendations related to the use of RCCA are listed below. Cavalline (2018) provides proactive pre-construction decisions regarding the locations and sites for recycling operations, process and operational practices for effective recycling operations, and construction practices to reduce the negative impacts to air quality, water quality, and the local community. A summary of these recommendations is shown in Table 7.2.

Table 7.2 Construction Control to Protect Environment (Cavelline, 2018)



	Mitigation Strategies			
Consideration	**Location**	**Site Layout and Controls**	**Process Controls**	**Operations**
Air quality (emissions and dust)	• Consider prevailing wind conditions in site selection • Use natural topography, roadway features, buildings, or vegetation as wind screen	• Minimize haul distances • Reduce vehicle movements • Maintain haul roads (surfacing, chemical stabilization of surfaces, application of water) • Provide wind screens for processing operations and stockpiles	• Application of water (misters, spray rigs/nozzles for prewetting and crushing operations) • Maintain vehicles and plant equipment – Maximize fuel efficiency, utilize emissions checks – Avoid leaving plant equipment and/or vehicles operating unnecessarily	• Work during periods of low wind velocities if mitigation techniques are not effective • Reduce vehicle speeds • Shrouds or tarps on haul trucks • Vehicle wheel and chassis washes • Limit stockpile height and minimize disturbance • Cover stockpiles or provide a wind barrier • Comply with OSHA's crystalline silica rule (OSHA 2016, 2017)
Water quality	• Select processing and stockpile locations away from receiving waters	• Construct runoff collection trenches around stockpiles and processing equipment • Use enhanced or redundant BMPs around perimeter of stockpiles and processing equipment (EPA 2017)	• Utilize conventional stormwater BMPs, such as berms, straw bales, and grass/filter channels around stockpiles and processing equipment (EPA 2017) • Trap runoff and sediment, preventing discharge of wash water to open stormwater inlets or receiving waters	• Cover stockpiles and maintain perimeter BMPs • Monitor and maintain BMPs around stockpiles and processing equipment • Mitigate pH and solids content of runoff as needed using localized treatment such as mechanical catchments and floc/pH logs
Waste generation	• Identify appropriate locations for washing equipment • Identify appropriate on-site locations for beneficial reuse of waste material (if allowed)	• Capture wash water using approved methods	• Use evaporative techniques in appropriate areas to reduce wash water volume	• Optimize crushing operations to minimize fines • Promote beneficial reuses of waste in pavement or fill applications
Community impacts	• Use on-site or nearby recycling (to reduce impact of haul and transport vehicles) • Locate away from sensitive areas, businesses, or homes	• Encourage two-way transport to reduce trips • Provide noise attenuation barriers	• Use chutes/conveyors to reduce noise	• Minimize drop height of material • For off-site recycling using public roadways, reduce trips during peak hours

Specific recommendations related to production and construction activities are given below.

Recommendations for RCCA Production and Handling

Onsite RCCA production and handling can be managed as similar to other construction activities that require specific attention to protect the receiving waters, minimize dust, and other regulations. It is recommended to control the runoff from RCCA stockpiles to mitigate the effects of high alkaline leachate, sediments, and other pollutants from the receiving waters. This can be achieved by using conventional stormwater Best Management Practices (BMPs) around stockpiles, such as berms, straw bales, and filter fabrics (Snyder, 2018). Some of the example treatments are shown in the following figures.

Figure 7.1 Demolished Material Stockpiled Beneath Bridge Prior to Crushing with Silt Fence and Vegetative Buffer Used (Snyder, 2018)

Figure 7.2 Spray Nozzle for Dust Control on the Aggregate Conveyor (Snyder, 2018)

Figure 7.3 RCCA Stockpile Tarped with Plastic and Bounded by Perimeter Berm of Wrapped RCCA (Snyder, 2018)

Recommendations for Construction Operations-Avoid or Minimize Use of RCCA Open-Graded Bases as Haul Roads

One of the main problems associated with the construction of RCCA open-graded base layers is the use of partially constructed bases as haul roads. When heavy trucks and equipment travel on exposed open-graded base layers, RCCA particles can crush into smaller pieces producing finer RCCA particles. This will not only change the gradation of the open-graded material but also create more calcium-rich leachate. Therefore, it is recommended to limit the use of exposed open-graded base layers as haul routes.

Recommendations for Construction Operations-Use of Bioswales and Chemical Methods Mitigate Leachate Problems

Use of bioswales near the drainage outlets can mitigate problems associated with calcium-rich leachate from RCCA bases. Bioswales can act as a filter for suspended particles and naturally reduce the high pH of the leachate. For identified high precipitate sites, a localized plan for mitigating high alkalinity and precipitate can be designed as shown in the figure below.

Figure 7.4 Localized Mitigation of High-pH Leachate from a Drain Near Receiving Waters using pH Log and Bioswale (Snyder, 2018)

REFERENCES

Abbaspour, A., Tanyu, B.F., and Cetin, B., “Impact of Aging on Leaching Characteristics of Recycled Concrete Aggregate”, Environ Sci Pollut Res, Springer, 2016.

ASTM D-4874. 1995. Standard Test Method for Leaching Solid in a Column Apparatus. American Society for Testing and Materials, Annual Book of ASTM Standards

Aydilek, A.H., “Environmental Suitability of Recycled Concrete Aggregate in Highways”, Final Report, Report no. MD-15-SPO109B4G-2, Maryland State Highway Administration, Baltimore, Maryland, 2015.

Bruinsma, J. E., K. R. Peterson, and M. B. Snyder, Chemical Approach to the Formation of Calcite Precipitate from Recycled Concrete Aggregate Base Layers. Transportation Research Record: Journal of the Transportation Research Board, No. 1577, pp 10–17, 1997.

Cavalline, T., “Protecting Water Quality Through Planning and Design Considerations”, Tech Brief, Concrete Pavement Recycling Series, National Concrete Pavement Technology Center, Ames, Iowa, 2018a.

Cavalline, T., “Protecting the Environment during Construction”, Tech Brief, Concrete Pavement Recycling Series, National Concrete Pavement Technology Center, Ames, Iowa, 2018b

Chen, J., Brown, B., Edil, T.B., Tinjum, J. “ Leaching Characteristics of Recycled Aggregate used as Road Base”, Student Project Report, University of Wisconsin System Solid Waste Research Program, 2012.

CPRoad Map, “Using Recycled Concrete Aggregate in Pavement Base Products”, Map Brief July 2018, www.cproadmap.org/publications/MAObriefJuly2018.pdf, accessed August 10, 2020.

DRU, “Concrete Recycling, Reuse of Returned Plastic Concrete and Crushed Concrete as Aggregate”, Caltrans Division of Research and Innovation, 2012.

EPA, “NPDES Stormwater Sampling Guidance Document”, Environmental Protection Agency, 1992.

EPA, “Introduction to Hazardous Waste Identification”, United States Environmental Protection Agency, 2005.

EPA, “Industrial Stormwater Monitoring and Sampling Guide”, Environmental Protection Agency, 2009.

EPA, “Hazardous Waste Test Methods / SW-846”, Environmental Protection Agency, https://www.epa.gov/hw-sw846.

FHWA, CPTP Tech Brief, Daylighted Permeable Bases, Federal Highway Administration, 2009

Hiller, J.E., Despande, Y.S., Qin, Y., and Shorkey, C.J., “Efficient Use of Recycled Concrete in Transportation Infrastructure”, Final Report, Report No. RC-1544, Michigan Department of Transportation, Lansing, Michigan 2011.

NEN 7343. 1995. Leaching Characteristics of Building and Solid Waste Material, Leaching Tests, Determination of the Leaching of Inorganic Components from Granular Materials with the Column Test. Netherlands Normalization Institute, Delft.

NOAA, 2019., Climate Data Online Tool, National Centers for Environmental Information, National Oceanic and Atmospheric Administration, ncdc.noaa.gov, accessed July 17, 2019.

NORDTEST. 1995. Solid Waste, Granular Inorganic Material: Column Test. Nordtest Method NT ENVIR 002, Espoo, Finland

MDOT, 2012, MDOT Standard Plans R80 Series, https://mdotcf.state.mi.us/public/design/files/englishstandardplans/files/R080E.pdf, accessed August 15, 2020.

Muethel, R.W., “Calcium Carbonate Precipitate from Crushed Concrete”, Final Report, Report Number R-1297, Michigan Department of Transportation, Lansing, Michigan, 1989.

Snyder, M.B. “Use of Crushed Concrete Products in Minnesota Pavement Foundations”, Final Report, Report No. MN/RC-96/12, Minnesota Department of Transportation, St. Paul, Minnesota, 1995

Snyder, M.B., Cavalline, T, Flick, G., Taylor, P., and Gross, J., “Recycling Concrete Pavement Materials: A Practitioner’s Reference Guide”, National Concrete Pavement Technology Center, Iowa State University, Ames, IA, 2018

Tom Van Dam, Kurt Smith, Carrie Truschke, and Stan Vitton, “Using Recycled Concrete in MDOT’s Transportation Infrastructure”, Final Report, Report Number RC-1544, Michigan Department of Transportation, Lansing, Michigan, 2011.

USGS, United States Geological Survey, pH and Water, https://www.usgs.gov/special-topic/water-science-school/science/ph-and-water?qt-science_center_objects=0#qt-science_center_objects, Accessed December 28, 2020.

Vollpracht, A., Lothenbach, B., Snellings, R. et al. The pore solution of blended cements: a review. Mater Struct 49, 3341–3367 (2016). https://doi.org/10.1617/s11527-015-0724-1, Accessed December 28, 2020.

APPENDIX A: FIELD SAMPLE LOCATIONS

Samples ID	X*	Y*	Construct Year	Pavement Type	Base Type	Region Type	Location
I275SR-I94-1	-83.415904°	42.226040°	2010	PCC	RCA	Urban	I275 South Ramp to I94, On west side of road On west side of road ~20 feet back from E94/W94 sign on east side of road Wooden stake painted fluorescent orange
I275SR-I94-2	-83.415730°	42.225597°	2010	PCC	RCA	Urban	I275 South Ramp to I94 On west side of road ~100 feet south of I275SR-I94-1 Wooden stake painted fluorescent orange
I69E-DAV-1	-83.49668611	43.01202778	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 282 feet east of S. Oak Road bridge
I69E-DAV-2	-83.49564444	43.01215278	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 559 feet east of S. Oak Road bridge
I69E-DAV-3	-83.4945	43.01228611	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 870 feet east of S. Oak Road bridge
I69E-ELB-1	-83.37767222	43.02966111	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 858 feet east of Golf Road bridge
I69E-ELB-2	-83.37660278	43.02979444	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 1170 feet east of Golf Road bridge
I69E-ELB-3	-83.37547778	43.02986667	2009	PCC	Limestone	Rural	I-69 eastbound, Approximately 1449 feet east of Golf Road bridge
I69E-GOO-1	-82.752222	42.978333	2015	PCC	RCA	Rural	20 yards from I-69 sign after Kinney road entrance ramp
I69E-GOO-2	-82.736667	42.972222	2015	PCC	RCA	Rural	30 yards from Mile Marker 186
I69E-GOO-3	-82.736667	42.971111	2015	PCC	RCA	Rural	50 yards west of Fox Road overpass
I69E-GOO-4	-82.669167	42.971667	2015	PCC	RCA	Rural	200 yards west of Goodells Roads overpass
I69E-GOO-5	-82.658056	42.974722	2015	PCC	RCA	Rural	10 yards from Mile Marker 190
I69E-GOO-6	-82.649167	42.971389	2015	PCC	RCA	Rural	Between bridge and caution sign
I69E-PH-1	-82.499444	42.973333	2011	PCC	RCA	Urban	20 yards from hospital exit 199 sign
I69E-PH-2	-82.499444	42.9725	2011	PCC	RCA	Urban	In between Exits 1 and 3
I69E-PH-3	-82.496944	42.973055	2011	PCC	RCA	Urban	30 yards from truss sign
I69W-DAV-1	-83.465875	43.01654722	2010	PCC	RCA	Rural	I-69 westbound, Approximately 2046 feet west of S. Washburn Road bridge
I69W-DAV-2	-83.46708056	43.01658056	2010	PCC	RCA	Rural	I-69 westbound, Approximately 2367 feet west of S. Washburn Road bridge
I69W-DAV-3	-83.46810556	43.01655278	2010	PCC	RCA	Rural	I-69 westbound, Approximately 2627 feet west of S. Washburn Road bridge
I69W-ELB-1	-83.34169167	43.02933611	2010	PCC	RCA	Rural	I-69 westbound, Approximately 2952 feet west of Baldwin Road bridge
I69W-ELB-2	-83.34269167	43.02967778	2010	PCC	RCA	Rural	I-69 westbound, Approximately 3230 feet west of Baldwin Road bridge
I69W-ELB-3	-83.34369167	43.03003611	2010	PCC	RCA	Rural	I-69 westbound, Approximately 3546 feet west of Baldwin Road bridge

Samples ID	X*	Y*	Construct Year	Pavement Type	Base Type	Region Type	Location
I69W-PH-1	-82.5	42.973055	2011	PCC	RCA	Urban	150 yards before traffic merge
I69W-PH-2	-82.5	42.973055	2011	PCC	RCA	Urban	100 yards before traffic merge
I69W-PH-3	-82.5	42.973055	2011	PCC	RCA	Urban	100 yards before Range road overpass
I75NR-Eureka-1	-83.239233	42.195955	2013	PCC	RCA	Urban	I75 N Ramp to Eureka Road
I75NR-Eureka-2	-83.238688	42.196277	2013	PCC	RCA	Urban	I75 N Ramp to Eureka Road
I75NR-sqrlk-1	-83.22583333	42.61166667	2017	PCC	RCA	Urban	I75 North Ramp to Square Lake Road Wooden stake painted fluorescent orange
I75NR-sqrlk-2	-83.22666667	42.61194444	2017	PCC	RCA	Urban	I75 North Ramp to Square Lake Road Wooden stake painted fluorescent orange
I75NR-sqrlk-3	-83.22861111	42.61277778	2017	PCC	RCA	Urban	I75 North Ramp to Square Lake Road Wooden stake painted fluorescent orange DO NOT PARK NEAR THIS LOCATION, PLEASE PARK AT I75NR-sqrlk-2 AND WALK
I75NR-Uni-1	-83.24	42.663333	2015	PCC	RCA	Urban	NB I75 to University Drive Ramp
I75NR-Uni-2	-83.24	42.663889	2015	PCC	RCA	Urban	NB I75 to University Drive Ramp
I75SR-Adams-1	-83.21277778	42.60694444	2017	PCC	SA	Urban	I75 South Ramp to Adams Road Wooden stake painted fluorescent orange
I75SR-Adams-2	-83.21194444	42.60694444	2017	PCC	SA	Urban	I75 South Ramp to Adams Road Wooden stake painted fluorescent orange
I75SR-Adams-3	-83.21111111	42.60527778	2017	PCC	SA	Urban	I75 South Ramp to Adams Road Wooden stake painted fluorescent orange
I75S-Roc-1	-83.242111	42.089177	2009	PCC	Limestone	Urban	SB I75 Between Gibraltar Road and Huron River Drive
I94E-CAS-1	-82.63626667	42.807675	2010	PCC	RCA	Rural	I-94 eastbound, Approximately 548 feet south of Palms Road bridge
I94E-CAS-2	-82.63542222	42.80822222	2010	PCC	RCA	Rural	I-94 eastbound, Approximately 251 feet south of Palms Road bridge
I94E-CAS-3	-82.63501944	42.80846111	2010	PCC	RCA	Rural	I-94 eastbound, Approximately 125 feet south of Palms Road bridge
I94E-STC-1	-82.601225	42.83087778	2010	PCC	RCA	Rural	I-94 East bound, Approximately 2095 feet south of Arlington Road bridge
I94E-STC-2	-82.600525	42.83140278	2010	PCC	RCA	Rural	I-94 East bound, Approximately 1830 feet south of Arlington Road bridge
I94E-STC-3	-82.60005	42.83174722	2010	PCC	RCA	Rural	I-94 East bound, Approximately 1655 feet south of Arlington Road bridge
I94W-CAS-1	-82.64594167	42.80141389	2010	PCC	RCA	Rural	I-94 westbound, Approximately 1945 feet north of St. Clair Highway bridge
I94W-CAS-2	-82.64660278	42.80100833	2010	PCC	RCA	Rural	I-94 westbound, Approximately 1697 feet north of St. Clair Highway bridge
I94W-CAS-3	-82.64678333	42.80087222	2010	PCC	RCA	Rural	I-94 westbound, Approximately 1631 feet north of St. Clair Highway bridge

Samples ID	X*	Y*	Construct Year	Pavement Type	Base Type	Region Type	Location
I94WR-I275N-1	-83.40972222 °	42.22416667 °	2010	PCC	RCA	Urban	Traveling west on I94 ramp to I275 N, east side of road near ditch with running water. Can see big Bankruptcy billboard. Wooden stake painted fluorescent orange
I94WR-I275N-2	-83.41027778 °	42.22444444 °	2010	PCC	RCA	Urban	Traveling west on I94 ramp to I275 N, on east side, farther north of I94WR-I275N-1 Wooden stake painted fluorescent orange
I94W-STC-1	-82.61162222	42.82400278	2010	PCC	RCA	Rural	I-94 Westbound, Approximately 6032 feet north of Fred Moore Highway bridge
I94W-STC-2	-82.613275	42.8229	2010	PCC	RCA	Rural	I-94 Westbound, Approximately 5373 feet north of Fred Moore Highway bridge
I94W-STC-3	-82.61568333	42.82139167	2010	PCC	RCA	Rural	I-94 Westbound, Approximately 4546 feet north of Fred Moore Highway bridge
I96E-Nov-1	-83.495556°	42.489167°	2010	PCC	RCA	Urban	On south side of road, west side of railroad tracks West of Food Exit 162 sign, wooden stake painted fluorescent orange
I96E-Nov-2	-83.483953°	42.487367°	2010	PCC	RCA	Urban	On south side of road, east side of railroad tracks, right before guardrail Need to use Exit 162 (Novi Road) shoulder, wooden stake painted fluorescent orange
I96ER-I275-1	-83.451533	42.483877	2016	PCC	Limestone	Urban	I96 E Ramp to I275S
I96ER-I275-2	-83.450933	42.483711	2016	PCC	Limestone	Urban	I96 E Ramp to I275 S
I96ER-I275-3	-83.450422	42.4836	2016	PCC	Limestone	Urban	I96 E Ramp to I275S
I96W-Nov-1	-83.483611°	42.488056°	2010	PCC	SA	Urban	Recommend accessing by entering from Beck Road onto westbound I96 ramp onto I96 west. On east side of railroad tracks, on north side of westbound I96 ramp from Beck Road, wooden stake painted fluorescent orange
I96W-Nov-2	-83.494722°	42.489444°	2010	PCC	SA	Urban	On west side of railroad tracks, on north side of road West of I96W-Nov-1, wooden stake painted fluorescent orange
M53N-BRU-1	-83.02037	42.83707	2013	PCC	RCA	Rural	
M53N-BRU-2	-83.0206	42.84236	2013	PCC	RCA	Rural	
M53N-BRU-3	-83.0207	42.845443	2013	PCC	RCA	Rural	
M53N-BRU-4	-83.02168	42.86853	2013	PCC	RCA	Rural	
M53N-BRU-5	-83.02218	42.87059	2013	PCC	RCA	Rural	
M53N-BRU-6	-83.02263	42.87138	2013	PCC	RCA	Rural	
M53S-BRU-1	-83.02531	42.87411	2013	PCC	RCA	Rural	
M53S-BRU-2	-83.0233	42.87236	2013	PCC	RCA	Rural	
M53S-BRU-3	-83.02327	42.87218	2013	PCC	RCA	Rural	
M53S-BRU-4	-83.02135	42.85936	2013	PCC	RCA	Rural	
M53S-BRU-5	-83.02137	42.85855	2013	PCC	RCA	Rural	
M53S-BRU-6	-83.02114	42.85219	2013	PCC	RCA	Rural	

Samples ID	X*	Y*	Construct Year	Pavement Type	Base Type	Region Type	Location
M59ER-Dequ-1	-83.094444	42.625	2010	PCC	RCA	Urban	M59 E Ramp to Dequindre Road
M59ER-Roch-1	-83.134167	42.628055	2010	PCC	RCA	Urban	M59 E Ramp to Rochester Road
M59ER-Roch-2	-83.133889	42.6275	2010	PCC	RCA	Urban	M59 E Ramp to Rochester Road
M59ER-Roch-3	-83.095555	42.625278	2010	PCC	RCA	Urban	M59 E Ramp to Rochester Road
M59E-UTI-1	-82.99986	42.62675	2017	PCC	RCA	Urban	
M59E-UTI-2	-82.99911	42.6268	2017	PCC	RCA	Urban	
M59E-UTI-3	-82.99672	42.62689	2017	PCC	RCA	Urban	
M59WR-Dequ-1	-83.087778	42.625833	2010	PCC	RCA	Urban	M59 W Ramp to Dequindre Road
M59WR-Dequ-2	-83.086667	42.625555	2010	PCC	RCA	Urban	M59 W Ramp to Dequindre Road
M59W-UTI-1	-82.98644	42.62739	2017	PCC	RCA	Urban	
M59W-UTI-2	-82.98733	42.62733	2017	PCC	RCA	Urban	
M59W-UTI-3	-82.99047	42.62733	2017	PCC	RCA	Urban	
M5N-WLk-1	-83.445290°	42.529497°	1999	PCC	RCA	Urban	Walled Lake. North of 14 mile road, on east side, can see motel (may be Commerce Township). Wooden stake painted fluorescent orange
M5N-WLk-2	-83.445475°	42.530078°	1999	PCC	RCA	Urban	North of M5N-WLk-1 Wooden stake painted fluorescent orange
M5N-WLk-3	-83.445782°	42.530801°	1999	PCC	RCA	Urban	North of M5N-WLk-2. Tied tape to existing metal stake. Can see United Artist Theatre to the east. Used exiting metal stake and tied fluorescent orange tape around it.
UniR-I75N-1	-83.24	42.667778	2015	PCC	RCA	Urban	University Drive to NB I75 Ramp
UniR-I75N-2	-83	42.668333	2015	PCC	RCA	Urban	University Drive to NB I75 Ramp

APPENDIX B: LABORATORY TEST RESULTS

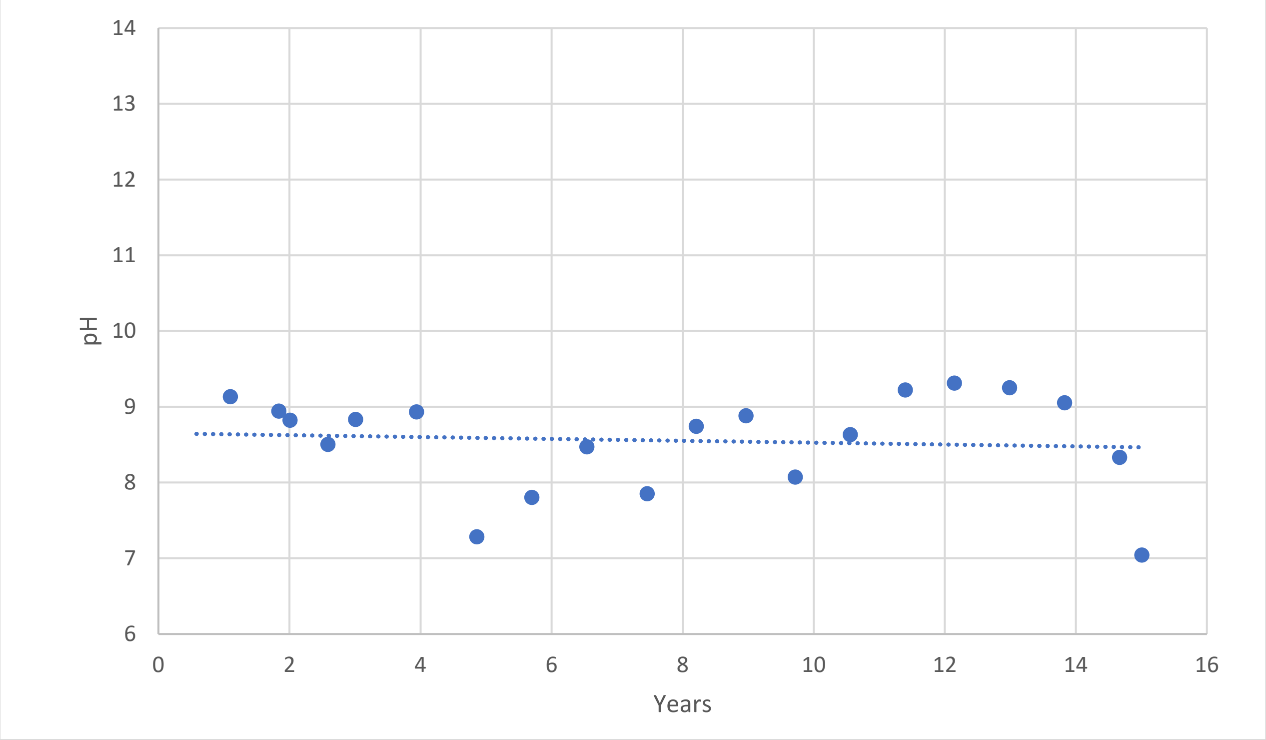


Figure B.1: Limestone 1 (LS 1) pH Values

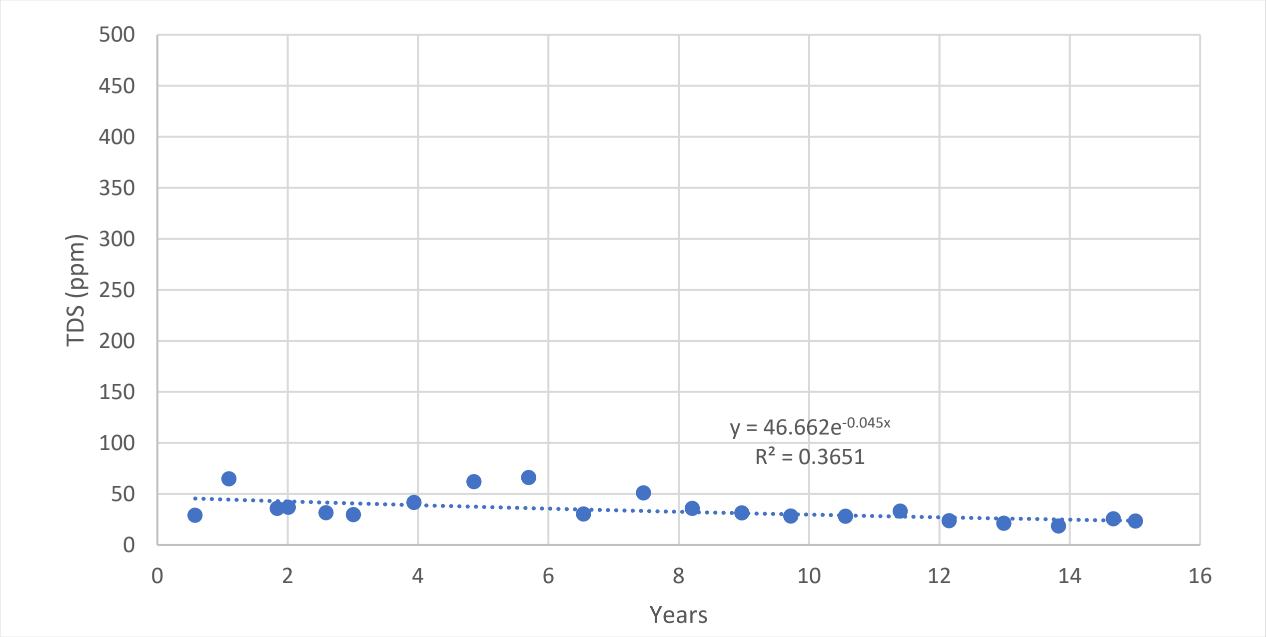


Figure B.2: Limestone 1 (LS 1) TDS Values

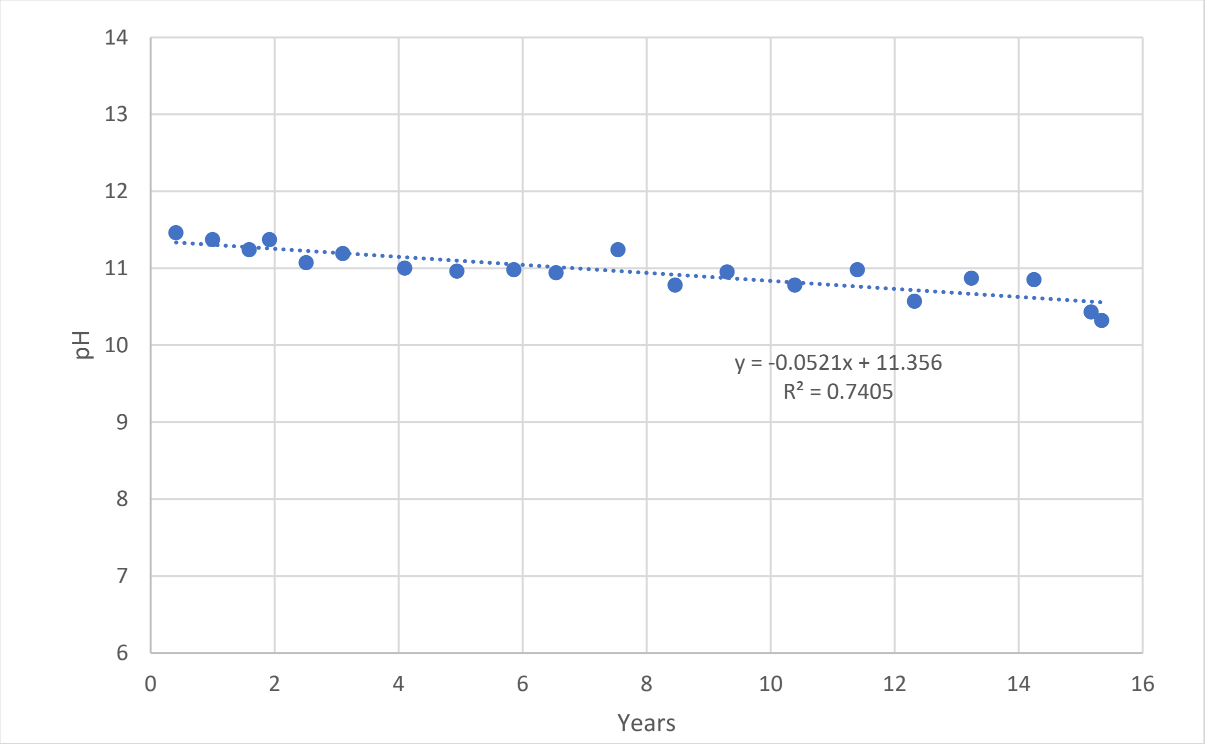


Figure B.3: Recycled Crushed Concrete Aggregate 1 (RCCA1) pH Values

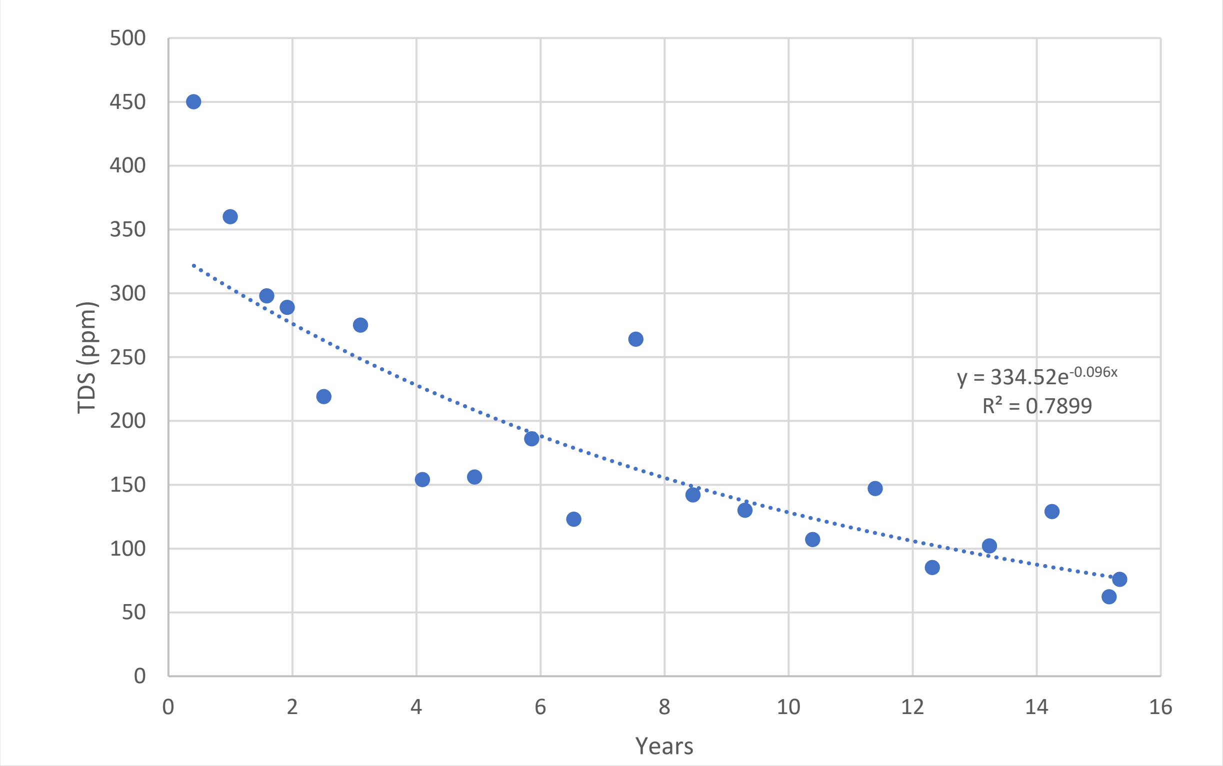


Figure B.4: Recycled Crushed Concrete Aggregate 1 (RCCA1) TDS Values

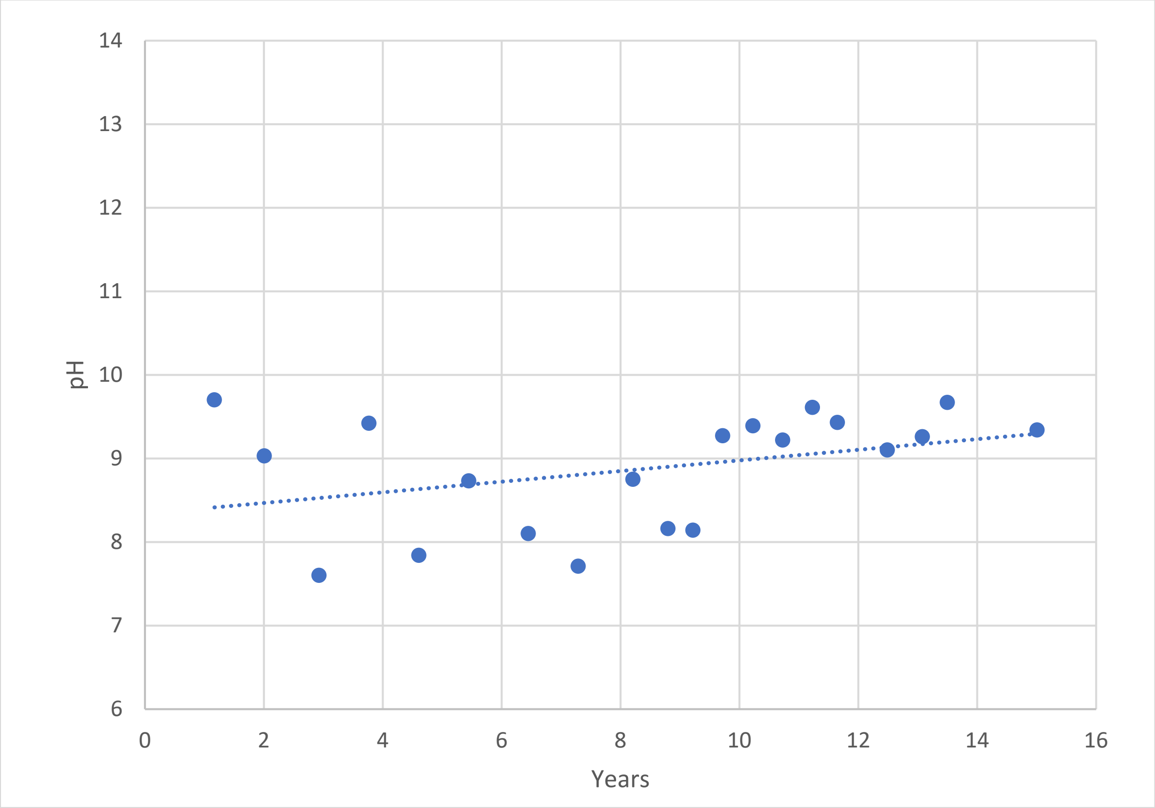


Figure B.5: Slag Aggregate 1 (SA1) pH Values

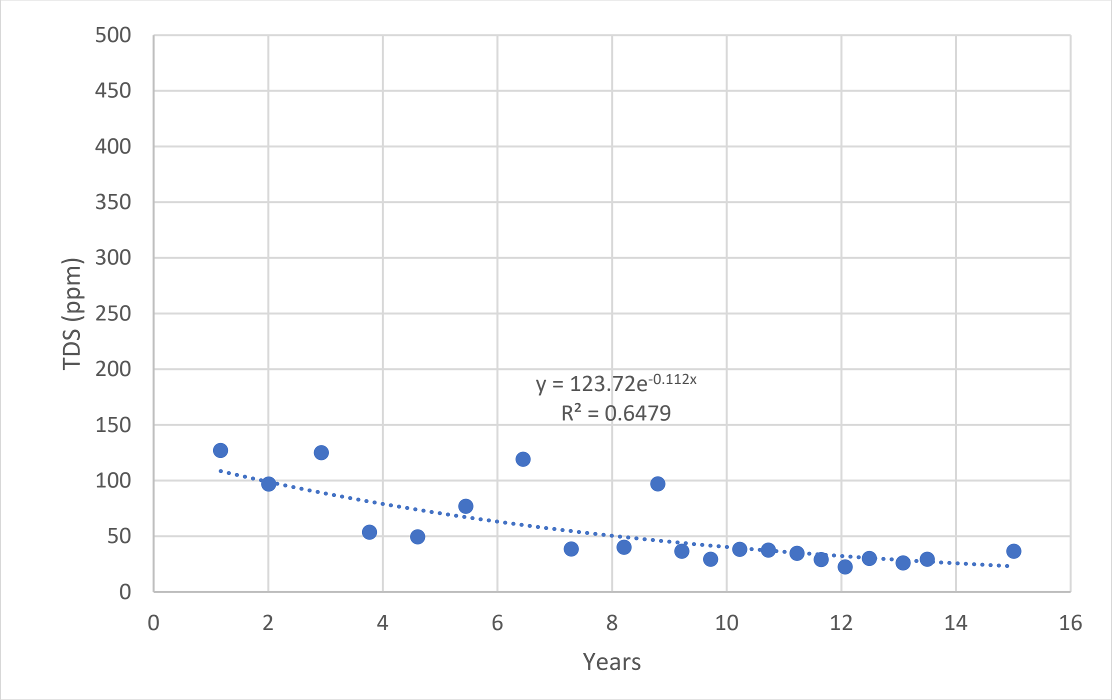


Figure B.6: Slag Aggregate 1 (SA1) TDS Values

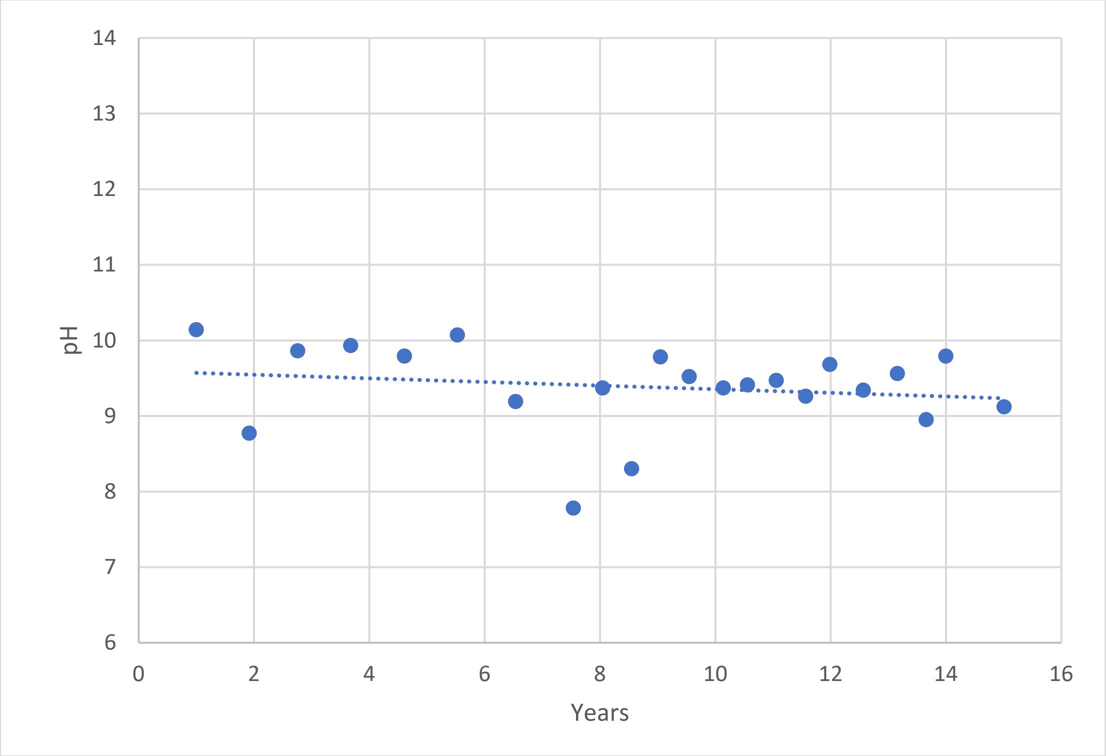


Figure B.7: Limestone 2 (LS2) pH Values

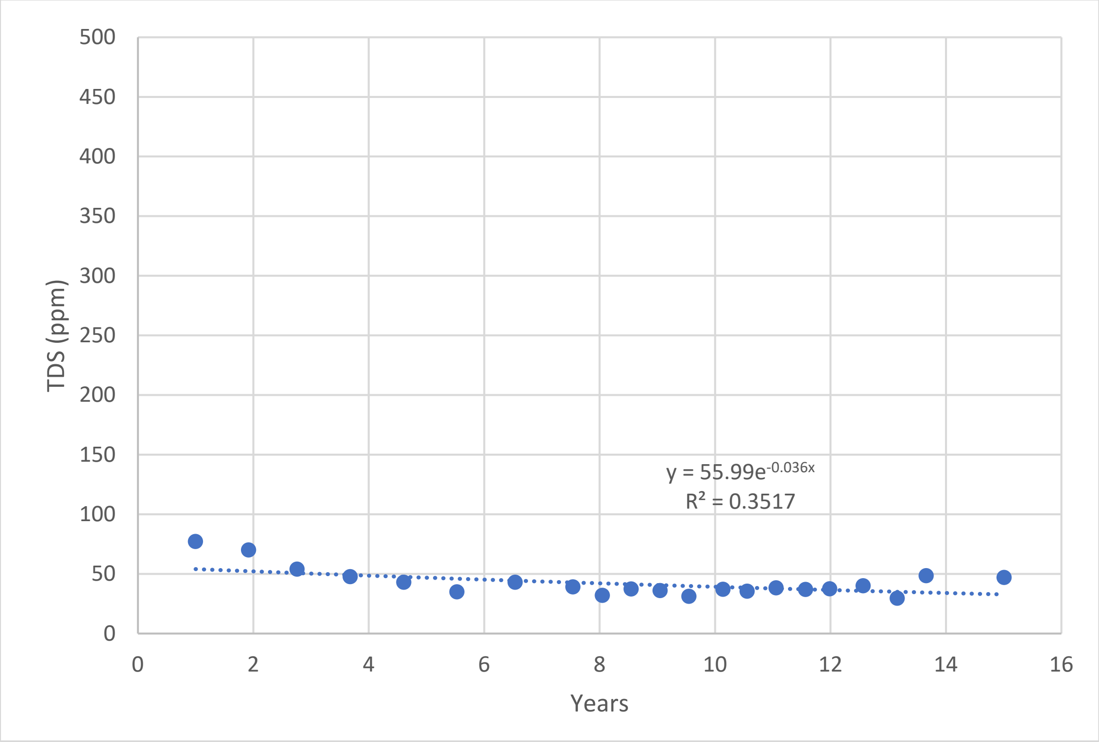


Figure B.8: Limestone 2 (LS2) TDS Values

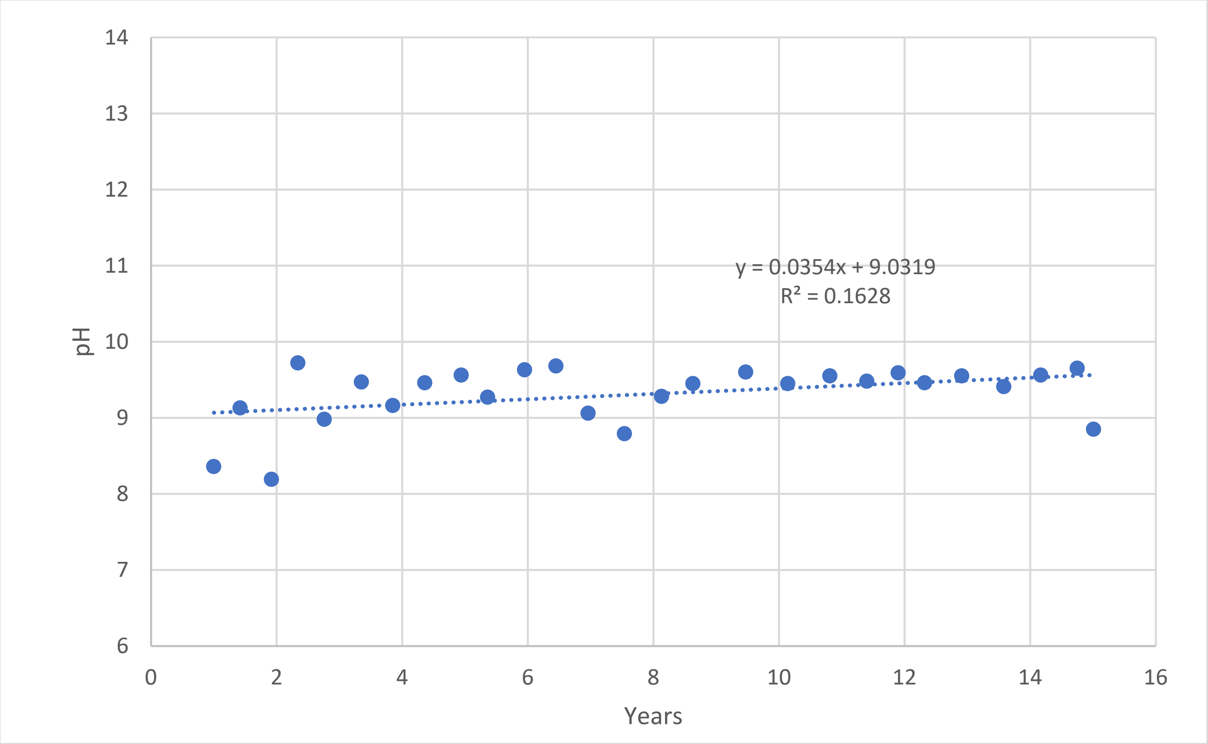


Figure B.9: Recycled Crushed Concrete Aggregate 2 (RCCA2) pH Values

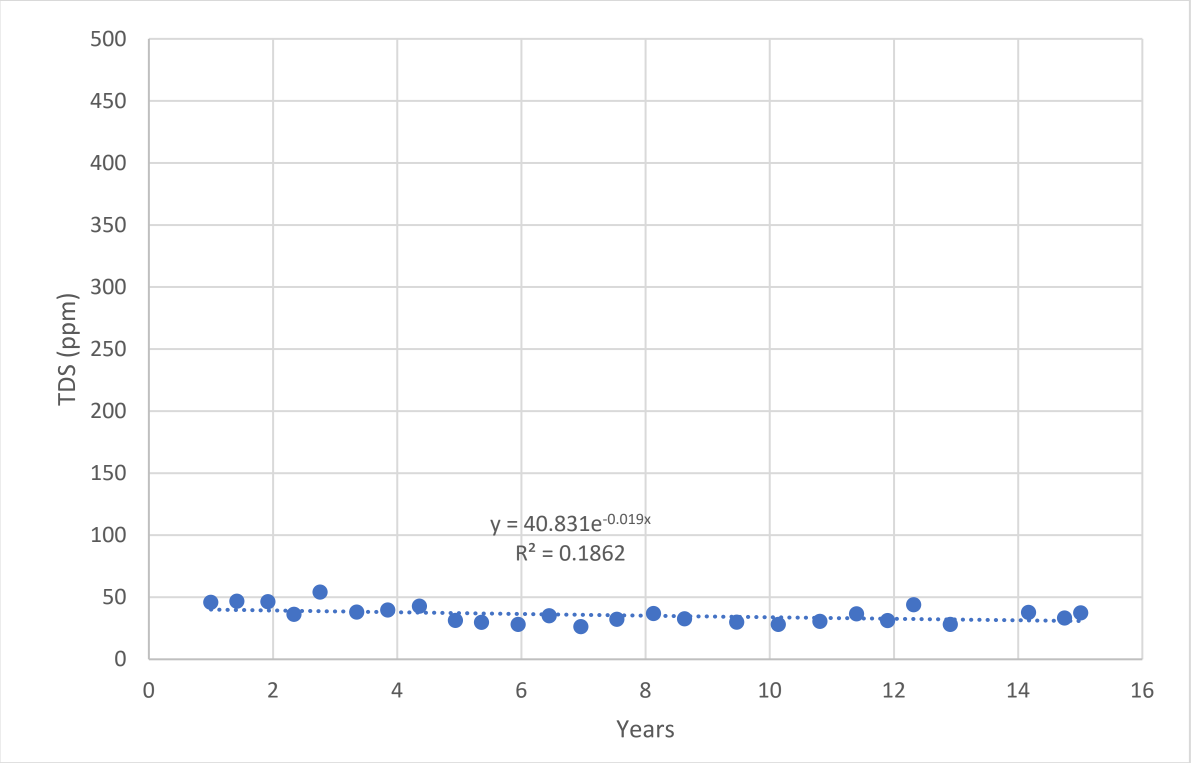


Figure B.10: Recycled Crushed Concrete Aggregate 2 (RCCA2) TDS Values

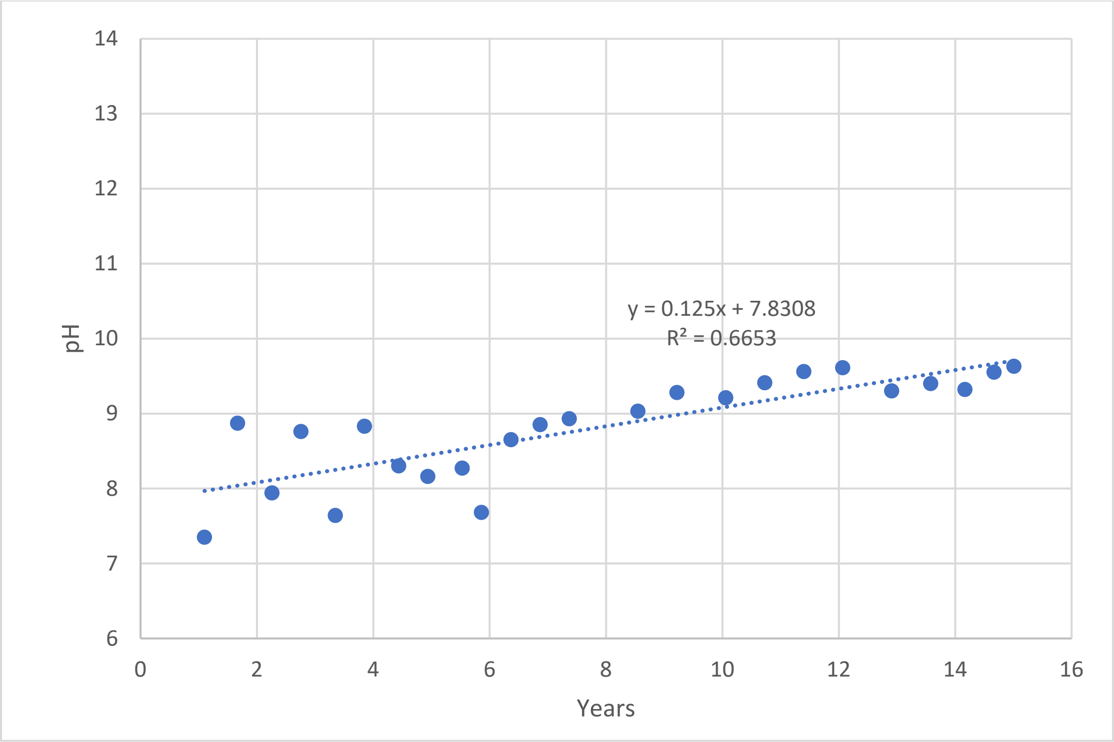


Figure B.11: Slag Aggregate 2 (SA2) pH Values

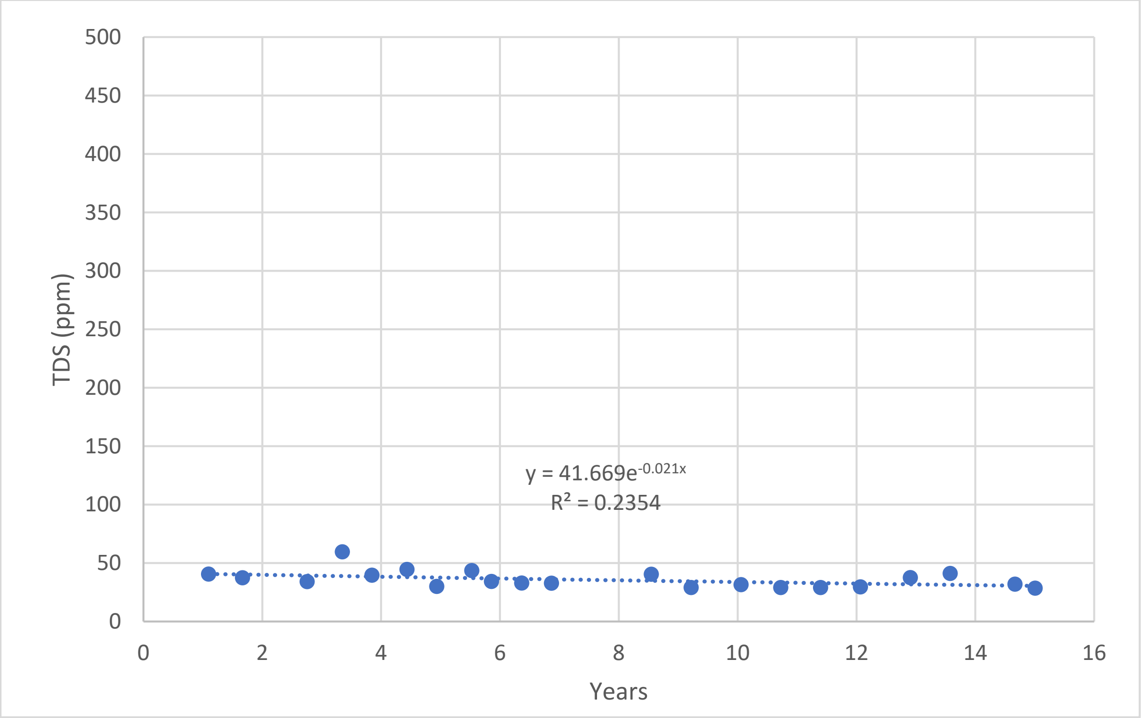


Figure B.12: Slag Aggregate 2 (SA2) TDS Values

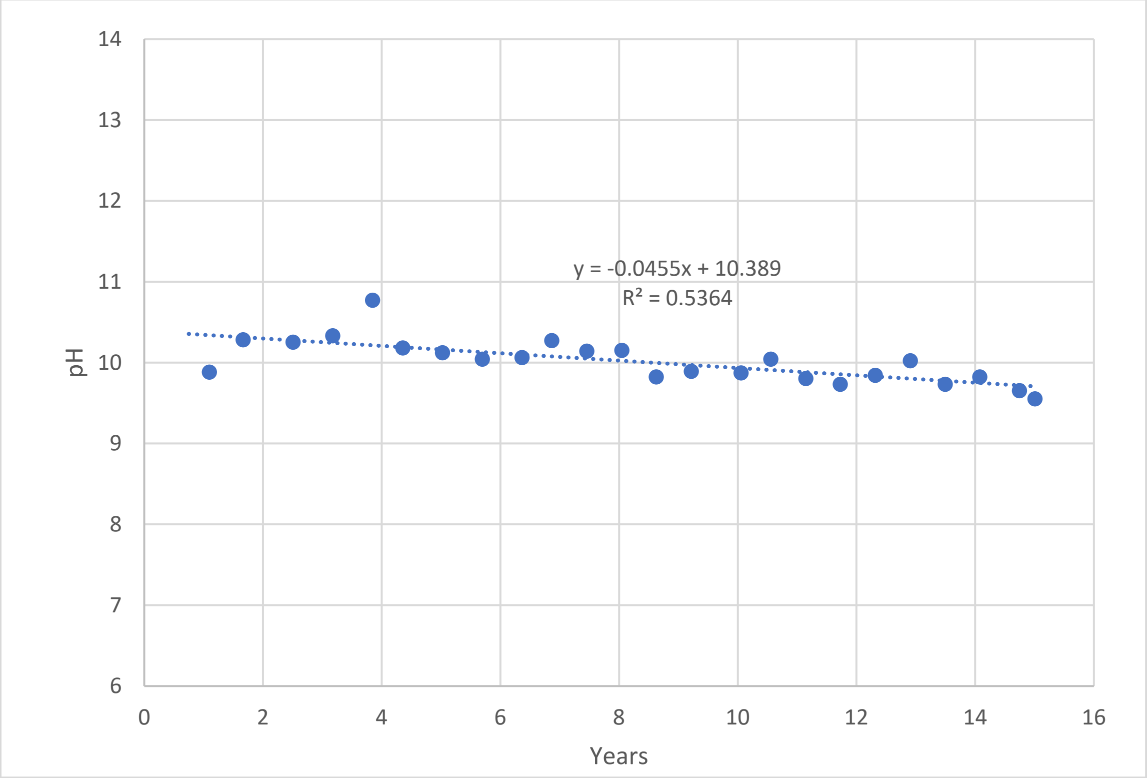


Figure B.13: Recycled Crushed Concrete Aggregate + Limestone 1 (RCCA+LS1) pH Values

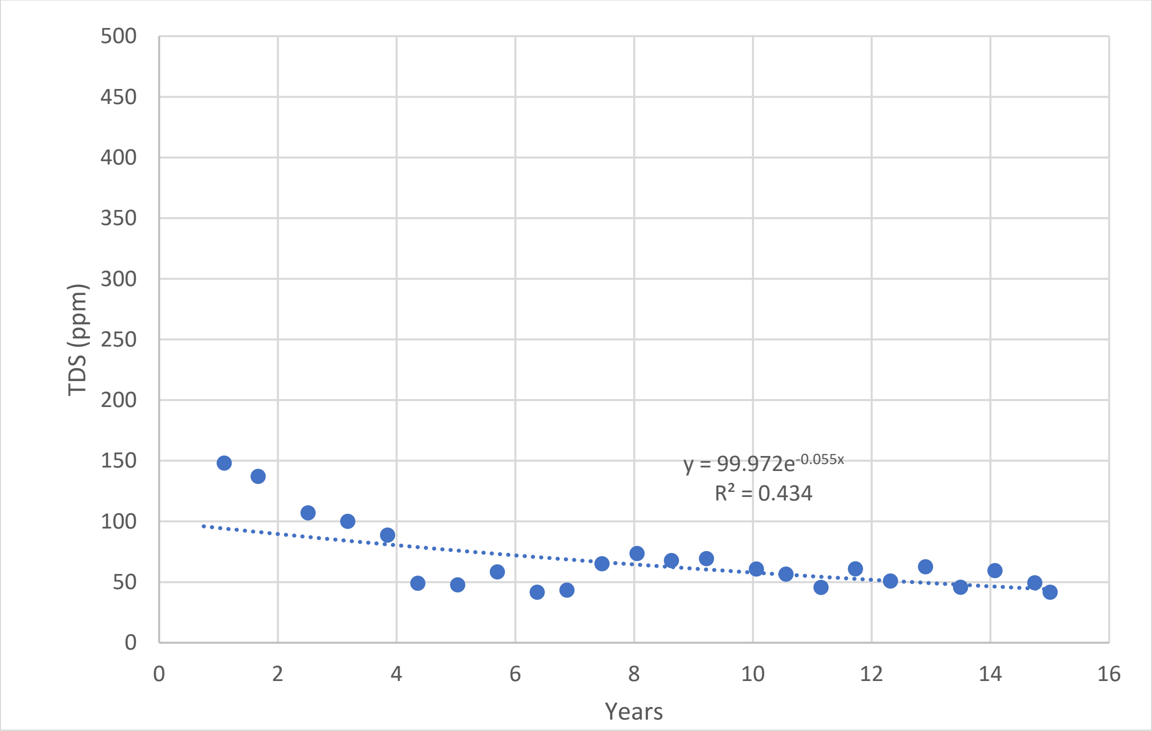


Figure B.14: Recycled Crushed Concrete Aggregate + Limestone 1 (RCCA+LS1) TDS Values

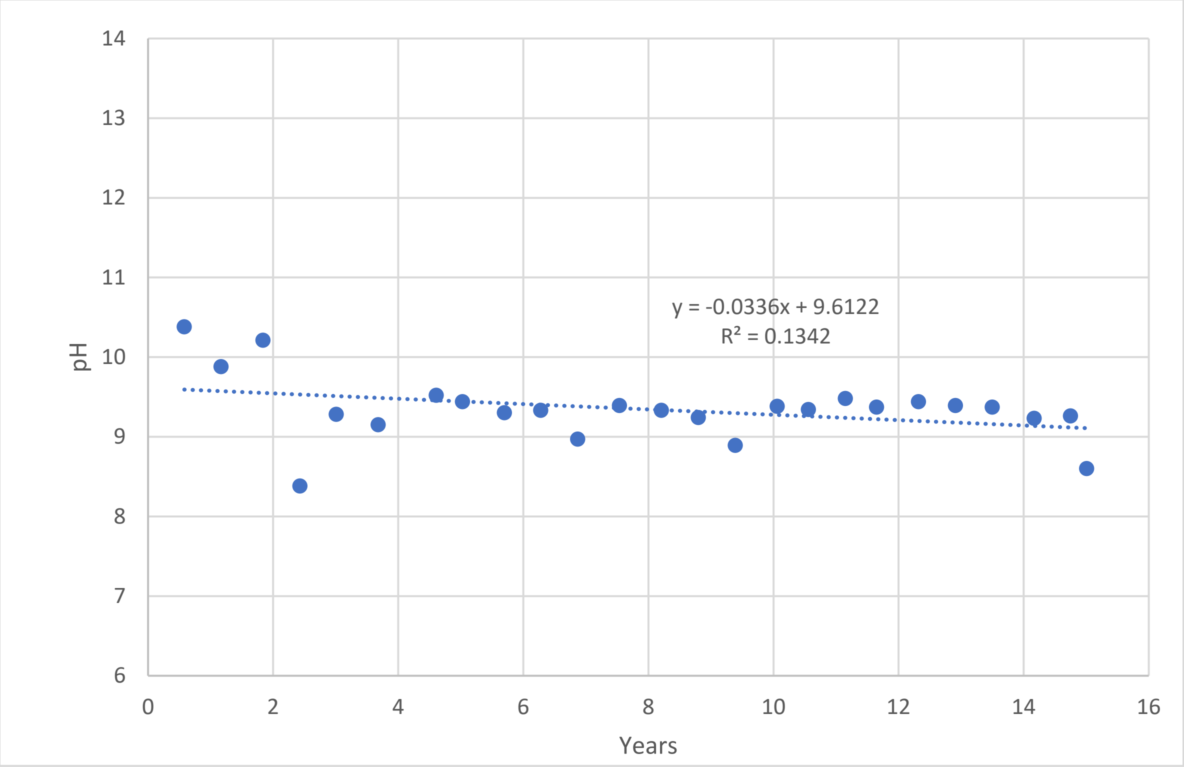


Figure B.15: Recycled Crushed Concrete Aggregate + Limestone 2 (RCCA+LS2) pH Values

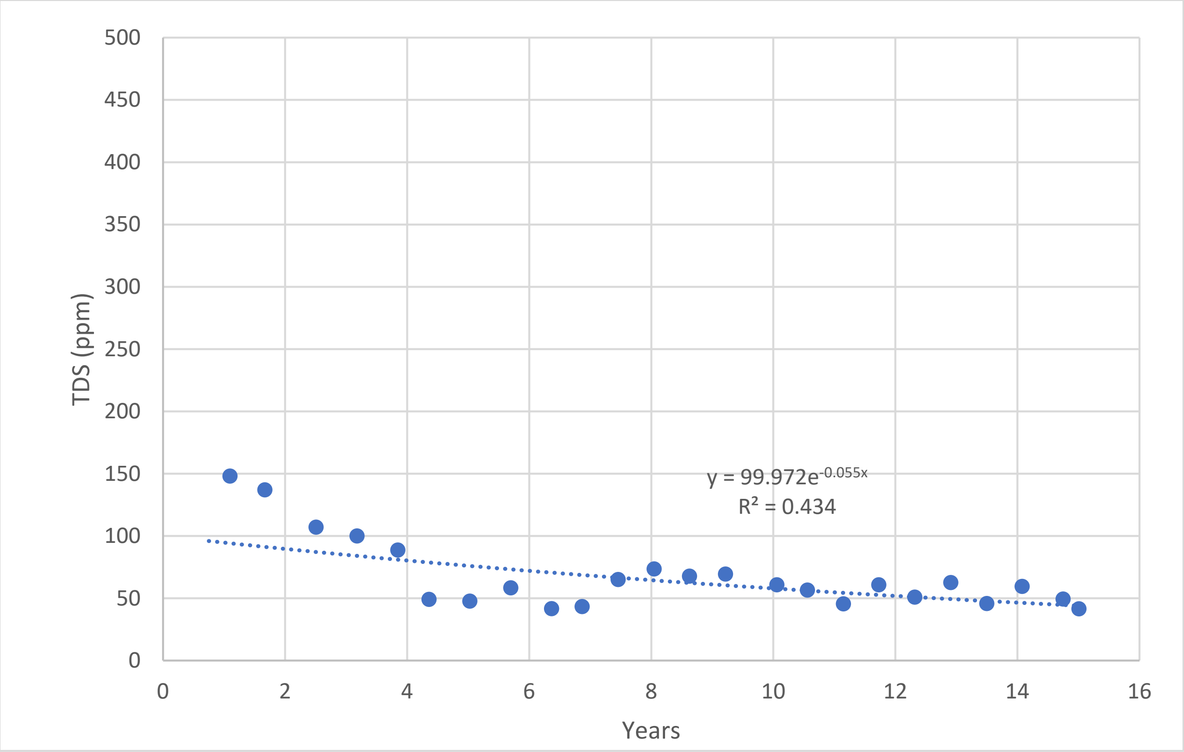


Figure B.16: Recycled Crushed Concrete Aggregate + Limestone 2 (RCCA+LS2) TDS Values

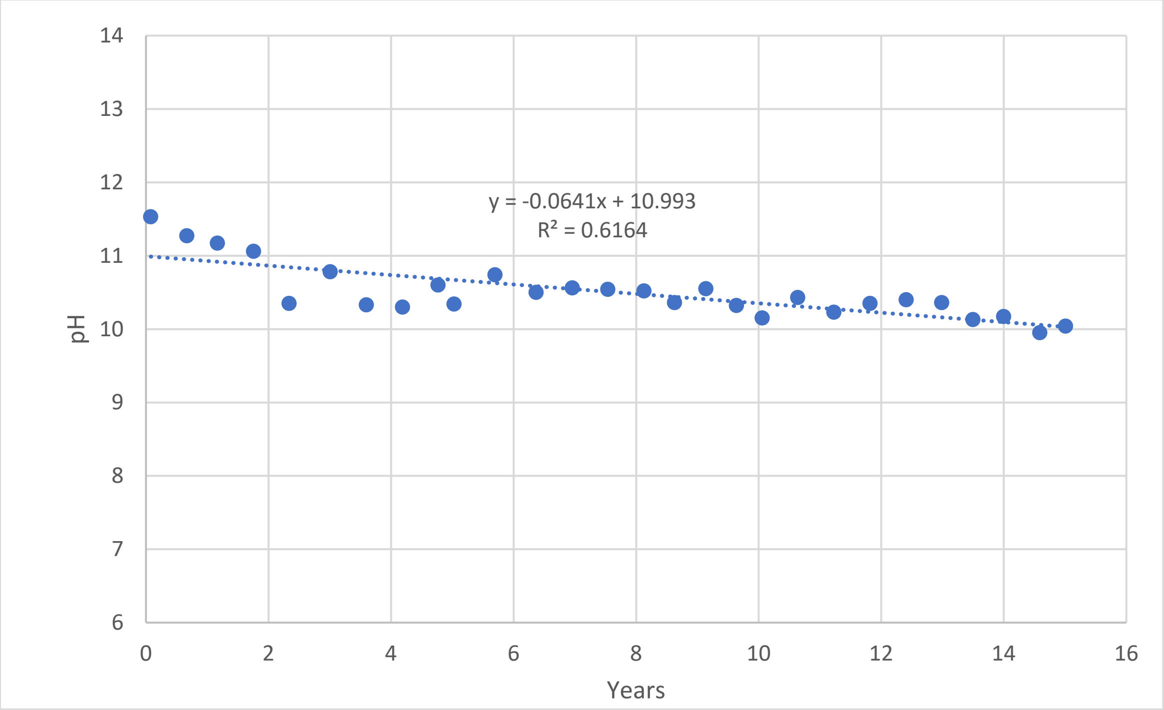


Figure B.17: Recycled Crushed Concrete Aggregate + Slag 1 (RCCA+SA1) pH Values

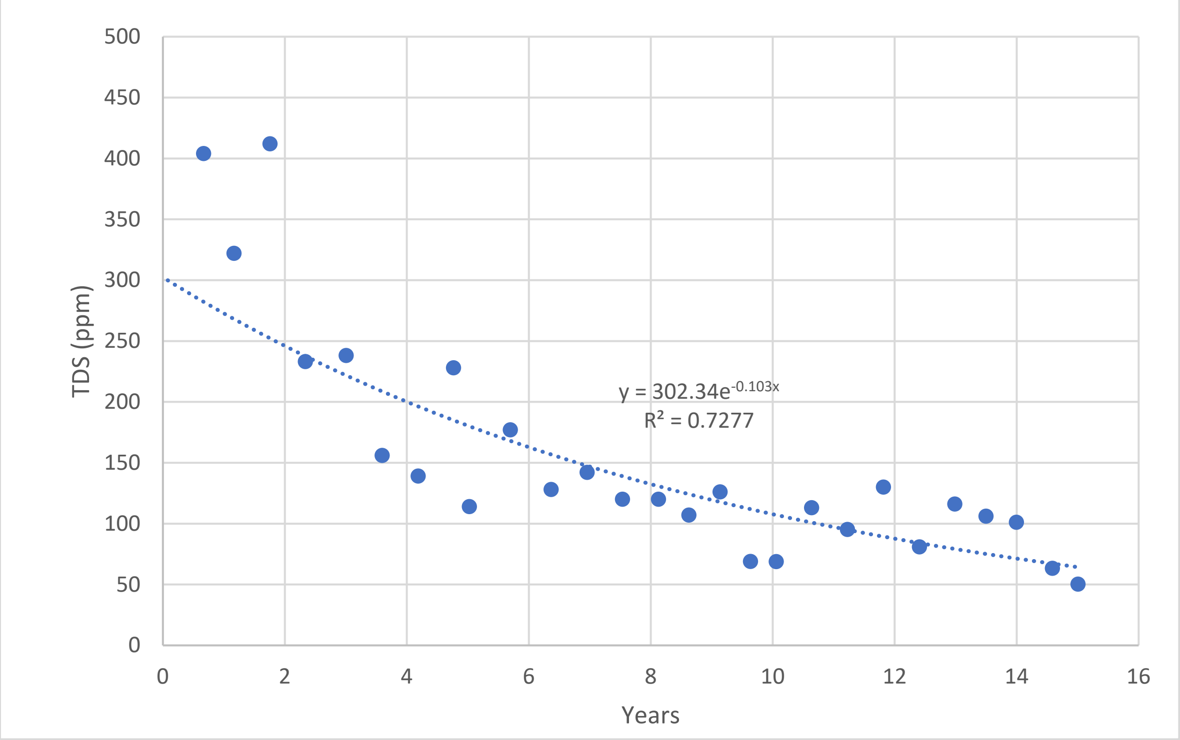


Figure B.18: Recycled Crushed Concrete Aggregate + Slag 1 (RCCA+SA1) TDS Values

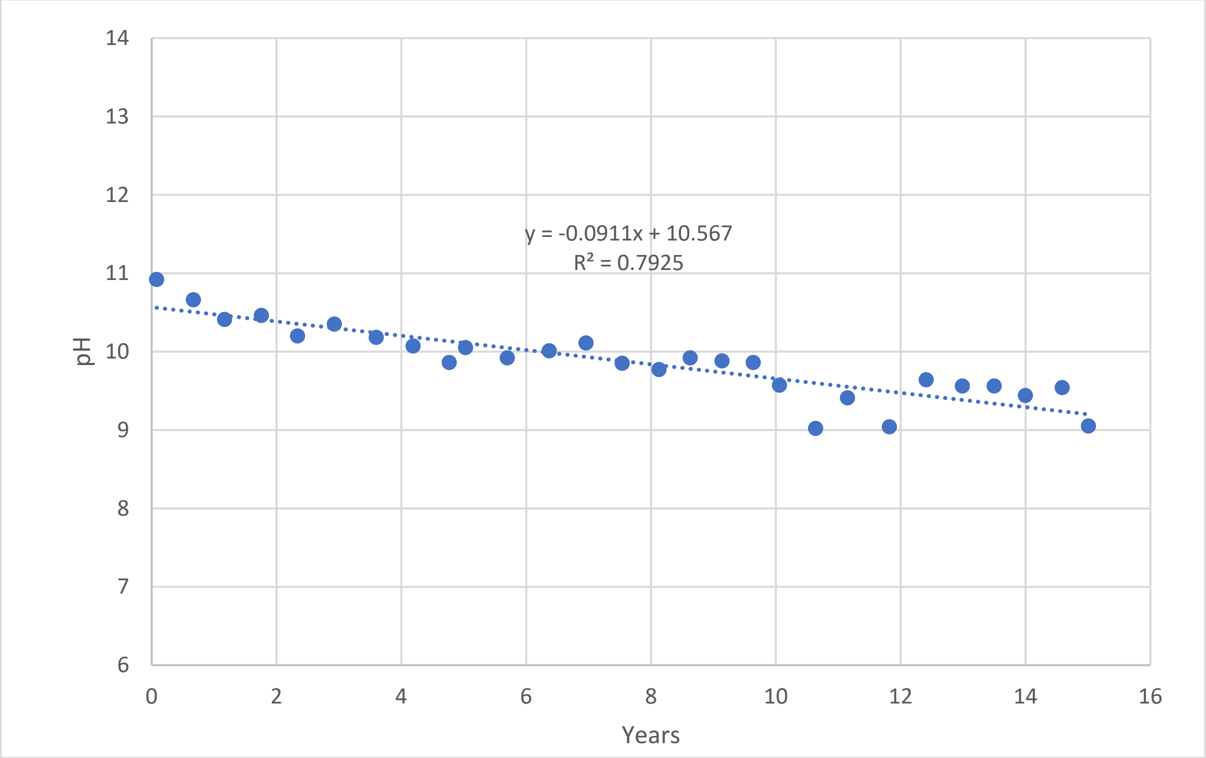


Figure B.19: Recycled Crushed Concrete Aggregate + Slag 2 (RCCA+SA2) pH Values

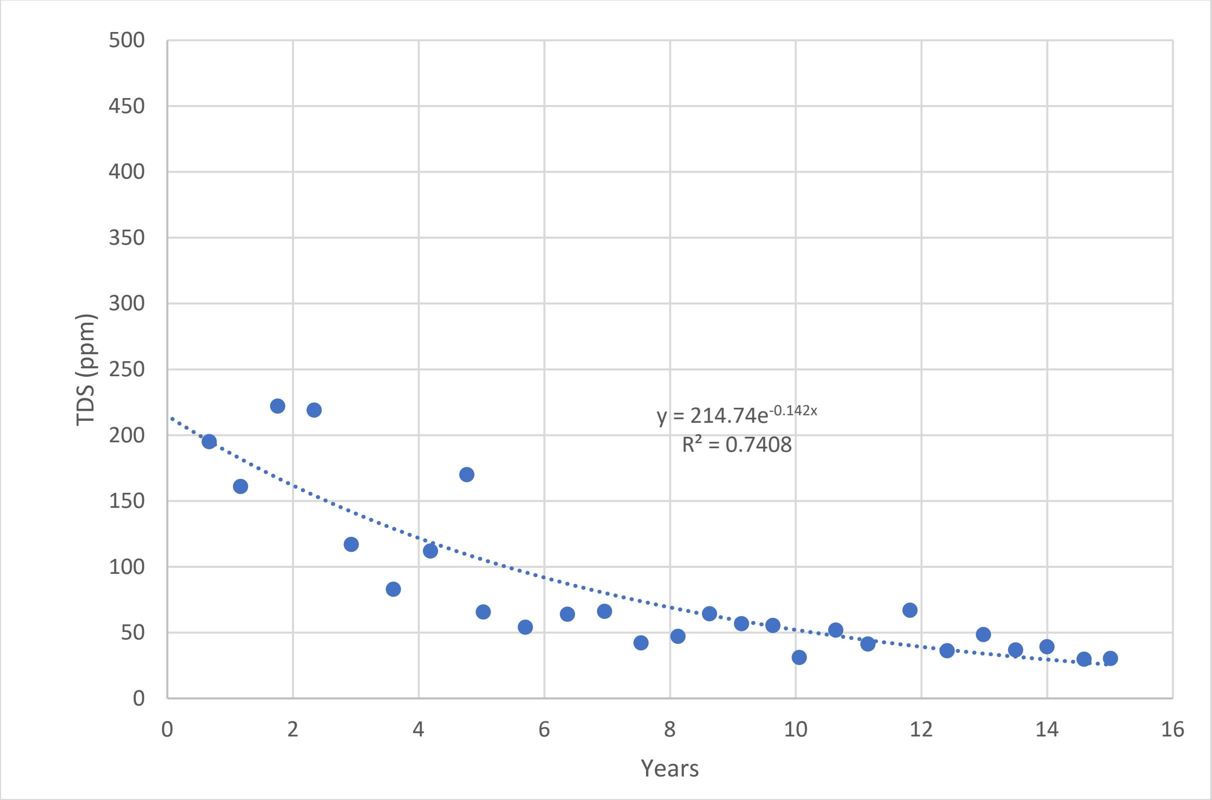


Figure B.20: Recycled Crushed Concrete Aggregate + Slag 2 (RCCA+SA2) TDS Values

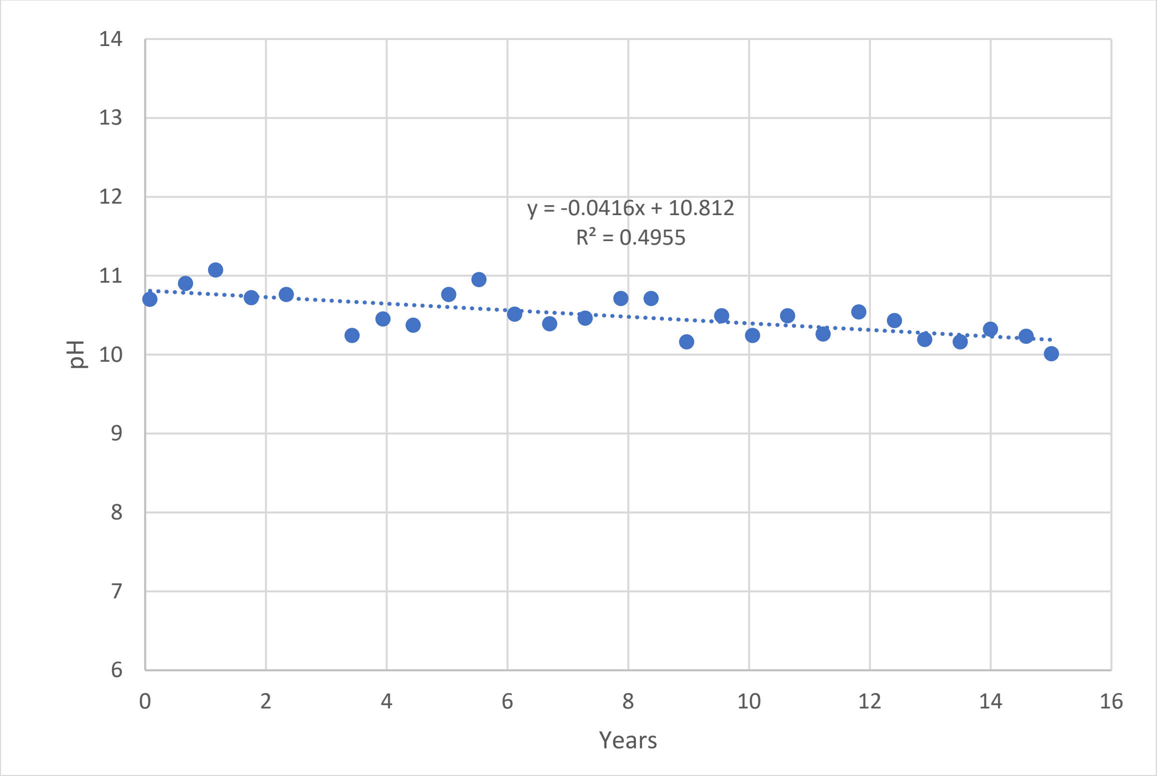


Figure B.21: Washed Recycled Crushed Concrete 1 (RCCA-Wash1) pH Values

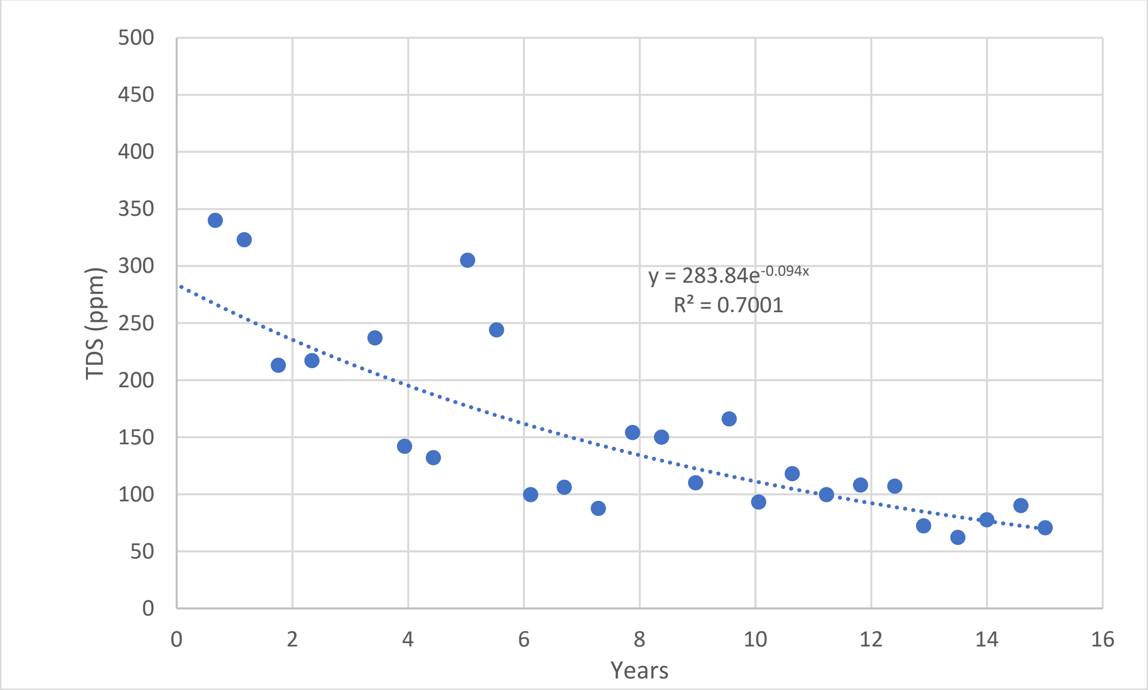


Figure B.22: Washed Recycled Crushed Concrete 1 (RCCA-Wash1) TDS Values

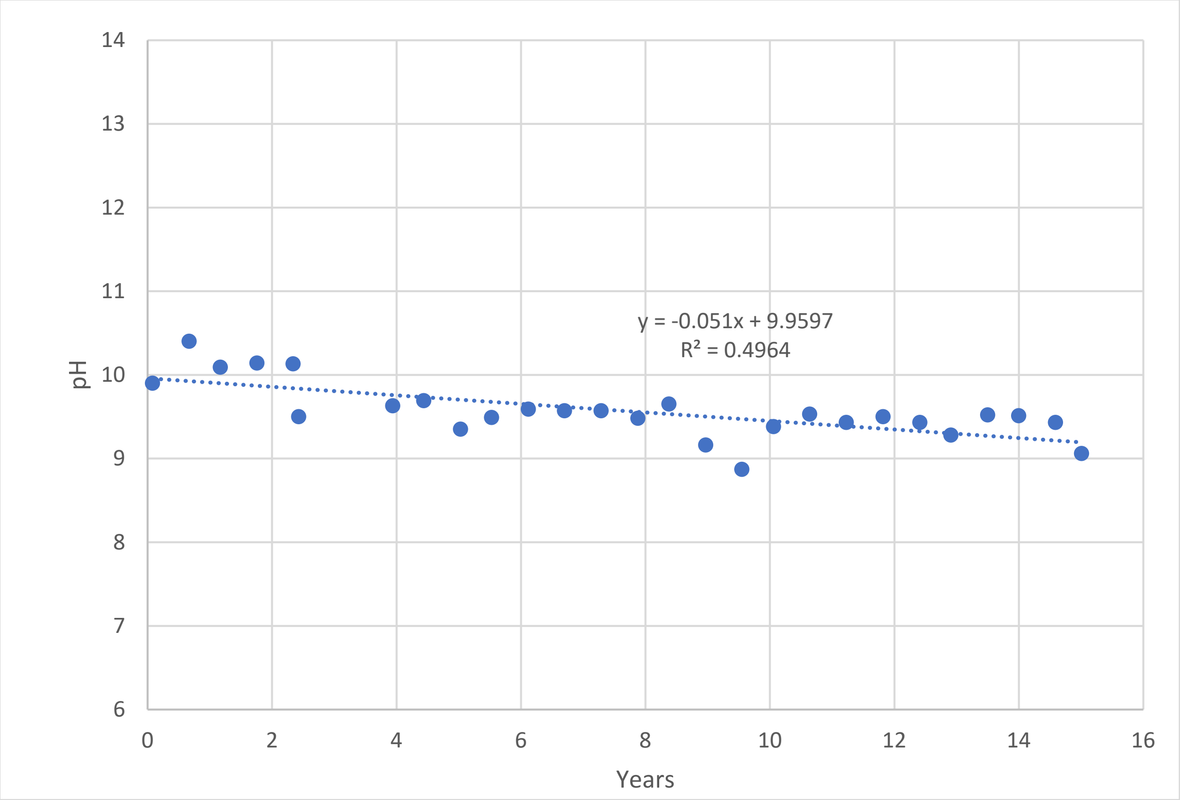


Figure B.23: Washed Recycled Crushed Concrete 2 (RCCA-Wash2) pH Values

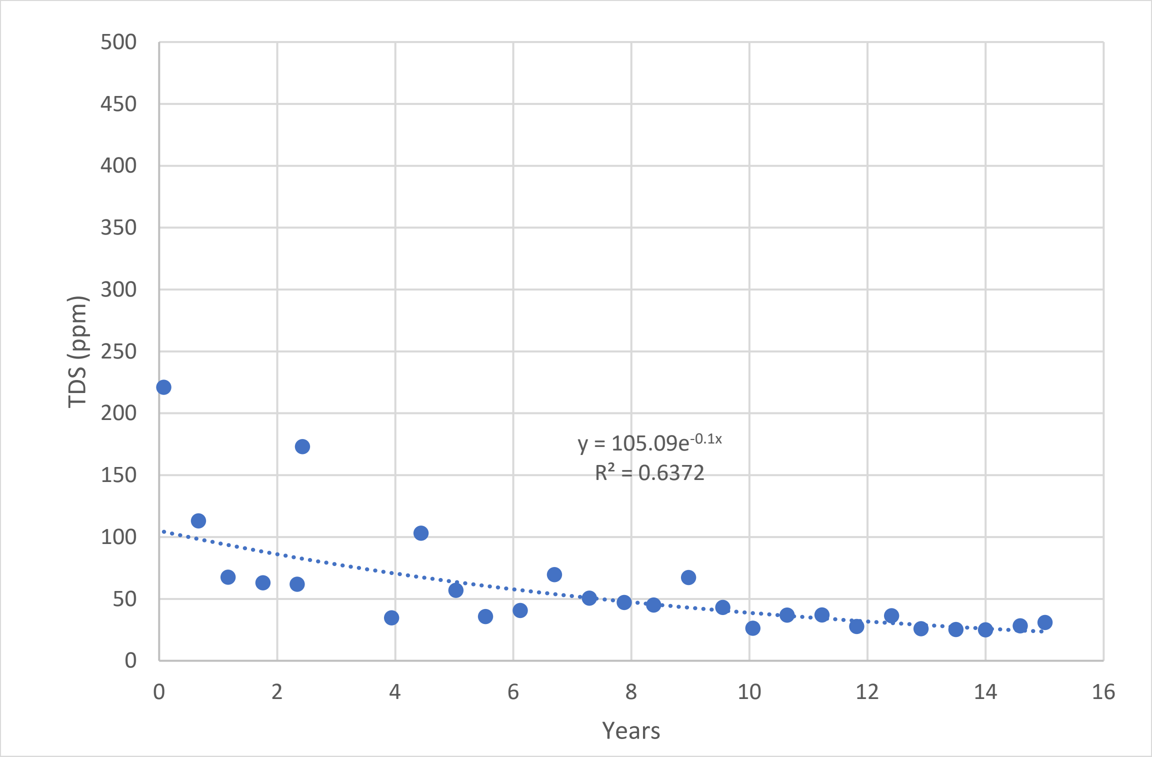


Figure B.24: Washed Recycled Crushed Concrete 2 (RCCA-Wash2) TDS Value