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16. Abstract

Two distinct but related issues of importance to FDOT were investigated: (1) the possible impact of recycled concrete aggregate (RCA) used as road base on the subsurface environment and (2) the management of concrete grinding residuals (CGR) resulting from grooving and grinding operations for Portland cement concrete pavements. Results from the literature and from testing on Florida-specific RCA indicate that the leachate produced by the contact of water with RCA is elevated in pH. Several factors were demonstrated to reduce leachate pH in the environment, but the extent to which this reduction will occur depends on environmental conditions that require additional testing to evaluate. CGR produced from concrete grinding operations is not hazardous waste, but is elevated in pH and requires appropriate management. Best management practices should be implemented for CGR, and examples of such practices are available. Management of CGR with concrete truck washout is a viable option. If CGR is discharged adjacent to roadways, care must be taken to avoid impact on ecosystems.

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SI* (MODERN METRIC) Conversion Factors

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH					**LENGTH**				
in	inches	25.4	millimeters	mm	**mm**	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	**m**	meters	3.28	feet	ft
yd	yards	0.914	meters	m	**m**	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	**km**	kilometers	0.621	miles	mi
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**	**SYMBOL**	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
AREA					**AREA**				
in^2	Square inches	645.2	square millimeters	mm^2	**mm^2**	square millimeters	0.0016	square inches	in^2
ft^2	Square feet	0.093	square meters	m^2	**m^2**	square meters	10.764	square feet	ft^2
yd^2	square yard	0.836	square meters	m^2	**m^2**	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	**ha**	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	**km^2**	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME					**VOLUME**				
fl oz	fluid ounces	29.57	milliliters	mL	**mL**	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	**L**	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	**m^3**	cubic meters	35.314	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	**m^3**	cubic meters	1.307	cubic yards	yd^3

NOTE: volumes greater than 1000 L shall be shown in m^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS					**MASS**				
oz	ounces	28.35	grams	g	**g**	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	**kg**	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	mega grams (or "metric ton")	Mg (or "t")	**Mg (or "t")**	mega grams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)					**TEMPERATURE (exact degrees)**				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C	**°C**	Celsius	1.8C+32	Fahrenheit	°F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION					**ILLUMINATION**				
fc	foot-candles	10.76	lux	lx	**lx**	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	**cd/m^2**	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL	SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**				
lbf	poundforce	4.45	newtons	N	**N**	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	**kPa**	kilopascals	0.145	poundforce per square inch	lbf/in^2

***SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.**

(Revised March 2003)

Executive Summary

Research provided a preliminary evaluation of the potential environmental impacts associated with two Portland cement concrete (PCC) related materials: recycled concrete aggregate (RCA) used as road base and concrete grinding residual (CGR) produced from grinding and grooving operations. Recycled concrete aggregate (RCA) is utilized for road base construction because of its excellent mechanical properties. Several past studies have evaluated possible issues posed by elevated pH and heavy metals in RCA leachate, though only minimal information is available for Florida. Grooving and grinding operations of PCC pavements produce a residual slurry with a 56% to 95% moisture content and an elevated pH. Concrete grinding residual (CGR) slurry has been managed in a variety of ways, including discharge adjacent to roadways and discharge into management-controlled retention ponds.

Laboratory tests were performed on eight RCA samples collected from various recycling facilities across Florida with a goal of examining the pH reached for different liquid-to-solid ratios (L/S) of water and RCA. Measured pH ranged from 10.5 to 12.3, depending on L/S. Through laboratory testing and chemical modeling, some degree of pH reduction was demonstrated for RCA leachate entering the environment as a result of factors such as carbonation from atmospheric carbon dioxide, neutralization with soil acidity, and neutralization with groundwater. Unknowns remain regarding the degree to which natural carbonation will continue to contribute to pH reduction over time. Leaching of heavy metals from RCA was evaluated as a part of literature review. These results, along with past experience on fate and transport modeling for the beneficial use of other waste materials, suggest that most trace elements leaching from RCA will be lower than risk-based regulatory thresholds, and those that do not will likely be attenuated in the environment. But this cannot be definitively concluded for Florida without additional testing of Florida RCA samples and site-specific modeling.

FDOT testing on CGR has found that CGR is not a hazardous waste, but the slurry does exhibit an elevated pH. The pH of CGR samples was measured over a range of L/S, and at different times during sampling and analysis, the pH ranged from 11.0 to 12.4, depending on the amount of liquid present. This pH is sufficiently elevated that appropriate CGR management steps should be required. Total elemental analysis of CGR found arsenic and barium to exceed Florida soil cleanup target levels for residential use, but these elements were well under commercial use thresholds, suggesting that land application of CGR as an amendment should have limited concern as long as application rates are limited. Best management practices for CGR have been developed by the concrete grinding industry, and several state DOTs recognize and require implementation of such requirements. Management of CGR using a similar approach as concrete truck washout is a common practice that should provide appropriate

protection. If CGR is discharged adjacent to roadways, this should only be conducted in a manner protective of adjacent aquatic ecosystems.

Additional research was outlined for an expanded evaluation of possible RCA impacts on Florida's environment and on metal infrastructure that might be exposed to a high pH RCA leachate. RCA samples from throughout Florida should be tested for heavy metal leaching using standardized leaching procedures, as should an examination of the effect of pH on leachability. Additionally, more realistic experimental simulations should be performed to evaluate the interaction of RCA leachate (with its associated pH and trace element content) with natural soils. Key factors that require investigation include soil type, soil depth, and infiltration rate. These experiments should include an examination of the effect of a high pH soil environment under an RCA base on metal piping. All of these results should be included as part of a Florida-specific beneficial use fate and transport model to assess whether any limitations for RCA are warranted, and if so, what should they be.

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List of Abbreviations and Acronyms

ACPA	American Concrete Pavement Association
AASHTO	American Association of State Highway and Transportation Officials
BMP	Best Management Practice
cc	cubic centimeter
CGR	concrete grinding residual
DEP	Department of Environment Protection
DOT	Department of Transportation
EPA	Environmental Protection Agency
FAC	Florida Administrative Code
FDEP	Florida Department of Environment Protection
FDOT	Florida Department of Transportation
ft	feet
FHWA	Florida Highway Administration
GCTLs	groundwater and surface water cleanup target levels
g	grams
L/S	liquid-to-solid ratio
lb	pounds
LBR	limerock bearing ratio
LEAF	Leaching Environmental Assessment Framework
MCLs	maximum contaminant levels
meq	milliequivalents
mg/kg	milligram per kilogram
mg/L	milligram per liter
mm	millimeter
mL	milliliter
ORP	Oxidation/ Reduction Potential (mV)
PCC	Portland Cement Concrete
RCA	recycled concrete aggregate
RPM	rotations per minute
SCTLs	soil cleanup target levels
TWRI	Techniques of Water Resources Investigations
USGS	U.S. Geological Survey
µg/kg	microgram per kilograms
µg/L	microgram per liter

1.0. Introduction

1.1. Scope of Issues

Recycled concrete aggregate (RCA) is defined by the Federal Highway Administration (FHWA) as reclaimed Portland cement concrete (PCC) that is produced by crushing process from concrete pavement, bridges, sidewalks, curbing, and other concrete structures. Currently in the state of Florida, RCA is used beneficially as a road base material during new road construction. Although the benefit of preventing recycled concrete from being landfilled is fairly clear, the impacts of using RCA in road construction should be fully understood. The Florida Department of Transportation (FDOT) has expressed concern with the generation of high pH leachate from RCA road base having negative impacts on aluminized storm water piping (loss of the aluminized coating) and increasing the pH of soil and groundwater.

FDOT has also expressed concern regarding the proper management of concrete grinding residue (CGR). CGR is a byproduct of grooving and grinding operations on Portland cement concrete bridge slabs and roadways. CGR is a fine powder suspended as slurry that is generated as a result of the planning of new or existing concrete roadways to make them smooth. CGR is also generated during joint cutting. CGR is a slurry byproduct created when a diamond blade's cooling water mixes with the concrete fines created during smoothing, grinding, and joint cutting. The FDOT's concern with CGR slurry is that the high pH may have potentially negative environmental impacts.

1.2. Objectives

The primary objectives of this research were to examine the extent of pH change that can occur in soil underlying an RCA base layer and to examine the risks and other issues associated with CGR dust and slurry management. The inherent objectives were to assess the RCA leachate for its water quality parameters such as pH and alkalinity. Soil neutralization capacity was further evaluated to measure the buffering capacity of soil against the alkaline pH of RCA. Field visits, sample collection, and laboratory tests were conducted to determine the risks associated with the current management practices of CGR. A set of draft best management practices (BMP) for CGR was developed.

1.3. Organization of Report

This report is organized into six chapters. Chapter 2 reviews the literature pertaining to the use of RCA and the environmental risks associated with RCA. Following the literature review, a description of the experiment methodology is presented along with the results. The interaction of RCA leachate with soils is evaluated in further sections of chapter 2, which includes experimental methodology and results. Chapter 2 is summed up by a risk assessment regarding the concerns associated with RCA as road base.

Chapter 3 reviews the literature on CGR slurry including the basic characterization of CGR slurry and BMPs developed by the International Grooving and Grinding Association. A survey regarding CGR management was conducted by the Hinkley Center for Solid and Hazardous Waste Management at the University of Florida with the assistance of the FDOT. This survey was sent out to all U.S. state's DOT offices, Puerto Rico, and the U.S. Virgin Islands. A review of survey results is included in chapter 3. Further sections of chapter 3 include the experimental methodology used, the characterization of CGR, and results. A set of recommended BMPs is presented.

Chapter 4 summarizes the results from the project. Chapter 5 includes the research plan that is recommended for further characterization. This is followed by references and appendices in chapter 6.

2.0. Environmental Issues Pertaining to Use of Recycled Concrete Aggregate

2.1. Background and Motivation

The Federal Highway Administration (FHWA) defines RCA as the reclaimed Portland cement concrete material produced by the crushing and processing of concrete pavement, bridges, sidewalks, curbing, and other concrete structures. RCA is produced at mobile as well as fixed crushing operations, generally operated by commercial contractors and facility operators. As part of this process, crushed concrete is screened to produce products of a specific size gradation. The aggregate retained on the 4.75 mm (No. 4) screen is typically referred to as "coarse aggregate" and the material passing that screen is referred to as "fine aggregate" (FHWA, 2004). Many studies have been conducted to assess the suitability of RCA as a construction material for a variety of applications, including bulk fill, bank protection, base or fill for drainage structures, road construction, and embankments. RCA has been proven an efficient alternative to natural aggregate for the increasing demand for road construction materials needed such as base, sub-base and pavement aggregate, as it provides excellent mechanical properties including higher resilient modulus, lower specific gravity, and lower alkali-silica reactivity (ACPA, 2008).

2.2. RCA Fundamentals

According to a USGS survey of various concrete and demolition companies throughout the United States, about 17.7 million metric tons of RCA was sold in 2013. Florida was among the top 10 states recycling concrete. Estimates of construction and demolition debris generated and recycled in the U.S. suggest this number might be much larger (Cochran & Townsend, 2010).

The FHWA conducted a survey of state transportation agencies in 2004 to assess the applications of RCA and associated environmental impacts. According to the survey, 38 state DOTs use RCA as aggregate base as shown in Table 2.1 and Figure 2.1 (FHWA, 2004). Some states such as Ohio, Iowa, Minnesota and Virginia have raised concern over the high alkalinity of water after it has come in contact with RCA base (and the resulting high pH), its potential to exceed drinking water standards (pH 6.5 to 8.5) and other issues (FHWA, 2004; Reiner, 2006). An increase in pH of soils and/or surface waters could pose various environmental and public health concerns, such as vegetation toxicity and risk to aquatic life.

Several studies have been conducted by various state Departments of Transportation (DOTs) to analyze the risks associated with the use of RCA for road construction applications and to evaluate mitigation measures. Box tests conducted by the Ohio DOT and the Iowa DOT found possible occurrence of high alkaline leachate generated from the direct contact of water with RCA, however, no mitigation measures were discussed. The Minnesota DOT measured pH values of approximately 9.5 when RCA was used near longitudinal drains, suggesting that high pH water draining from RCA might be neutralized by soils or acidic rain, thus any assessment needs to consider dilution and neutralization as a result of receiving water properties. The study also recommended having management practices of stockpiling RCA at storage sites with adequate storm water controls to prevent the leachate from flowing to a surface water body (Reiner, 2006). The Virginia DOT determined the effect of dilution of RCA leachate on storm water run-off impacting surface water, and recommended that 60:1 water to RCA ratio in grouts would keep the pH of run-off from RCA at near neutral pH values. These studies will be discussed in more detail later in this literature review.

Table 2.1. Survey by the Federal Highway Administration in 2004, states using recycled concrete aggregate (RCA) as road base (FHWA, 2004)

Arizona	Arkansas	California	Colorado	Connecticut
Delaware	Florida	Georgia	Illinois	Indiana
Iowa	Kansas	Kentucky	Louisiana	Massachusetts
Michigan	Minnesota	Mississippi	Nebraska	Nevada
New Jersey	New Mexico	New York	North Carolina	North Dakota
Ohio	Oklahoma	Pennsylvania	Rhode Island	South Carolina
South Dakota	Texas	Utah	Virginia	Washington
West Virginia	Wisconsin	Wyoming		

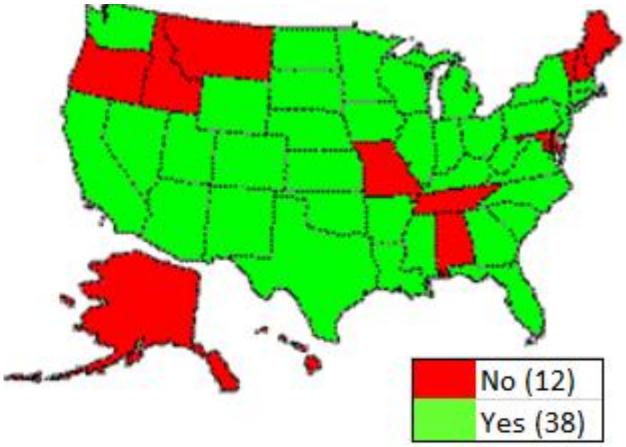


Figure 2.1. Survey by the Federal Highway Administration in 2004, states recycling recycled concrete aggregate (RCA) as road base (FHWA, 2004)

A survey by Deal et al. in 1997 on North American aggregate producers found that the bulk (~68%) of RCA was used as road base. Figure 2.2 shows the results from this survey for different applications of RCA (Deal, 1997). A road base is the layer of specified material and thickness, immediately beneath the road pavement which supports the structural course and thus must be able to withstand the traffic load on the pavement. The FDOT recently changed its specification language eliminating the use of the word “limerock” from Section 911 of the road and bridge construction manual which broadens the scope of materials that can be used for base and stabilizing base applications and thus may lead to an increase in use of RCA (FDOT, 2015, 2016). RCA providers and producers must meet extensive FDOT specifications for gradation, stability and plastic properties as per Florida Rule Chapter, 14-103, F.A.C. The approved RCA product for use as a road base aggregate is referred to as “B12”, where B stands for Base product and 12 is the number in the list of all base products.

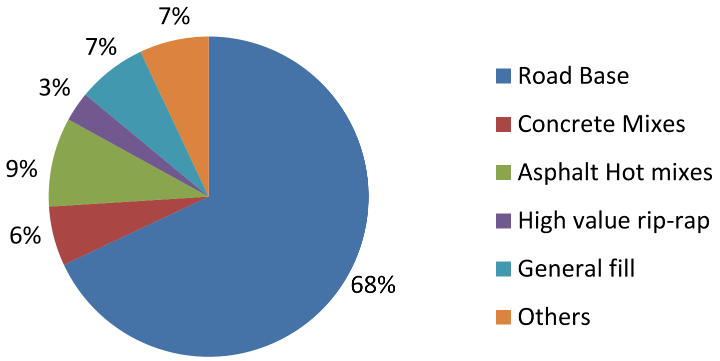


Figure 2.2. Recycled concrete aggregate used in various road construction activities according to a survey on North American aggregate producers in 1997 (Deal, 1997)

A number of researchers have published data on the physical and chemical properties of RCA. Laboratory tests performed by (Kuo et al.,2001) evaluated the quality and overall properties of RCA, including limerock bearing ratio (LBR), Los Angeles (LA) Abrasion Loss test, soundness, sand equivalent, optimum moisture, maximum dry density and hydraulic conductivity. Table 2.2 summarizes the basic physical and mechanical properties of RCA examined by this research Kuo et al., (2001). RCA characteristics presented by other researchers are consistent with this research (Bennert & Maher, 2008; Wen et al., 2014).

Table 2.2. Physical and chemical properties of recycled concrete aggregate as evaluated by laboratory experiments in 2001 (Kuo et al., 2001)

Property	Method used for evaluation	Value
Limerock Bearing Ratio	FM5-515	197.6
Los Angeles Abrasion Loss	FM1-T096	44.02%
Soundness	AASHTO-T104	52%
Sand equivalent		47-84%
Optimum Moisture	FM5-521	11.2%
Maximum dry density	FM5-521	113.8 lb/ft3
Hydraulic Conductivity		0.283 ft/day

**Ideally, for good pavement design hydraulic conductivity should be greater than 0.283 ft/day* (Senior, 1994)

RCA suppliers must obtain a permit from the Florida Department of Environment Protection (FDEP) under Florida Administrative code (FAC) 62.701.730. The RCA must qualify as "clean debris." DEP rules state that "clean debris" is any solid waste which is virtually inert, not a pollution threat to ground water or surface waters, not a fire hazard, and is likely to retain its physical and chemical structure under expected conditions of disposal or use. The term includes brick, glass, ceramics, and uncontaminated concrete including embedded pipe or steel.

After crushing and processing, FDOT requires that RCA for road base shall conform to the particle size distribution identified in FM 1-T27; Table 2.3 presents the gradation requirements for a certified RCA B12 product (FDOT, 2016).

Table 2.3. Florida Department of Transportation (FDOT) gradation requirements for recycled concrete aggregate to be a certified product for use as road base, called as a B12 product in FDOT language (FDOT, 2016)

Sieve Number	Sieve Size	Percent by weight passing
2 inch	50 mm	100
3/4 inch	19.1 mm	65 to 95
3/8 inch	9.52 mm	40 to 85
No 4	4.75 mm	25 to 65
No 10	2 mm	20 to 50
No 50	300 µm	5 to 30
No 200	75 µm	0 to 10

In addition to the gradation specifications, the characteristics in Table 2.4 must be met to be considered a B12 product (FDOT, 2016).

Table 2.4. Characteristics of recycled concrete aggregate required to be met for a certified product for use as road base, called as a B12 product in FDOT language (FDOT, 2016)

Property	Value
Plasticity	Non-Plastic
Limerock Bearing Ratio (LBR)	150 or more
Deleterious substances (The following limits shall not be exceeded)	
Bituminous concrete	1% by weight
Bricks	1% by weight
Wood and other organic substances	0.1% by weight
Reinforcing steel and welded wire fabric	0.1% by weight
Plaster and gypsum board	0.1% by weight

2.3. Literature Review: RCA as Road Base

While crushed concrete is generally considered benign with respect to environmental concerns, there are some scenarios where the potential for adverse groundwater and surface water impacts has caused concern. Presence of calcium oxides from the cement mixture in crushed concrete could result in an increased pH through reaction with water, and this high pH solution could pose concerns. Since RCA also contains some heavy metals from natural as well as waste product components (and from the chemicals that the concrete was exposed to over its life) heavy metal leaching is another concern raised by the use of RCA for road applications. These issues have been evaluated by some researchers; the following sections review some of these published studies.

2.3.1. Elevated pH Resulting from RCA

The pH value of water that has been in contact with RCA is generally in the range of 10-12. This value has been shown to drop to near 9 after sufficient water has passed through the RCA (Ohio Department of Transportation, 2002a; Tinjum & Edil, 2013). Because of its high pH, a potential concern associated with RCA leachate is that the high pH water may cause loss of the protective aluminized stormwater pipe coating and subsequent corrosion of metal stormwater pipes underneath the RCA road base. There is also concern that water that has been in contact with RCA may kill vegetation near the stormwater pipe outlets (Steffes, 1999). High pH from RCA runoff is due to the release of hydroxyl ions (OH^-) from the cement paste residues in crushed concrete (Aydilek, 2015; Kuo et al., 2001; Reiner, 2006; Chen et al., 2013). A study by Aydilek et al. (2015) observed a direct relation between the amount of calcium present in an RCA sample and the pH produced by the sample; high pH was observed for samples with greater calcium oxide (CaO) and calcium (Ca) contents. This results from calcium oxide reacting with water to form calcium hydroxide, which then dissolves and releases hydroxide ions (OH^-).

Various laboratory and field tests have been performed and compared to assess the effect of external factors on the environmental impacts of RCA leachate. Results of field tests have shown slightly lower pH than that of laboratory tests because of the reaction between material and atmospheric carbon dioxide (Chen et al., 2013; Engelsen et al., 2006; Ohio Department of Transportation, 2002a). The atmospheric carbon dioxide (CO_2) reacts with the hydroxide to produce bicarbonate and carbonate ions which then react with the calcium to form calcium carbonate ($CaCO_3$), neutralizing some alkalinity of the RCA.

Particle size plays another important role in determining the pH of leachate from the RCA. The presence of more fines in an RCA sample increases the pH of the eluate because of the increased surface area. More interaction with the aqueous solution therefore results in enhanced leaching (Aydilek, 2015; Snyder & Bruinsma, 1996). In the study by Aydilek et al. (2015), not all of the results were consistent. For one of the RCA samples in this study, the pH displayed a slightly decreasing trend with an increase in particle size; for the other RCA sample there was a consistent trend of increasing pH with smaller particle size (Aydilek, 2015).

The Ohio Department of transportation performed a series of tests including box tests, bucket tests and blends of RCA and soil in 2002 to determine the range of pH of RCA leachate. A box test was designed to analyze the alkaline run-off from RCA (Ohio Department of Transportation, 2002a). RCA samples were compacted, water was added, and periodic samples from the drains were collected and analyzed. Water was in direct contact with the RCA and thus the samples had maximum rehydration levels. Water samples collected on the first day had pH measurements of around 11, while for limestone the pH was approximately 8. The RCA samples leveled off at a pH in the range of 9-10 after a few days, the limestone was relatively stable at a pH of 8. This study recommended avoiding the use of RCA as base in low lying areas or wet areas where alkaline run off could be of concern (Ohio Department of Transportation, 2002a; Reiner, 2006). pH results from this study are presented in Table 2.5 (Ohio Department of Transportation, 2002a). Bucket tests were undertaken which involved soaking of different aggregate samples like RCA, limestone and mixtures of the two at different ratios in water. The pH was measured periodically and it was found that a sample of at least 60% of limestone (40% RCA) will have a pH of about 9 (Mulligan, 2002).

Table 2.5. Test pH results of RCA with time. Laboratory tests were performed by Ohio DOT with demineralized water passing through various RCA samples and analyzed for pH of the leachate produced. RCA leachate was recirculated through RCA. Fresh A sample was the sample when RCA leachate recirculation was stopped after day 40 and only demineralized water was passed through RCA (Ohio Department of Transportation, 2002a)

Day Sampled	Limestone	RCA1	RCA2	RCA3
1	7.66	11.07	11.2	11.51
2	7.52	11.25	11.14	11.2
12	8.13	9.76	8.21	9.93
20	7.86	10.03	9.56	9.94
27	8.04	10.31	9.71	9.98
34	7.91	10.22	9.5	9.94
40	7.94	9.12	8.82	9.53
Fresh A	8.2	9.93	9.22	9.58

The Ohio DOT study also evaluated the effect of soil on decreasing the pH of leachate generated by RCA (Ohio Department of Transportation, 2002b) and found a decreasing trend of pH with increase in soil-to-RCA ratio. Both low pH and high pH soil samples were selected to examine the extent of neutralization that can take place in the mixture. Results from the tests on RCA blends with slightly alkaline soil are presented in Table 2.6 (Ohio Department of

Transportation, 2002b). The difference between RCA and soil pH was 0.77 units, and it is evident from the data that it did not offer a significant amount of neutralizing capacity. The same test was performed with an acidic soil of initial pH 5.12. Table 2.7 shows the results of this test.

Table 2.6. The pH change in RCA leachate because of neutralization offered by an alkaline soil mixed in different ratios by weight with RCA sample at different time (Ohio Department of Transportation, 2002b)

Wt % alkaline soil	RCA:Soil weight (lbs RCA:lbs Soil)	Initial pH	4 Hours	48 hours	120 hours
0%	10:0 Mixture	10.19	10.31	10.57	10.69
9.1%	10:1 Mixture	9.78	9.87	10.44	10.65
16.6%	10:2 Mixture	9.56	9.68	10.12	9.98
23.1%	10:3 Mixture	9.51	9.56	9.8	9.78
28.6%	10:4 Mixture	9.43	9.58	9.9	9.57
33.3%	10:5 Mixture	9.34	9.53	9.91	10.18
100%	0:10 Mixture	9.42	9.54	9.93	10.01

With an increase in time, all samples had an increase in pH, which subsequently decreased with time. In samples with more than 50% soil, pH values started at 11 and remained near 11 through the course of experiment. An increase in pH over time, irrespective of mixture composition, was explained by the release of bases through the presence of calcium in the material, which reacts with water to form calcium hydroxide (Ohio Department of Transportation, 2002b).

Table 2.7. The pH change in RCA leachate because of neutralization offered by an acidic soil mixed in different ratios by weight with RCA sample at different time (Ohio Department of Transportation, 2002b)

Wt % acid soil	Initial pH	4 hours	48 hours	120 hours	264 hours	432 hours
0%	12.09	12.15	12.29	12.28	12.27	12.26
10%	11.6	11.91	12.09	12.08	12.06	12.08
20%	11.11	11.69	11.87	11.83	11.82	11.8
30%	10.36	11.27	11.61	11.63	11.6	11.65
40%	10.08	11.1	11.38	11.38	11.43	11.39
50%	9.16	10.54	11.13	11.18	10.94	11.14
100%	5.12	5.27	5.47	5.53	5.8	6.2

2.3.2. Constituent Release from RCA

A growing trend in the U.S. is to beneficially use waste materials as ingredients in construction products (instead of virgin material). Various waste materials such as fly ash and slag are utilized during the manufacture of both cement and concrete to reduce cost, conserve resources, and improve performance properties (Mehta & Gjørv, 1982). These additives may potentially contain heavy metals and trace elements such as vanadium, chromium, and lead (Mullauer et al., 2015). These elements may leach from crushed concrete when it is recycled and used in an application such as road base.

Total elemental analysis of RCA completed by a number of researchers has found barium (Ba), copper (Cu), nickel (Ni), cobalt (Co), arsenic (As) and chromium (Cr) as major trace elements, possibly a result of the addition of fly ash or slag (Aydilek, 2015; Chen et al., 2012a). Aqueous solubility is one of the determining factors for release of the constituents. For cement-based products, the pH of salts containing weak acids called oxyanions have higher solubility at high pH (Engelsen et al., 2006). As described earlier, solution pH is affected by external factors such as the amount of precipitation, degree of saturation, temperature, and soil type (Engelsen et al., 2012). Constituent release varies with the change in liquid-to-solid (L/S) ratio (the cumulative amount of water exposed to RCA per mass of RCA), and this was examined by Engelsen et al. (2006). Metal cations such as copper (Cu) and nickel (Ni) were found to suddenly increase in leachate concentration in the first wash-out, whereas, As and V tended to form oxyanions with Ca in alkaline conditions and had a significant decrease in release after L/S of 0.05 (an indication of solubility-controlled leaching; Engelsen et al., (2006)). As characterized by the U.S. Environment Protection Agency (EPA), solubility-controlled leaching is the release of constituents depending on the solubility of the species, which also depends on the pH of solution (U.S. Environmental Protection Agency, 2014). A more detailed examination of the case study by Engelsen et al. (2006) is provided in later sections of this report. Table 2.8 compares the total concentrations of elements in samples from various studies. For the sake of comparison, Florida's direct exposure risk-based target levels are provided.

Table 2.8. Total elemental concentrations found in recycled concrete aggregate from different studies compared to Florida soil cleanup target levels (residential and commercial) (Chen, et al., 2012a; Chen et al., 2013; Engelsen et al., 2006, 2010)

Study	SCTLs[1] (mg/kg) residential; commercial/ industrial	(Chen et al., 2012a; Chen et al., 2013)- ***EPA Method 3050B***				(Engelsen et al., 2006)	(Engelsen et al., 2010)
		RCA[2] (column test)	RCA-Fresh (field test)	RCA-stock (field test)	Natural Aggregate (field test)	RCA (mg/kg)	RCA[3] (mg/kg)
Major Elements							
Ca		4.9-16.3%	>20%	>20%	>20%	6.26	-
Fe	53,000; -	1.0-2.3%	0.83%	0.65%	0.33%	2.37	-
Al	80,000; -	0.8-1.7%	0.52%	0.41%	0.1%	6.25	-
Mg		0.3-2.0%	8.47%	8.69%	>10%	-	-
Na		0.3-0.6%	0.84%	0.37%	0.45%	1.95	-
K		0.13-0.2%	0.15%	0.11%	0.08%	2.58	-
Trace Elements							
As (mg/kg)	2.1; 12	2.2-6.5	10.9	11.2	6.3	<10	-
Ba (mg/kg)	120; 130,000	40.8-165.2	20.4	22.8	3.7	-	-
Cd (mg/kg)	82; 1,700	0.1-0.2	0.6	0.4	0.3	<0.72	<0.7
Co (mg/kg)	1,700; 42,000	1.2-4.0	2.9	2.3	0.4	-	-
Cr (mg/kg)	210; 470	6.2-20.2	6.7	6.3	2.5	69	49-116
Cu (mg/kg)	150; 89,000	6.1-16.5	13.8	10.7	2.6	12	12-49
Mn (mg/kg)	3,500; 43,000	-	-	-	-	-	272-635
Mo (mg/kg)	440; 11,000	0.1-1.0	1.1	0.5	0.3	-	3.7-8.7
Ni (mg/kg)	340; 35,000	3.0-21.0	5.1	4.6	1.3	14	14-34
Pb (mg/kg)	400; 1,400	2.1-9.1	3.6	3.2	3.7	31	12-62
Sb (mg/kg)	27; 370	0.2-0.9	2.8	2.2	1.7	<3.3	-
Se (mg/kg)	440; 11,000	0.8-1.3	16.7	17.4	16.3	-	-
Zn (mg/kg)	26,000; 630,000	20.4-32.4	26.8	18.9	17.6	-	45-553
V (mg/kg)	67; 10,000	-	-	-	-	53	35-92
Material pH	6.5-8.5	11.3-12.6	12.3	11.8	10.0	~13	11.6

Note: [1]Florida Soil Cleanup Target Levels. [2,3]Range of the values selected from both studies.

All of the RCA samples reported in the various studies presented in Table 2.8 meet the Florida Soil Cleanup Target Levels (SCTL) except for As, which exceeds its Florida soil cleanup target levels for residential (SCTLs) use. This suggests that, while some trace heavy metals are present in RCA, they are not typically of high enough concentration to pose a risk with respect to direct human exposure (ingestion, inhalation, dermal contact). Florida's residential SCTL for arsenic is relatively low and a number of waste materials have been found to exceed this risk threshold.

The primary issue with regard to heavy metals and RCA relates to chemical leaching and impact on receiving waters (groundwater, surface water), not on direct human exposure. As the amount of chemical that leaches from RCA (or any waste material) does not always correlate to the total amount of that element present, leaching tests are needed to evaluate this pathway of risk. A number of studies where RCA leaching was evaluated are presented in the following section.

2.3.3. Case Studies

This section briefly discusses studies conducted to evaluate RCA and its potential environmental impact when used in a road base application.

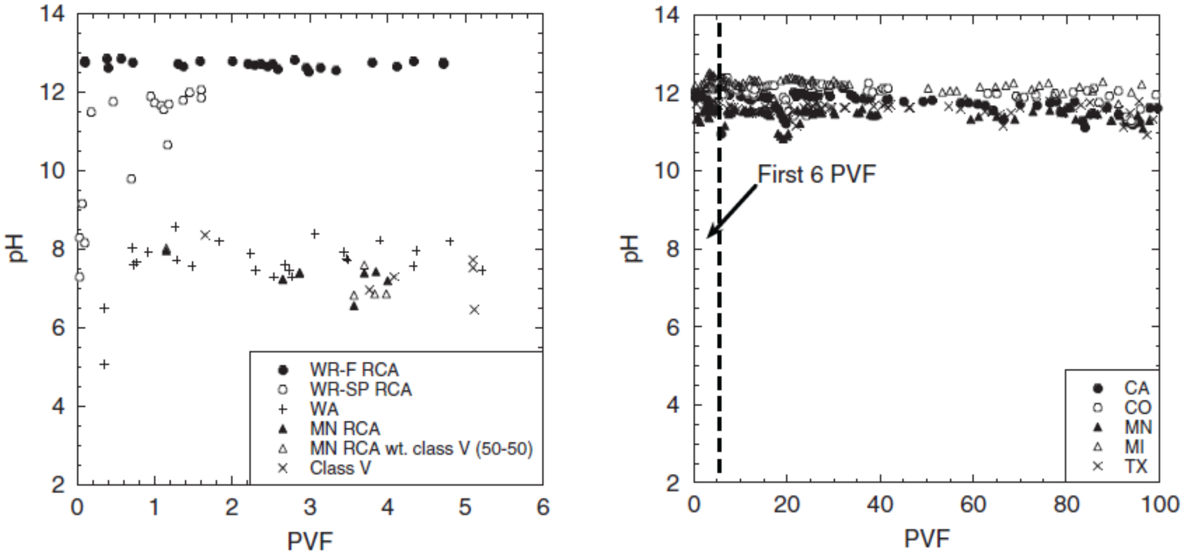
Case Study 1: University of Wisconsin

A series of studies were conducted by the University of Wisconsin to analyze the leaching of alkaline substances and heavy metals when RCA is used as road base (Chen et al., 2012a; Chen et al., 2012b; Chen et al., 2013; Ginder Vogel, 2015). Seven samples were selected from a wide variety of geographical regions: California (CA), Colorado (CO), Michigan (MI), Minnesota (MN), Texas (TX), Wisconsin Fresh (WR-F), and Wisconsin Stockpiled (WR-SP). Two natural aggregate samples were also used for comparison with RCA. Two field leaching test sites were constructed with three experimental cells on each.

Leachate properties such as pH and chemical composition will depend on the permeability of the material and amount of liquid passing through it. Figure 2.3 presents leachate pH as a function of pore volumes of flow (PVF). Column leaching tests were compared with the field leaching tests on the same samples to analyze the effect of field parameters on leachate characteristics. The pH values in the laboratory column tests were consistently as high as 12 and no decreasing trend was observed, whereas field leaching tests for many of the samples displayed a more neutral pH (6.6 to 8.0) over a period of time; this was attributed to the presence of carbon dioxide in the air and its reaction with the basic solution.

In the field tests, fresh and stockpiled samples of Wisconsin RCA were compared and these samples followed different pH trends. Since the stockpiled material interacted with atmospheric air more than the fresh samples, this led to the change in the cement hydration phases (i.e., carbonation, hydration and water absorption). A layer of calcium carbonate formed around the stockpiled material by the reaction of carbon dioxide and calcium-bearing minerals from the cement paste (the carbonation process). In the case of the WR-SP sample, the stockpiled RCA leachate started at a lower pH and then increased as the outer calcium carbonate layer washed off.

The column leaching tests of the RCA samples found that several elements exceeded EPA drinking water standards at least once over the range of PVF (elements included arsenic (As), chromium (Cr), lead (Pb) and selenium (Se)).



(a) (b)

Figure 2.3. The pH of leachate produced from recycled concrete aggregate plotted against pore volumes of flow, (a) field leaching tests (b) column leaching tests (Chen et al., 2013)

The pH-dependent batch tests were conducted on the RCA samples, keeping an L/S of 10:1 by weight. Leaching of copper (Cu), chromium (Cr) and zinc (Zn) was observed. Figure 2.4 shows the observed trend in release of Cu and Zn with respect to pH (Chen et al., 2012b). Cu and Zn leached more in acidic conditions and had significantly lower leaching at neutral and alkaline conditions, irrespective of total concentration in RCA samples. At neutral pH conditions, leaching of Cu and Zn was higher in the finer samples. Elements forming oxyanions like Cr tended to leach more in alkaline conditions. Also, a relationship of particle size on element release was observed.

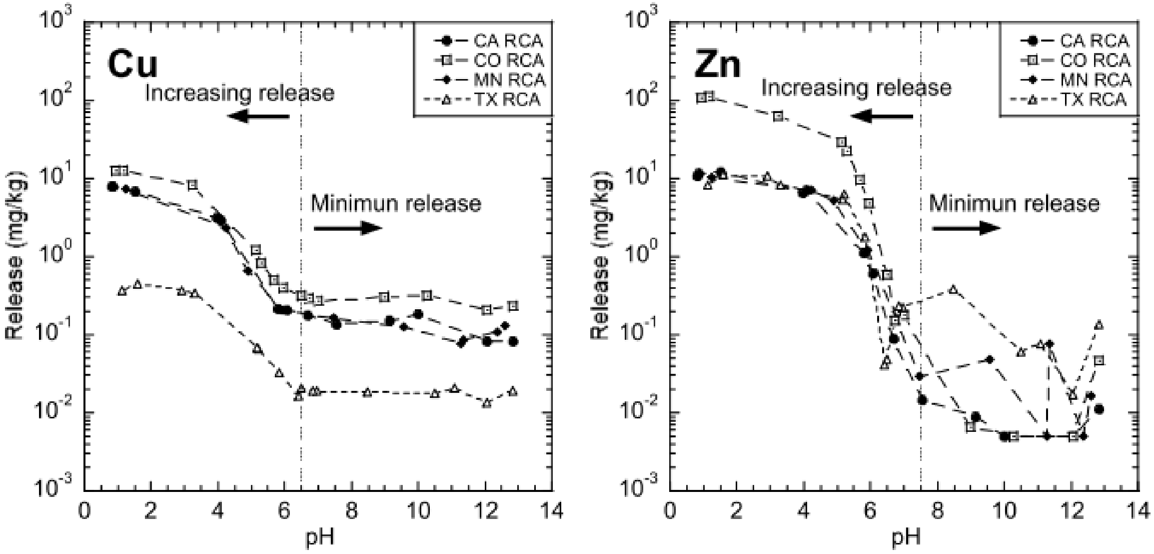


Figure 2.4. Leaching of copper and zinc from leachate produced by recycled concrete aggregate as a function of pH of solution (Chen et al., 2012b)

Case Study 2: University of Oslo

A series of tests were conducted on RCA samples from 2004 to 2010 to analyze constituent release (Engelsen et al., 2006, 2010, 2012). To study the effect of carbonation on leachate pH, an RCA field testwithout an asphalt layer was also tested along with the asphalt-covered RCA test field. A natural aggregate test field was used as a reference. The RCA test field not covered with asphalt layer was directly exposed to the atmosphere (Engelsen et al., 2012). Figure 2.5 shows the pH trend with respect to time for these field tests. The RCA test bed not covered with an asphalt layer dropped in pH more rapidly than the RCA test bed covered with the asphalt layer. A similar trend was observed by Aydilek et al. (2015) when samples were cured for different periods to determine the effect of hydration. Effluent pH was found to decrease with an increase in curing time from 1, 7 and 28 days.

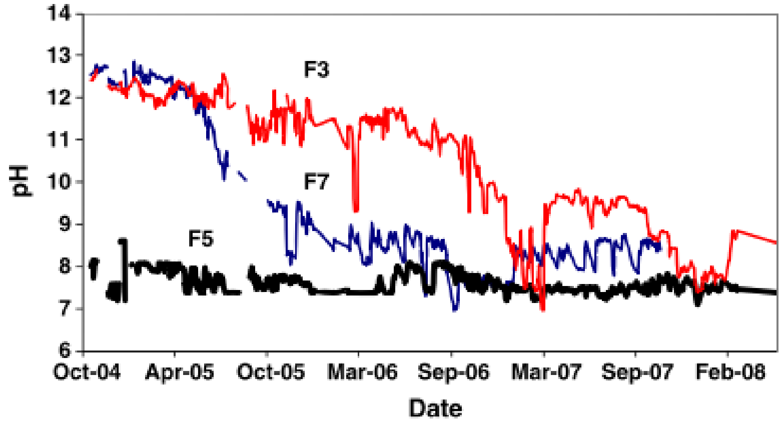


Figure 2.5. pH of the infiltration water from different test fields with time. F3 is RCA field with asphalt layer, F7 is RCA test field without asphalt layer and F5 is natural aggregate test field for comparison (Engelsen et al., 2012)

Additionally, release of elements like chromium (Cr), copper (Cu) and vanadium (V) was found to be in much larger quantities from RCA aggregates than from natural aggregate in the first 100 days of exposure, but the release decreased over time. The effect of pH and time on constituent release from the sample was studied. At a high pH, concentrations of elements released in field conditions were higher than the corresponding release in the laboratory leaching tests, which could be explained by initial surface wash off. From pH ranging from 9.0 to 11.0, the release of the cations Cu and Ni decreased, but the leaching concentration from the field was higher than in the laboratory studies. Elements forming oxyanions (Cr, Mo and V) exhibited higher metal release with increasing pH (Engelsen et al., 2010). Figure 2.6 shows the trend of trace element release with respect to time and pH (Engelsen et al., 2012). Release of all elements decreased below a pH of 8.0, which was explained by the formation of a carbonation layer which serves as a physical barrier to constituent release (Engelsen et al., 2012).

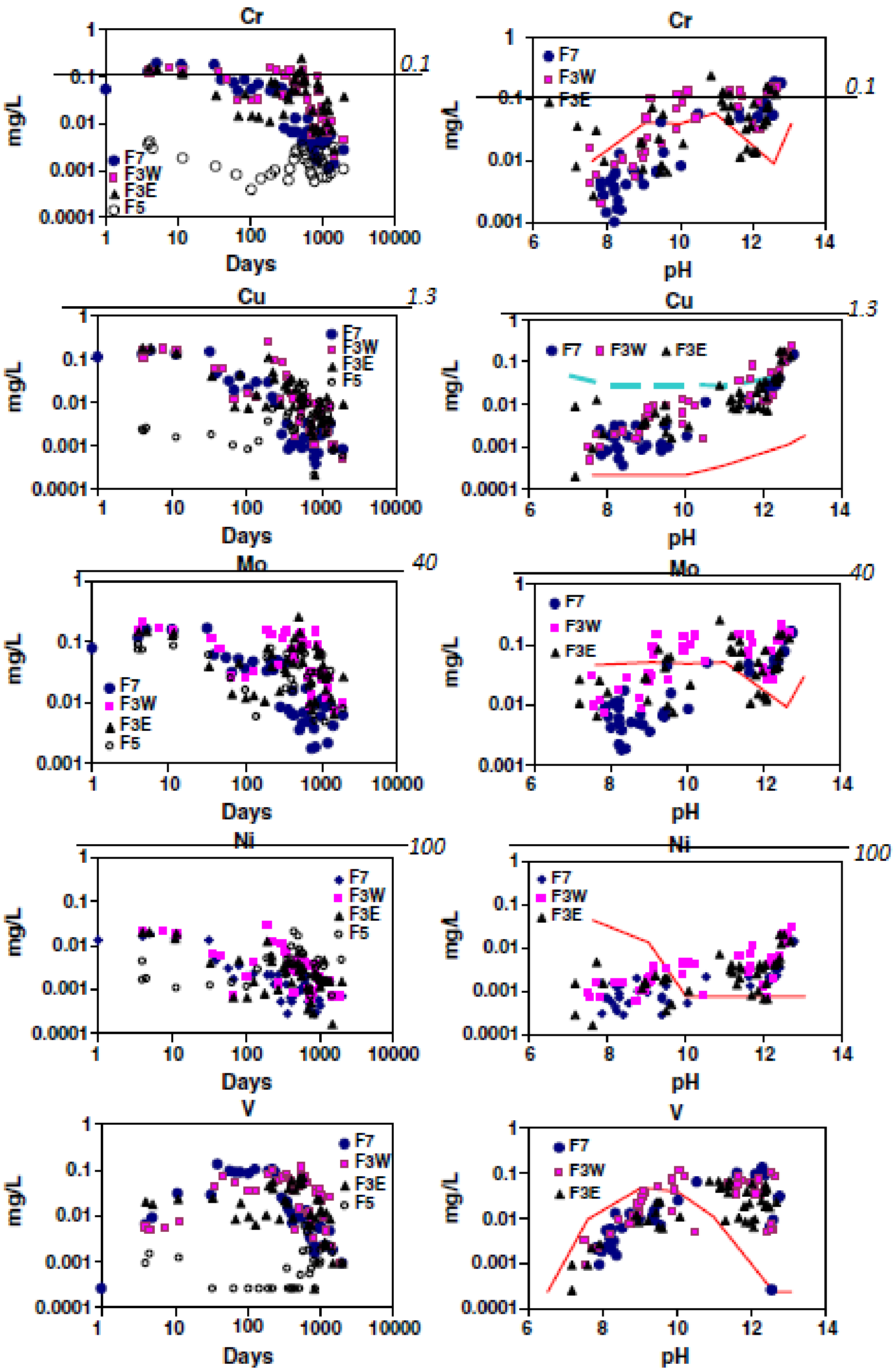


Figure 2.6. Constituent release from leachate produced from recycled concrete aggregate with respect to time and pH (Engelsen et al., 2012)

Notes: F7 contains RCA not covered with Asphalt. F3W and F3E contain RCA covered with Asphalt. F5 contains natural aggregate covered with Asphalt. Straight solid line represents the EPA drinking water standards. Curved solid line represents the pH dependent data in laboratory for a sub batch collected at field site. Dashed line represents the pH dependent data for a sample that contains humic substances

A model was designed to project the infiltration water concentrations to the concentrations in groundwater and surface water, considering the dilution effect. Concentration values were derived by multiplying the dilution factor by the concentration from infiltration water and then comparing it to the respective risk thresholds. Table 2.9 compares the leachate concentrations with the EPA primary and secondary drinking water standards (Engelsen et al., 2012). When the leached concentration is directly compared with the drinking water standards, As and Cr exceed those standards for most of RCA samples at some point of time. Considering the groundwater to pore water dilution factor as 0.071 and surface water to groundwater dilution factor as 0.05, all the elements would meet the threshold limits.

Table 2.9. Lowest and highest concentrations of trace elements in leachate produced from recycled concrete aggregate, compared to EPA maximum contaminant level of drinking water standards (2004-2010) (Engelsen et al., 2012)

	Concentration (µg/L)								
	F3W 2004/05	F3W 2006-10	F3E 2004/05	F3E 2006-10	F5 2004/05	F5 2006-10	F7 2004/05	F7 2006-10	MCLs[1] (ug/L)
As	<3.5-30	<3.5-29	<3.5-19	<3.5-25	<3.5-6.1	<3.5-9.6	<3.5-34	<3.5-5.9	10
Cd	<0.1	<0.1-0.1	<0.1	<0.1-0.2	<0.1-0.1	<0.1-2.2	<0.1	<0.1	5
Cr	30-140	2.0-129	11-156	2.7-241	<0.3-4.1	0.6-3.2	7.9-187	1.6-13	100
Cu	11-237	1.0-13	7.2-181	<0.2-28	0.8-6.9	0.2-26	0.8-156	0.4-3	1300
Mo	26-205	7.4-139	11-150	6.4-252	5.8-88	4.9-84	6.5-159	1.7-17	40000
Ni	0.7-20	<0.7-4.5	<0.7-21	<0.7-6.9	1.1-9.7	<0.7-20	<0.7-17	<0.7-2.0	100000
Pb	<2.5-5.3	<2.5-2.4	<2.5-3.2	<2.5-2.7	<2.5	<2.5-4.2	<2.5	<2.5	15
V	4.9-81	3.2-115	6.3-60	<0.3-70	<0.3-1.5	<0.3-6.1	<0.3-129	1.5-13	-
Zn	<1.3-14	<1.3-5.3	<1.3-2.4	<1.3-5.6	<1.3-3.7	<1.3-8.3	<1.3-8.1	<1.3-7.4	5000

Note: F3W and F3E contain RCA covered with Asphalt. F5 contains natural aggregate covered with Asphalt.F7 contains RCA not covered with Asphalt.

[1]EPA drinking water standards and secondary standards

2.4. Leaching from Florida RCA Samples

With the increasing demand for construction materials, virgin aggregate is being replaced, to some extent, by RCA because of its excellent mechanical properties. Some environmental concerns with using RCA as road base have been raised as possible issues. Percolation of rain water through an RCA road base will result in an alkaline solution with a pH of around 10.0-12.0. This might result in the corrosion of drainage pipes, negatively affect the vegetation around the drainage area, and cause an impact on underlying groundwater. The leaching of heavy metals from RCA has also been suggested as a potential issue.

L/S-dependent batch tests were performed in laboratory to analyze the pH levels of leachate generated from various RCA samples collected from recycling facilities across Florida. Observed pH was in the range of 10.5-12.3, with highest pH being reached at maximum L/S.

2.4.1. Sample Collection

For evaluation of environmental impacts of RCA, eight RCA samples and two limerock samples were collected from various recycling facilities in Florida from FDOT Districts 1, 2, 3, 4 and 7. Limerock samples were analyzed as control samples. Among all the RCA samples collected, three were approved ‘B12’ samples. Crushed concrete was processed at recycling facility to make aggregates and then stockpiled at the facility. Eight random sampling points across the target pile were selected to collect the subsamples. All collected subsamples were homogenized on a plastic tarp with clean stainless steel shovels to make a representative sample of the facility. Two 5-gallon buckets were filled with the mixed material to make duplicates. Samples were labeled and sealed to avoid any contamination and moisture loss.

Duplicate samples of each recycling facility were analyzed in this study. Table 2.10 and Figure 2.7 illustrate the sampling location and sample names. RCA samples were free from glass, wood, and other debris when inspected visually.

Table 2.10. Eight recycled concrete aggregate (RCA) samples and their duplicates analyzed in the study to analyze environmental impacts of RCA as road base

Sample Name	Duplicate	Location
ECR1	ECR2	Fort Pierce
ER1	ER2	West Palm Beach
MR1	MR2	Sarasota
PJ1	PJ2	Fort Pierce
RRF1	RRF2	Jacksonville
SG1	SG2	North Clearwater
TS1	TS2	Tallahassee
WS1	WS2	Bradenton

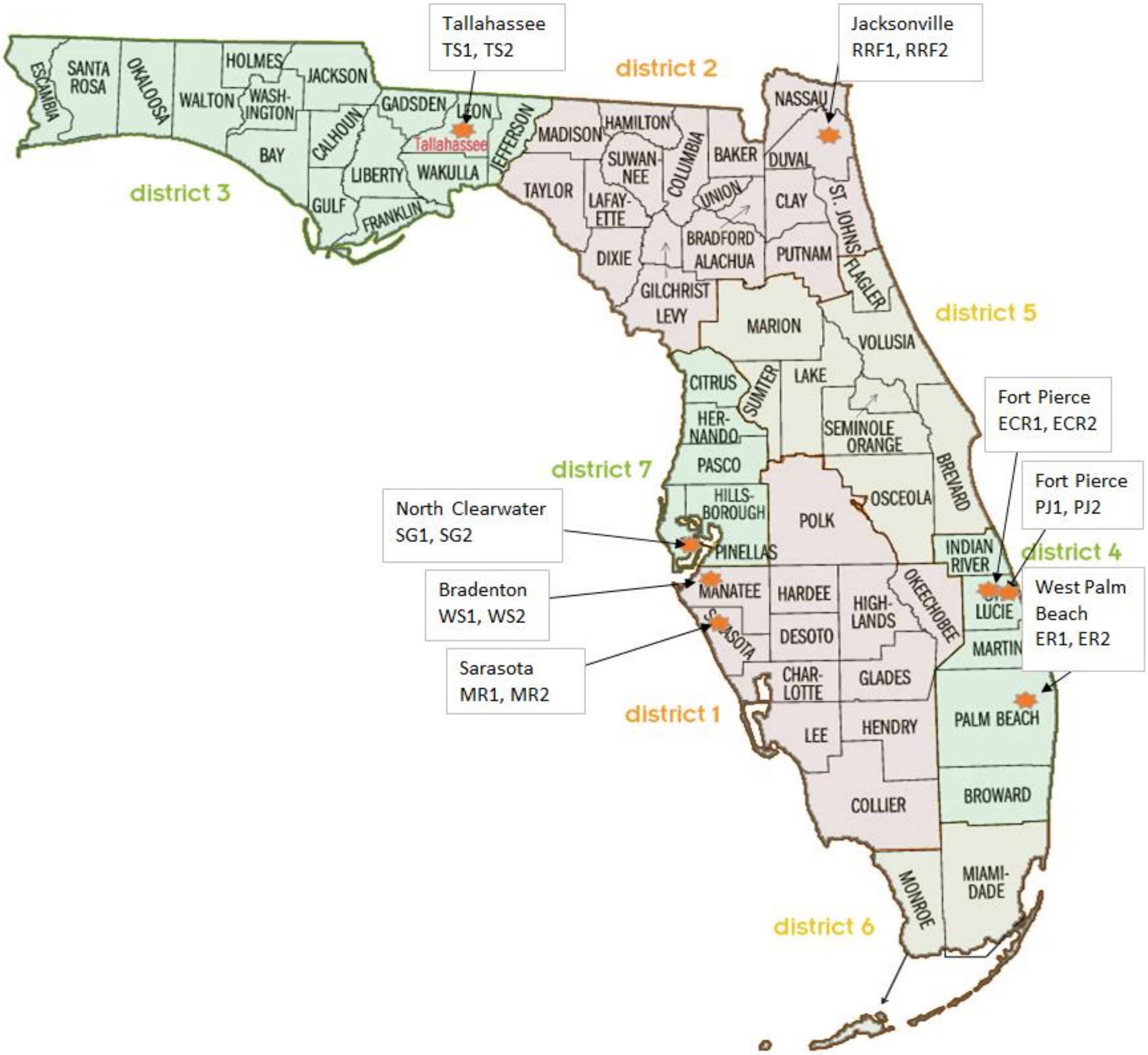


Figure 2.7. Florida sampling locations for recycled concrete aggregate (RCA) used in the study to assess the environmental impacts of RCA as road base. Districts refer to FDOT Districts.

2.4.2. Characterization and Leaching Methodology

Moisture content for all the samples was found using Florida method FM 1-T 255 for coarse and fine aggregates. Duplicate samples were analyzed from each source for quality assurance. Sieve analysis was performed on approximately 1,000-g oven-dried samples, using sieves of 50 mm, 19.1 mm, 9.52 mm, 4.75 mm, 2 mm, 0.3 mm, and 0.075 mm, in accordance with Florida method FM 1-T027. EPA LEAF 1316 test guidelines were followed to run liquid-solid partitioning between water and RCA materials under equilibrium conditions. Five parallel batch tests per sample were performed using reagent water at L/S of 10, 5, 2, 1, and 0.5. Samples were mixed by rotation for 24 hours at 28 ± 2 rpm. The vessels were centrifuged at 4,000 ± 100 rpm for 15 minutes to clarify the solution. All extractions were filtered through polypropylene 0.45 µm membrane. Conductivity and pH were measured according to ASTM 1125 and EPA standard procedure 9040 (SW-846), respectively.

Alkalinity was measured to determine the equivalent amount of carbonate species present in RCA leachate and the amount of strong acid required to neutralize it. Standard titration procedure was followed, using 1.6 N sulfuric acid. Acid-neutralization curves were plotted against the amount of acid added, and alkalinity, expressed as mg/L of $CaCO_3$ was calculated on the basis of carbonate equivalence point (i.e., near pH= 4.5). The method guidelines were followed from the method given in TWRI chapter A6 from Book 9 by USGS (USGS, 2012).

A volume of 50 mL of all the filtered samples was digested using an automated block digester. The process uses trace metal grade nitric acid and hydrochloric acid according to EPA method 3010a. The digested samples were made up to volume 50 mL by adding deionized water and analyzed for calcium concentration with an inductively coupled plasma atomic absorption spectrophotometer (ICP) using EPA method 6010b.

Table 2.11. Analytical methods used in the study for recycled concrete aggregate (RCA) characterization and leaching to evaluate the environmental impacts of RCA as road base

Characteristic	Method
Moisture content	FM 1-T 255
Particle size distribution	FM 1-T027
Leaching batch test	EPA LEAF 1316
pH	SW-846 Method 9040
Alkalinity	USGS TWRI Book 9 Chapter A6
Conductivity	ASTM 1125
Calcium Leaching	EPA SW-846 Method 3010a/6010b

2.4.3. RCA Test Results

Figure 2.8 shows the particle size distribution of the RCA samples analyzed in the study. All the samples met Florida gradation requirements for a B12 product, except ECR and SG samples from Ft Pierce and North Clearwater, respectively. Percent fines passing No. 4 (4.75 mm) and No. 10 (2 mm) sieve exceeded its respective limit of 65% and 50% for ECR, whereas SG sample did not meet the minimum requirement for percent passing 3/4 inch, 3/8 inch, No. 4, and No. 10 sieve.

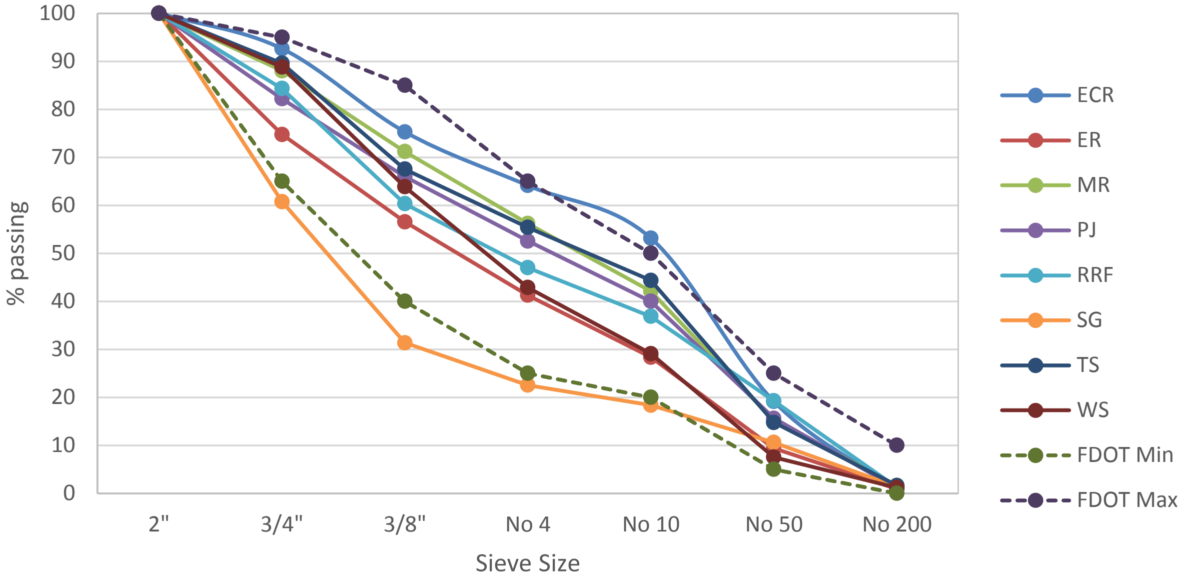


Figure 2.8. Particle size distribution (in accordance with FM 1-T027) of recycled concrete aggregate samples collected from eight recycling facilities in Florida, compared to FDOT gradation limits for certified road base product. Data shows average for duplicates of each sample.

Duplicate batch tests of each sample at L/S of 10, 5, 2, 1, and 0.5 were performed for the study. Moisture content of the ECR, ER, MR, RRF, SG, PJ, TS and WS was 7.65%, 14.64%, 7.64%, 7.97%, 7.64%, 7.44%, 14.27%, and 10.14%, respectively, and was taken into consideration while performing the batch tests. The pH and conductivity measured after the filtration of extracted samples is plotted against L/S in Figure 2.9 and Figure 2.10, respectively. The pH values of RCA samples were in the range of 10.5-12.3, whereas the pH of limerock samples was less than 9 at all L/S ratios. With a decrease in L/S, pH for RCA samples tended to increase, which could be the result of high concentrations of calcium components present and the resultant formation of hydrated lime. The dilution, however, did not cause significant pH drop. On the other hand, the pH from limerock samples was found to increase with increase in L/S, which could be the result of formation of hydrated lime ($Ca(OH)_2$) from calcareous minerals in natural aggregate. Conductivity represents the concentration of dissolved, ionized constituents that are present in a polarized solution such as water. For solutions with a high liquid-to-solid ratio, dilution effectively lowers the conductivity, whereas the opposite happens in solutions with lower liquid-to-solid ratios. Conductivity is an effective method to measure the ionic strength of a liquid. This may be beneficial to characterizing how leachate interacts with an RCA or CGR media, as it can represent ions being removed from the media itself.

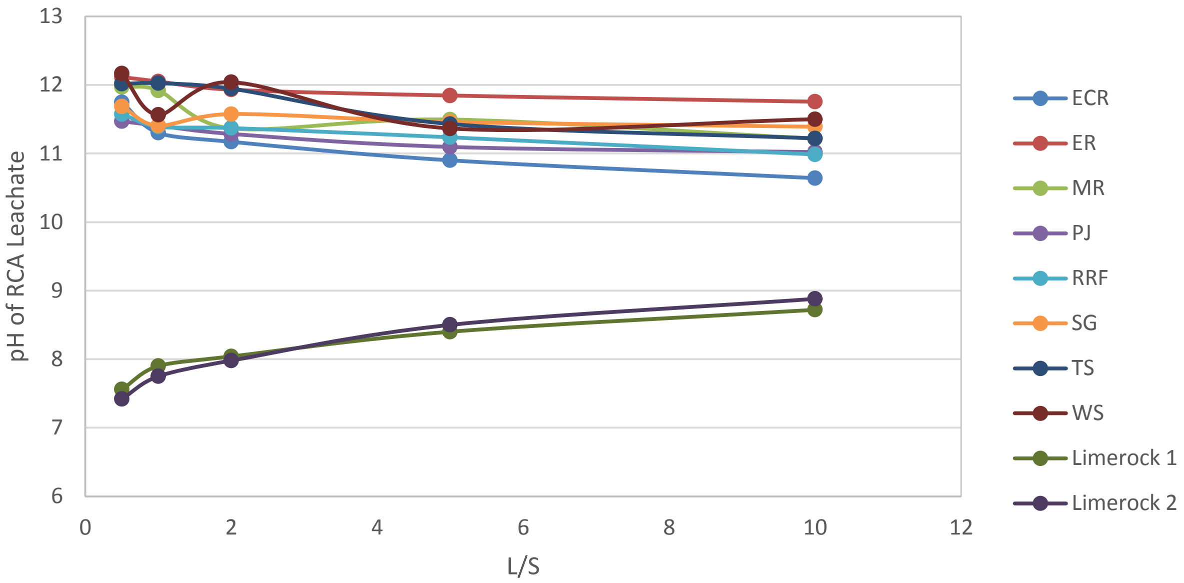


Figure 2.9. pH of leachate generated from recycled concrete aggregate samples collected from eight recycling facilities in Florida at different liquid-to-solid ratios. RCA samples were analyzed to assess the environmental impacts of RCA as road base. Data shows average pH for duplicates of each sample.

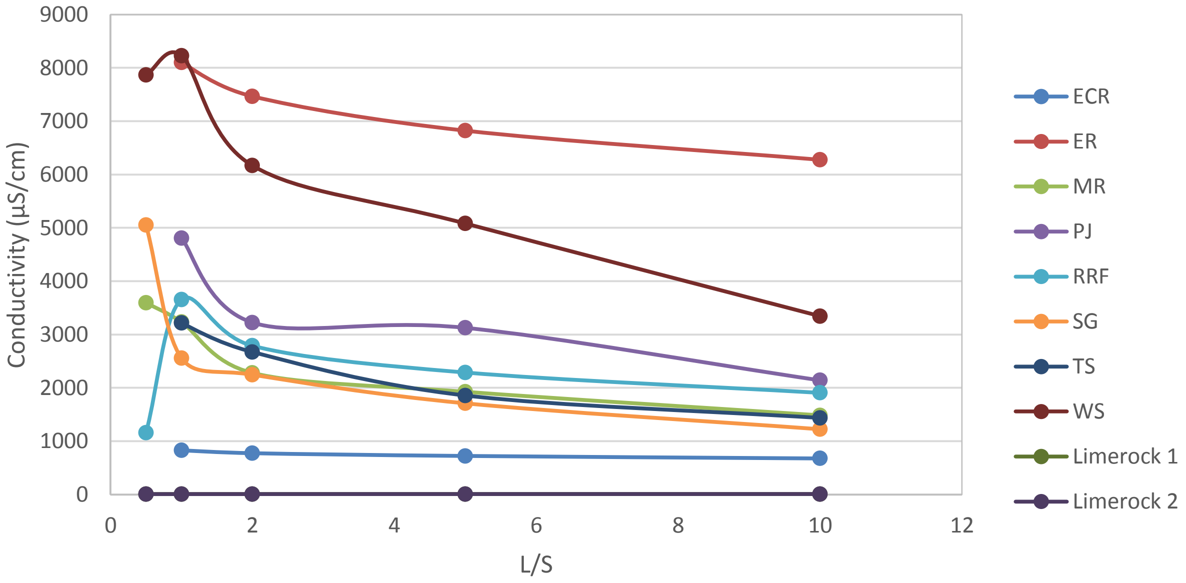


Figure 2.10. Conductivity (µS/cm) of leachate generated from recycled concrete aggregate samples collected from eight recycling facilities in Florida. RCA samples were analyzed to assess the environmental impacts of RCA as road base. Data shows average for duplicates of each sample.

Alkalinity represents the capacity of a solution to neutralize an acid. Alkalinity of filtered RCA samples was measured and reported in terms of mg/L of $CaCO_3$, values are given in Table 2.12. With a decrease in L/S ratio, the amount of $CaCO_3$ will increase and thus be exhibited by increasing alkalinity of the sample. The method of calculation for alkalinity is given in Appendix D.

Table 2.12. Alkalinity as mg/L of $CaCO_3$ of recycled concrete aggregate samples collected from eight recycling facilities in Florida. Data shows average for duplicates of each sample.

Samples	Alkalinity as $CaCO_3$ (mg/L) of RCA leachate generated from RCA samples at various L/S			
L/S	10	5	2	1
ECR	59.0	176.5	73.5	139.5
ER	1805.0	1764.2	1932.4	2029.3
MR	353.0	435.0	528.8	660.9
PJ	632.9	770.7	971.8	1612.9
RRF	621.6	649.8	1111.3	1281.1
SG	264.2	364.8	471.2	438.5
TS	188.0	291.3	209.2	355.4
WS	772.6	1148.2	1538.9	2022.3

Calcium leached from all the RCA samples at different L/S ratios are given in Figure 2.11.

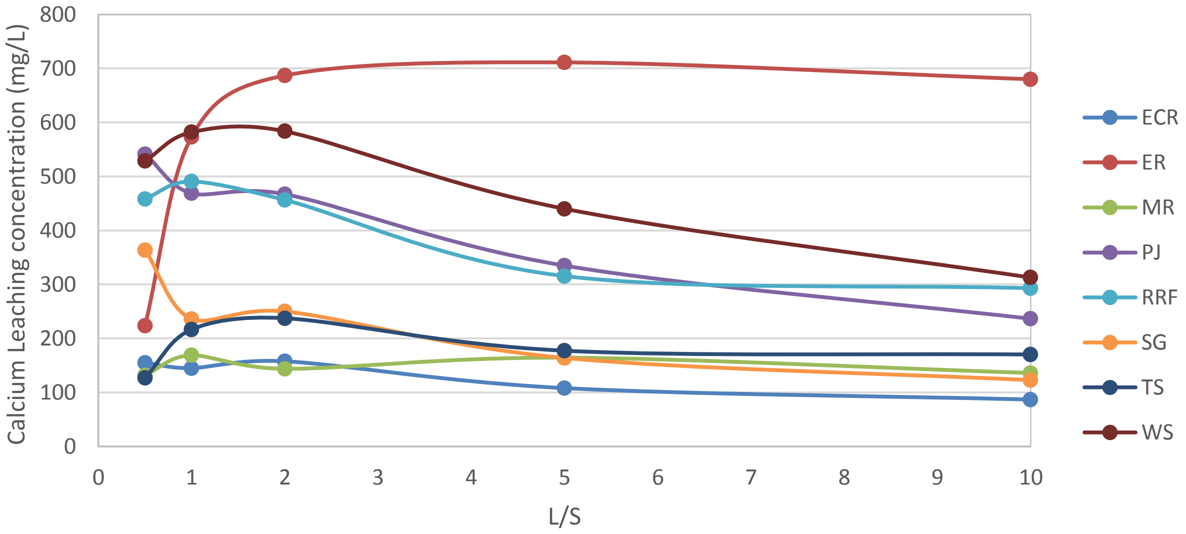


Figure 2.11. Leached concentration of calcium from extractions from recycled concrete aggregate samples at different L/S ratios. Data shows average pH for duplicates of each sample.

2.5. RCA Leachate Interaction with Soil

As seen in the previous section, RCA produces highly alkaline leachate which will interact with soil layers lying under the road base before entering groundwater. To estimate the effect of neutralization by soil, different soil samples were used.

2.5.1. Soil Sample Collection

Nine soil samples were collected from field and stockpiles; details are given in Table 2.13. FS1, FS2, FS3 soils were collected from FDOT stockpiles. FS1 and FS2 were classified as A-3 materials based on AASHTO classification system, and FS 3 was an A-2-4 type. Newnan's lake samples were collected from 0 to 25 inches in layers, NLU being the topmost layer of 0-15 inches, NLM was collected from 15-20 inches of depth and NLB from approximately 22 inches deep. Palm Point Park (PP) sample was collected west of Newnan's lake and consisted of the top 10 inches of soil. Citra soil was collected from IFAS (Institute of Food and Agricultural Sciences) farms in Citra. Lakeland soil was collected from the City of Lakeland in Polk County.

Table 2.13. Location of soil samples collected from Florida for soil interaction assessment with recycled concrete aggregate

Soil Sample	Location	Field/Stockpile
FS 1	Starvation Hill	FDOT stockpile
FS 2	Starvation Hill	FDOT stockpile
FS 3	Coastal	FDOT stockpile
NLU	Newnan's Lake, Gainesville	Field
NLM	Newnan's Lake, Gainesville	Field
NLB	Newnan's Lake, Gainesville	Field
PP	Palm Point park, Gainesville	Field
CS	Citra, Marion County	Field
LS	Lakeland	Field

2.5.2. Soil and RCA Leachate Interaction Methods

All the soil samples were tested for the moisture content and pH values. Florida method FM 1-T 265 was followed for the calculation of moisture content of soils. All the field samples were air dried for 24 hours in the hood to avoid any contamination and then oven-dried at 105˚C overnight. Calculation of the moisture content is calculated as follows.

$$MC = \frac{W1 - W2}{W1 - W_c} \times 100$$

Where, MC = moisture content of soil
W1 = mass of container and moist soil (g.)
W2 = mass of container and oven-dried soil (g.)
W_c = mass of container (g.)

The pH of each soil was measured in water following procedure from "Soil Sampling and Methods of Analysis" (Soon & Hendershot, 1993). To measure the pH, 10 g of soil was mixed with 20 mL of deionized water and stirred for 30 minutes intermittently, and then allowed to settle without stirring for 1 hour. A pH probe was then inserted to measure pH of the clear supernatant sample.

Extractable acidity was calculated following the method by (Thomas, 1982). Potassium chloride (1M) was used as replacing solution for active acidity present in soil. The sample was then filtered and titrated using 0.1 M sodium hydroxide (NaOH) until the phenolphthalein endpoint was reached. KCl-extractable acidity was then calculated as given in equations below (Dhananjaya & Ananthanarayana, 2009; Reeuwilk, 2002; Soon & Hendershot, 1993). To calculate the KCl-exchangeable aluminum acidity, 1 M potassium fluoride (KF) was used as aluminum complexing agent which will cause a dissociation of the aluminum hydroxide complexes present in solution to Al^{3+} and OH^-. The solution was then titrated using 0.1 M hydrochloric acid (HCl). Aluminum and hydrogen acidities were calculated as follows (Dhananjaya & Ananthanarayana, 2009; Reeuwilk, 2002; Soon & Hendershot, 1993)

$$KCl\ acidity = \frac{(V_1 - V_2) \times M1 \times 100}{g}$$

$$KCl\ exchangeble\ Al = \frac{V_3 \times M2 \times 100}{g}$$

$$Hydrogen\ acidity = KCl\ acidity - KCl\ exchangeable\ Al$$

Where, V_1 is the volume of NaOH added in the sample to reach the phenolphthalein pink endpoint (mL)
V_2 is the volume of NaOH added in the blank KCl solution to reach the phenolphthalein pink endpoint (mL)
V_3 is the volume of HCl added in the sample to reach the phenolphthalein clear endpoint (mL)
M1 is the molarity of NaOH used for titration (M = 0.1 M)
M2 is the molarity of HCl used for titration (M = 0.1 M)
g is the amount of soil sample (g = 10 g)

To determine the effect of the soil acidity on RCA leachate, one RCA sample (ER) was selected to analyze the soil interaction because it had high pH and alkalinity as determined in section 2.4.3. Alkaline leachates were generated using deionized water and RCA at L/S 2:1 and 1:1 for soil- RCA leachate batch tests. These leachates were mixed with 100 g of soil samples at a fixed volume of 200 mL and change in pH of RCA leachate was analyzed before and after mixing with soil.

Along with batch tests, laboratory column leaching tests were conducted on two different soil samples. RCA leachate was passed through the columns to simulate the soil column below a road base. Out of eight RCA samples, ER was selected to generate the leachate at L/S of 1:1. ER had a moisture content of approximately 15%. To achieve the L/S of 1:1, 17.5 Kg of ER was mixed with 12.5 L of deionized water. The sample mixture was rotated for 24 hours, followed by filtration using a 0.45 µm membrane. Four soil columns were installed in the laboratory with approximately 300 g of a soil sample collected from Newnan's lake (Gainesville, FL), NLU, which had a high extractable acidity. A peristaltic pump provided an upward flow of RCA leachate at 0.25 mL/min in three of the soil columns, with nanopure water used at the same flow rate in the fourth column as a control. Columns were saturated with nanopure water prior to initiating leachate flow. The eluent from the columns was collected in sealed HDPE bottles at L/S ratios of 0.2, 0.3, 0.5, 0.5, 0.5, 2.5, 0.5, 4.5 and 0.5. The samples collected add up to a cumulative L/S ratio of 10:1. All nine collections were analyzed for pH, electrical conductivity, and redox potential immediately after sampling using methods mentioned in Table 2.14. A similar test was done for low acidity soil, FS1, to check the range of neutralization offered by the variety of available Florida soils. High acidity soil columns are referred to as column H, and low acidity soil columns as column L throughout the report.

Table 2.14. Analytical methods used in the study for soil characteristics and interaction with recycled concrete aggregate (RCA) to assess neutralization offered by soil for alkaline leachate produced by RCA

Parameter	Method
Moisture content of soil	FM 1-T 265
Soil pH	Soon & Hendershot (1993)
Extractable acidity of soil	Thomas (1982), Soon & Hendershot (1993)
Leaching batch tests	EPA LEAF Method 1316
Effluent pH	SW-846 Method 9040
Effluent Conductivity	ASTM 1125

2.5.3. Soil and RCA Leachate Interaction Results

The University of Florida developed a database of various soils across Florida with chemical, physical and mechanical properties (http://soils.ifas.ufl.edu/flsoils/index.asp). Soils around Florida are usually found to vary from acidic to slightly alkaline (3.1 to 8.8). Soil samples used in this study were acidic to slightly alkaline with pH ranging from 4.5 to 8.7. Stockpiled soils were alkaline, whereas other soils were acidic; Table 2.15 shows the pH of each soil and corresponding moisture content.

Table 2.15. Moisture content and pH of soil samples used for analyzing soil-recycled concrete aggregate interaction

Soil Sample	Moisture Content	pH
FS 1	5.30%	8.32
FS 2	3.52%	8.29
FS 3	6.06%	8.69
NLU	4.78%	4.58
NLM	1.78%	4.49
NLB	2.89%	4.63
PP	4.51%	5.00
CS	4.48%	5.14
LS	1.24%	5.13

Soils possess an inherent acidity which is the ability of soil to neutralize an alkaline solution passing through it. Extractable acidity is the amount of active acidity and exchangeable acidity present in soil because of presence of hydrogen ions and aluminum complexes in the soils either bound on clay minerals or near the surface. These ions may have the capacity to neutralize alkalinity of RCA leachate entering the soil layer by reacting with and neutralizing hydroxyl ions from alkaline solution. Florida soil database found that the extractable acidity in Florida soils could vary from 0 to 192 meq/100 g of soil. Extractable acidity determined for the tested soils was low and it can be related to their pH data. Extractable acidities for soils collected from FDOT stockpiles are given in Table 2.16.

Table 2.16. KCl-extractable acidity of soil used for analyzing soil-recycled concrete aggregate interaction

Sample	Amount of Soil	pH of soil	KCl extracted-acidity per 100g soil	KCl exchangeable Al per 100g soil	H+ acidity per 100 g of soil
	(gm)		meq/100 g-soil	meq/100 g-soil	meq-H^+/100 g-soil
FS1	10	8.32	0.01	0.03	-0.02
FS2	10	8.29	0.05	0.03	0.02
FS3	10	8.69	0.03	0.09	-0.06
NLU	10	4.58	0.53	0.06	0.48
NLM	10	4.49	0.06	0.00	0.06
NLB	10	4.63	1.28	1.17	0.11
PP	10	5.00	0.13	0.00	0.13
CS	10	5.14	0.31	0.16	0.15
LS	10	5.13	0.39	0.23	0.16

Table 2.17. Soil interaction with leachate produced from recycled concrete aggregate sample collected from West Palm Beach, Florida

Sample	Soil sample (g)	Leachate sample (mL)		pH of leachate*	(pH of soil + RCA leachate) blend
		Leachate 2	Leachate 1		
FS 1	100	200	0	12.00	10.96
FS 2	100	200	0	12.00	11.07
FS 3	100	200	0	12.00	11.71
FS 1	100	0	200	12.25	11.43
FS 2	100	0	200	12.25	11.41
FS 3	100	0	200	12.25	11.69
* pH of leachate generated from RCA before mixing with soil					
Leachate 2 is generated by Water: RCA :: 2:1					
Leachate 1 is generated by Water: RCA :: 1:1					

Soil-RCA batch tests showed that slightly alkaline soil offered a pH drop ranging from 0.29-1.04 units depending on leachate used with the soil. Table 2.17 provides the comparison between pH of RCA leachate before and after mixing with different types of soils.

The pH of the filtered RCA leachate generated for use in the laboratory column tests was recorded as 11.96. The first effluent samples collected from the soil columns had a neutral pH value for both H and L columns, at pH of 6.69 and 7.21, respectively. Column H showed a significant drop in pH during early collections, reaching values as low as 3.97, followed by an increase in pH with the increase in L/S. The decrease in pH was accompanied by the presence of organic material dissolved in the effluent. The severe drop in pH may be explained by the presence of reduced metals in reduced form, such as iron, creating metal complexes and causing the subsequent increase in acidity. Samples taken at the time of the pH drop were analyzed for ferrous iron using a spectrophotometer. The results showed approximately 0.35 mg/L ferrous iron in the column H effluent. As the experiment continued, the pH steadily rose back to the pH of the original RCA leachate. Column L started at neutral pH similar to column H, but had a continuous increase in pH with increase in L/S. Both of the columns reached the pH of approximately 12 by the time the L/S of 10:1 was reached. Since the column experiments were performed in triplicate, the average values were calculated and plotted against L/S ratio for both high and low acidity soils. Figure 2.12 shows the change in pH of effluent samples collected at different L/S values for column H and L. ORP and conductivity analyses were also performed on each of the samples, and plotted in Figure 2.13 and 2.14, respectively.

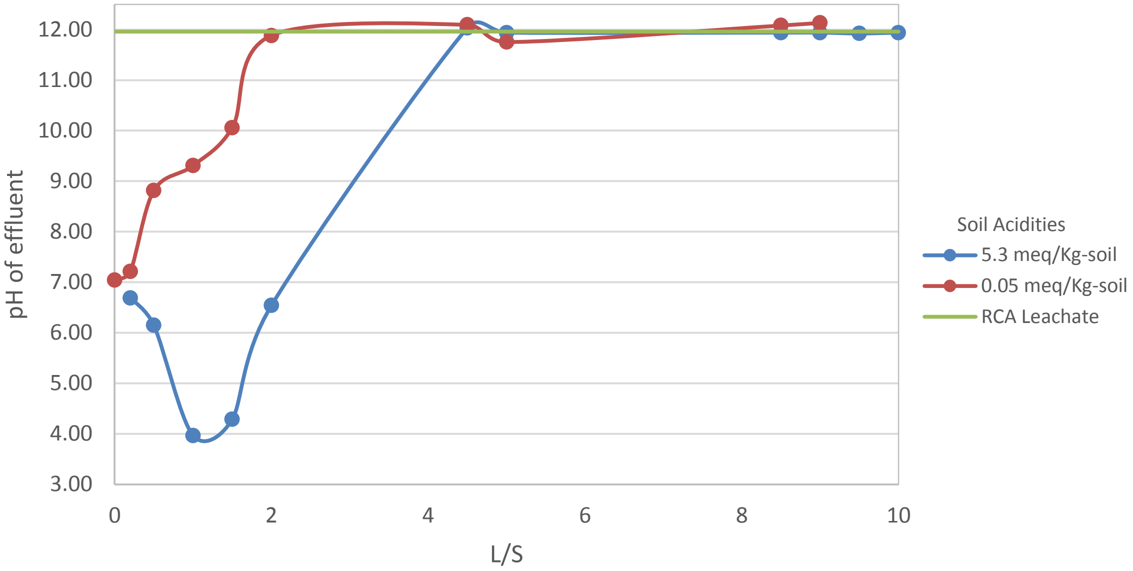


Figure 2.12. Change in pH of the effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through a soil column of high acidity soil and a soil column of low acidity soil. Effluent samples were collected at different L/S ratio. The initial pH of the RCA leachate was 11.96 before passing through soil column.

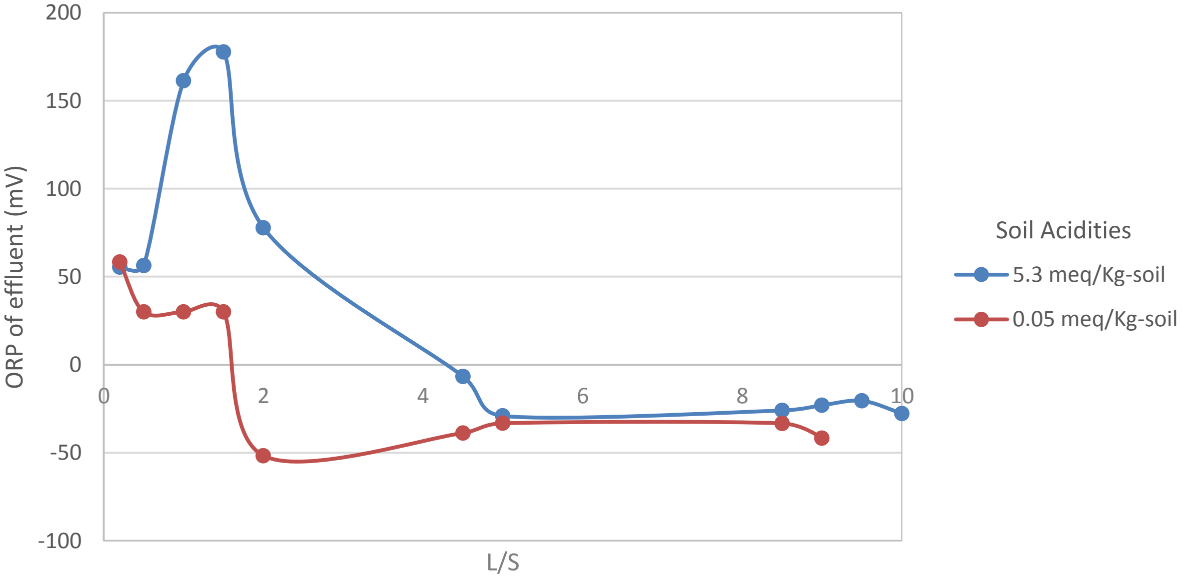


Figure 2.13. Change in ORP of the effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through a soil column of high acidity soil and a soil column of low acidity soil. Effluent samples were collected at different L/S ratio.

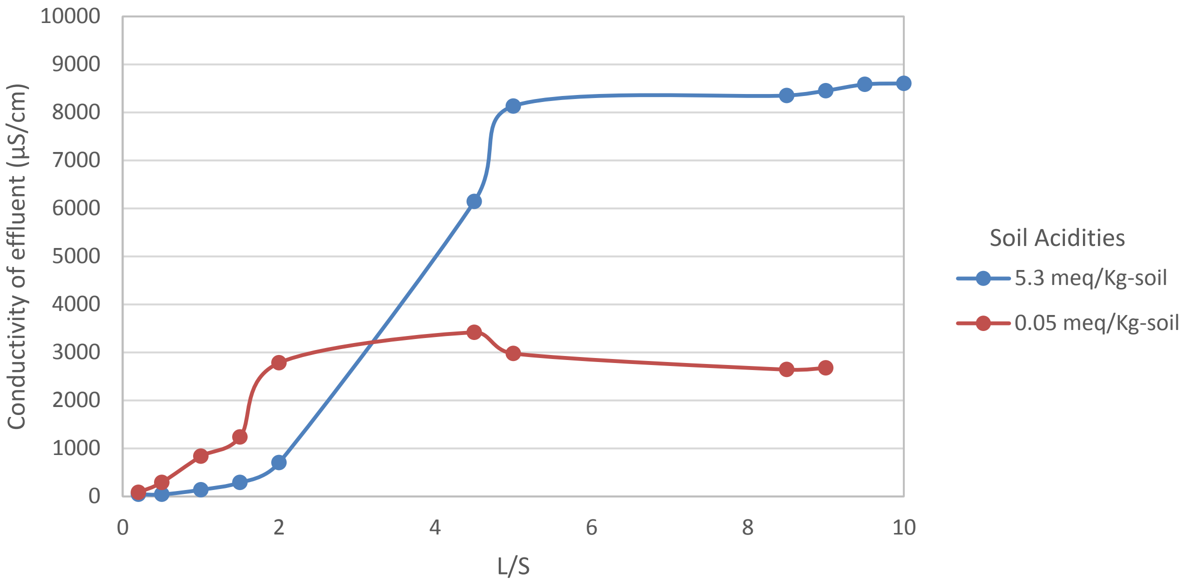


Figure 2.14. Change in conductivity of the effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through a soil column of high acidity soil and a soil column of low acidity soil. Effluent samples were collected at different L/S ratio.

Detailed results for all the triplicate soil columns and control are given in Appendix F and G for high acidity soil and low acidity soil, respectively.

2.6. Risk Assessment

As described earlier, the two primary issues of concern with respect to environmental and human health risk evaluated in this study were elevated pH and heavy metals. Heavy metals leaching was evaluated through a literature review, while the pH risk was evaluated through both a literature review and laboratory testing of Florida RCA samples. In this section, the potential risk posed by RCA in an application such as road base is assessed and discussed using the information presented already in this report.

A review of existing studies on RCA leaching did find that heavy metals are present at relatively small concentrations in RCA, a result of their occurrence in natural aggregates and possible waste products, as well as contact with chemicals during the normal life of the concrete. Total elemental analysis of RCA found the presence of barium, copper, nickel, cobalt, arsenic and chromium as major elements. All the elements except arsenic were found to meet the residential as well as commercial soil clean-up target levels for Florida, which are based on direct human exposure risk. Arsenic met the commercial SCTLs but exceeded the residential target (Chen et al., 2012a; Chen et al., 2013; Engelsen et al., 2006). Antimony, arsenic, chromium, copper, lead, molybdenum, nickel, and selenium were detected in the leaching analysis. Most of the elements were found to meet the regulatory limits of ground water, whereas arsenic, chromium, and lead exceeded the primary drinking water standards of 10, 15, and 100µg/L respectively for most of the samples at some occasions (Engelsen et al., 2012). Depending on the source of RCA, leaching of metals would differ. For example, RCA from Wisconsin site studied by Chen et al. (2012a) leached antimony and selenium above the drinking water standards (Chen et al., 2012a). pH dependent leaching tests shows high leaching of iron and doesn't meet the secondary drinking water standards at acidic and neutral pH range (Aydilek, 2015).

The results from the literature suggest that while contaminants leaching from RCA would likely be small and attenuated in the environment, the degree of risk posed in the Florida environment cannot be directly assessed without leach testing of RCA samples from Florida and application of a pollutant distribution and attenuation model for representative Florida-specific conditions.

The literature review indicated that water coming into contact with RCA would possess an elevated pH, and the laboratory data gathered confirmed this observation. pH measurements on RCA samples collected from eight concrete recycling facilities in Florida observed pH values to range from 10.5 to 12.3. These high pH values may be toxic to aquatic life. Increase in pH would produce free ammonia from its salts and may lead to death of most fish.

An EPA leaching procedure was conducted to evaluate how pH would change as function of the amount of water that passed (EPA method 1316). With decrease in liquid-to-solid ratio, amount of calcium present in the sample increased and thus the release of hydroxyl ions which lead to an increase in pH. At L/S of 0.5, average pH observed was 11.8 in contrast to 11.2 for L/S of 10.

The results clearly demonstrate that water passing through RCA will be elevated in pH, and that pH will remain elevated for a prolonged period. So assuming that elevated pH is problematic, the question that must be addressed is "to what extent will the pH be reduced in the environment because of environmental conditions or simple dilution?" Consider Figure 2.15 which conceptualizes the travel of high pH leaching solution from RCA used as a road base into the underlying environment. As the RCA leachate passes through the soil column underneath the RCA, several reactions will occur to reduce the pH of the leachate. These include reactions with soil acidity as described in the previous section, and carbonation of the soil water solution as a result carbon dioxide in the soil pore space produced by soil biological activity. Once this leachate reaches the groundwater, the pH will be diluted as a result of mixing with the lower-pH groundwater and the reaction of hydroxide with the acidity of the groundwater. These different mechanisms are assessed below.

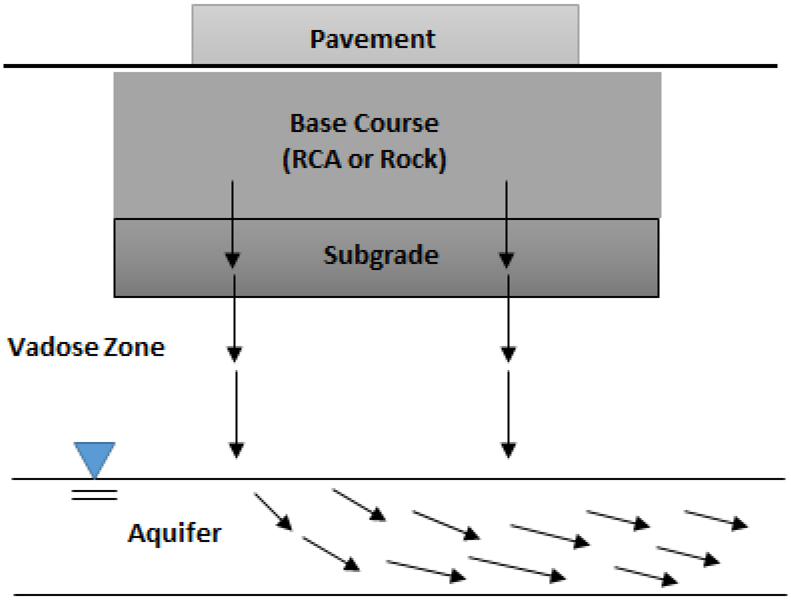


Figure 2.15. Conceptual modeling approach of the pH zone of impact to analyze the changes in pH that will be caused by leaching through the RCA base

The neutralization of pH as a result of carbon dioxide in the soil porosity and as a result of the soil acidity is illustrated through the following reactions.

$$CO_2(g) \leftrightarrow CO_2(aq)$$

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3$$

In the above reactions gas phase carbon dioxide is absorbed by water and is partially converted to carbonic acid (H_2CO_3). It is difficult to distinguish between carbonic acid and dissolved carbon dioxide in typical analytical procedures, so the combination of the two chemicals are referred to as $H_2CO_3^*$ as shown below.

$$[CO_2(aq)] + [H_2CO_3] = [H_2CO_3^*]$$

The bracketed terms refer to molar concentrations of the respective chemicals. $H_2CO_3^*$ is a weak acid and dissociates to produce two hydrogen ions as shown below,

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \ , \qquad pK_{a1} = 6.35$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \ , \qquad pK_{a2} = 10.33$$

The extent of the dissociation is dependent on the pH of the solution. At near neutral pH only the first dissociation takes place, but in high pH solutions, such as RCA leachate, both hydrogen ions are likely to be released. These hydrogen ions then react with hydroxide resulting in a pH depression.

$$H^{+} + OH^{-} \leftrightarrow H_2O$$

In order to assess the potential for carbon dioxide in the porosity to affect the pH, a desktop analysis was performed. The following assumptions were made:

- Field moist soil density = 1.5 g/cc
- Soil porosity = 0.4
- Partial pressure of carbon dioxide = 0.05 atm. (This represents 5 % of the gas in the pore space. Typical soil values range from 1 to 5 %, and for context, the atmosphere contains about 0.04 %.)

The pH of the RCA leachate was assumed to be 12.3, which is a pH that would be produced if calcium hydroxide solid would be allowed to equilibrate with water, and this pH value is consistent with both values reported in the literature and laboratory analysis reported elsewhere in this report. Under these conditions, which would tend to maximize neutralization (using the extreme of the carbon dioxide partial pressure range), calculations showed that there was no appreciable pH reduction. This analysis assumes that additional carbon dioxide is not generated by biodegradation of organic matter in the soil. If additional carbon dioxide was generated by microbial activity in the lower portion of the vadose zone, it would contribute to additional neutralization of the percolating leachate and may have an effect of decreasing the pH.

As indicated above, the dissociation of $H_2CO_3^*$ produces the carbonate ion (CO_3^{2-}), which in the presence of calcium will precipitate as calcium carbonate ($CaCO_3(s)$).

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3(s)$$

Calculations show that all of the carbonate produced by the dissociation of $H_2CO_3^*$ would react, but this reaction would still not have an appreciable effect on the pH.

In addition to reaction with carbon dioxide, the RCA leachate will react with soil acidity, which will tend to reduce the pH of the leachate. Soil acidity can be divided between “exchangeable” acidity and “hydrolytic “acidity. While hydrolytic acidity is characterized by hydrogen ions in the soil, exchangeable acidity is associated with soil cations such as aluminum, which once released from the soil into water react to form alumino-hydroxo species and release hydrogen ions, as shown in the equations below. These hydrogen ions will then neutralize a portion of the RCA leachate hydroxide ions and lower the pH.

$$Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^{+}$$

$$Al^{3+} + 2H_2O \leftrightarrow Al(OH)_2^{+} + 2H^{+}$$

$$Al^{3+} + 3H_2O \leftrightarrow Al(OH)_3(s) + 3H^{+}$$

$$Al^{3+} + 4H_2O \leftrightarrow Al(OH)_4^- + 4H^+$$

In order to assess the effect of soil acidity on the pH of the RCA leachate, neutralization calculations were performed for soil acidities ranging from 50 to 900 meq/kg. This range has been observed in reports of chemical properties for Florida soils (http://soils.ifas.ufl.edu/flsoils/index.asp). Calculations were performed for the following conditions:

- RCA leachate initial pH = 12.3
- Liquid (liters of water) to solid (kilograms of soil) ratios between 5 and 100.
- Soil and water mixtures were considered to equilibrate for the calculations

The resulting calculated titration of the RCA leachate with hydrogen ions associated with the acidity of the soil produced the typical steep titration curve where the pH will gradually decrease to about 10.5 and then drop steeply to lower pH values. Because the exchangeable acidity is assumed to react only when there is substantial hydroxide for the reaction, soils with higher milliequivalent (meq) acidities than the concentration of meq of hydroxide in the RCA leachate were considered to be unreactive. Equilibrium calculations resulted in a moderate depression of pH at low L/S ratios as shown in the Figure 2.16 below. It should also be noted that after successive pore volumes of leachate pass through the soil, the acidity and its corresponding neutralizing capacity will be expended, and accordingly the RCA leachate will then percolate through the soil without neutralization.

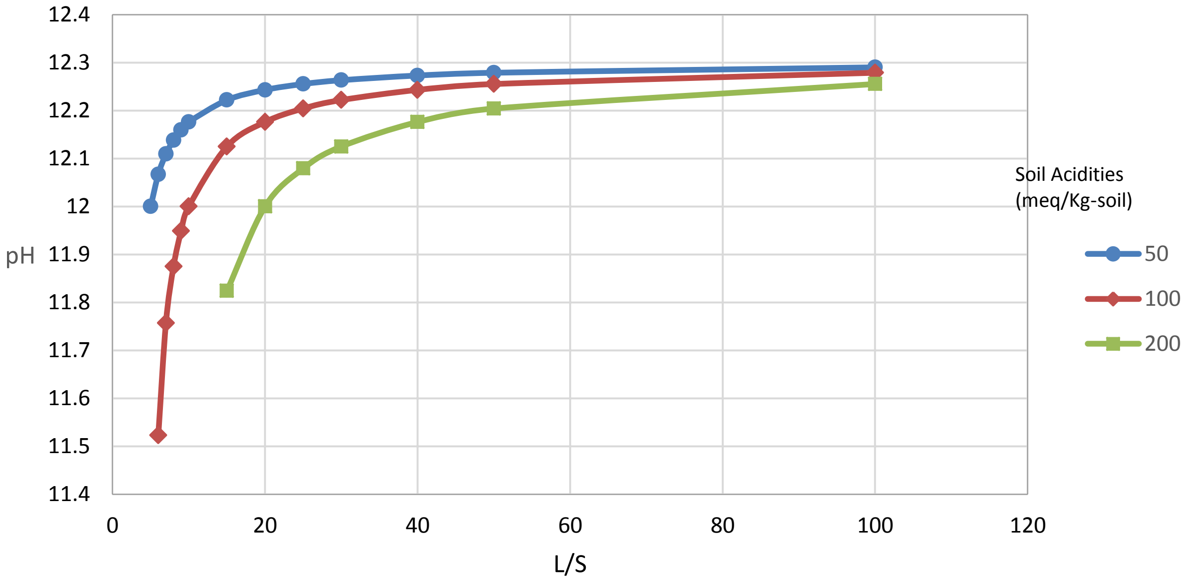


Figure 2.16. Change in pH values of leachate passing through soil with different soil acidities as a function of liquid-to-solid ratio

After the leachate has passed through the vadose zone below the RCA base layers of the roadway, the leachate will enter and mix with groundwater. In addition to dilution, the high pH leachate will tend to react with and thereby be partially neutralized by the acidity present in the groundwater, further reducing the pH. Acidity in groundwater is caused by different chemical species than acidity in soils. In water, acidity is caused by hydrogen ion, bicarbonate ion and $H_2CO_3^*$. In most groundwater, the inorganic carbon species, bicarbonate and $H_2CO_3^*$, provide most of the neutralizing capacity.

In order to assess the neutralizing potential of the groundwater and thereby the resulting pH of the mixture of the leachate with groundwater, calculations were made based on equilibrium principles. It is important to note that while the rate of reactions in soils may be slow, acid-base neutralization reactions in water are quite rapid, and are typically controlled by the rate of mixing. Accordingly, equilibrium calculations tend to be more accurate in water than in soils. The neutralization reactions shown below are complex and require many variable assignments. Accordingly, the calculation approach made the following assumptions for initial assessment:

- The groundwater has a pH of 7.5, a typical groundwater value in Florida
- Groundwater alkalinities of 50, 100 and 200 mg/L as $CaCO_3$ were investigated. Alkalinity was specified, as opposed to acidity, because alkalinity is easier to measure than acidity, and accordingly, it is more often specified as a water quality parameter than acidity. Assuming that alkalinity and acidity are functions of the pH and the total carbonate concentration (TOTCO3), which is a good assumption for Florida groundwater, knowing the alkalinity and pH of water allows the calculation of its acidity.
- A range of dilution factors (DF) from 2 to 100 were assessed. For example, for a DF of 5, one liter of leachate was theoretically mixed with 5 liters of groundwater.
- To provide a worst case scenario, a leachate pH of 12.3 was chosen. As discussed above, once the carbon dioxide and soil acidity have been reacted, the leachate will pass through the vadose zone soil without neutralization, so a pH of 12.3 is realistic for long-term investigations. On the other hand ground water is moving, so its neutralization capacity will be sustained with time, depending on the DF used.
- A groundwater calcium concentration of 1.0 mM and an ionic strength of 0.01 M were assumed.

The neutralization reactions are:

$$OH^- + H^+ \leftrightarrow H_2O, \quad pK_w = 14$$

$$OH^- + HCO_3^- \leftrightarrow CO_3^{2-}, \quad pK_{a1} = 6.35$$

$$2OH^- + H_2CO_3 \leftrightarrow CO_3^{2-}, \quad pK_{a2} = 10.33$$

These equilibrium equations were solved simultaneously with mass balances and a charge balance for the mixture to obtain resulting pH values as a function of dilution factors and alkalinity. Results of these equilibrium calculations are shown in the Figure 2.17 below.

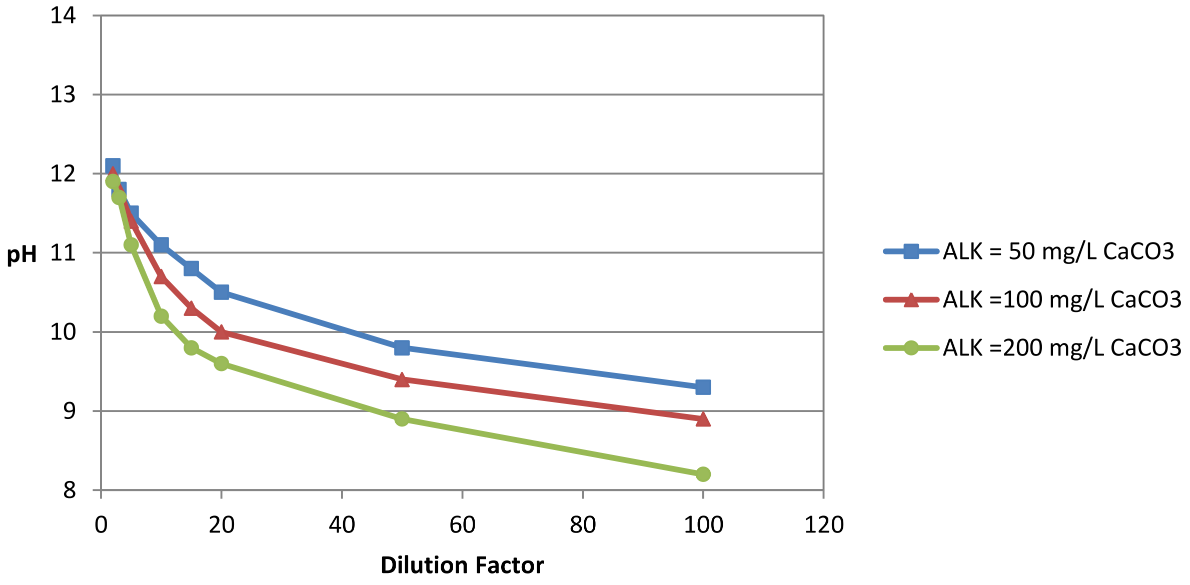


Figure 2.17. Change in pH of RCA leachate as a function of dilution factor from dilution of leachate into groundwater with different alkalinities of leachate.

As shown, an appreciable pH decrease was calculated with groundwater of this nature at high dilution factors. Also of interest is that the higher the alkalinity of the groundwater, the greater the neutralizing effect (the lower the resulting pH). This may appear to indicate that an alkaline leachate can be neutralized by alkalinity, but the neutralization is actually the reaction of the acidity of the groundwater with the leachate. As explained above, the acidity and alkalinity are related, and for pH values in the vicinity of neutrality, as the alkalinity increases, the acidity increases.

The resulting solutions after mixing are supersaturated with calcium carbonate, as the high calcium concentrations of the RCA leachate combine with the carbonates in the groundwater as well as the groundwater calcium concentrations. The figure above represents the pH of these supersaturated solutions. With time the supersaturated solution will come to equilibrium as calcium carbonate precipitates.

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3(s)$$

$$Ca^{2+} + HCO_3^{-} \leftrightarrow CaCO_3(s) + H^{+}$$

This calcium carbonate precipitation will cause an additional decrease in the pH. Preliminary calculations, not completed and verified at this time, indicate that the pH may decrease an additional 1 to 2 pH units.

Once the RCA solution reaches the underlying groundwater, the resulting pH of the groundwater will depend on the relative amount of RCA leachate interacting with the groundwater, as well as the chemistry of the RCA leachate and the groundwater.

High pH water solutions can cause aluminized metal piping to corrode. Although aluminum has a high potential to corrode, the initial corrosion causes the formation of an adherent aluminum oxide (Al_2O_3) coating on the pipe that resists further corrosion. High pH conditions tend to breakdown this adherent coating to form hydroxyl aluminate ions, thereby exposing the aluminum to further corrosion as shown in the following reaction:

$$Al_2O_3 + 2OH^- + 3H_2O \rightarrow 2Al(OH)_4^-$$

The aluminum will continue to corrode forming the hydroxyl aluminate ions until the underlying metal is exposed and begins to corrode.

Although this phenomenon was not in the scope of this study, is should be of concern when elevated pH water makes contact with aluminized pipe. Indeed, this enhanced corrosion was observed by Setiadi et al. (2006) for aluminum in contact with composite cements at high pH and by Akhoondan et al. (2013) for aluminum in contact with limestone backfill.

2.7. Data Gaps

The scope of the research presented included the measurements of pH from RCA leachate and the determination of the potential for soil to neutralize RCA leachate pH. Laboratory experiments did find that soil could neutralize pH to a degree under batch conditions. However, column tests indicated limited capability of soil to neutralize alkaline RCA leachate over time. Additionally, modeling of pH in the subsurface (both the soil underneath an RCA base and in the underlying groundwater) supports that pH will be reduced as a result of both neutralization by soil acidity and dilution with natural water. Both the laboratory and modeling analysis do suggest, however, that pH will still remain elevated under many scenarios. What could not be accounted for as part of this work effort were transient effects (how these reactions would proceed over time) and the conditions that would be likely to occur under natural environmental conditions. In several of the literature studies, for example, the long-term benefit of carbonation on neutralizing pH was described. Additional experiments would need to be conducted to better examine how RCA leachate passing through a soil column under more representative environmental conditions is neutralized. The potential deleterious effects of RCA leachate on metal pipe corrosion was not evaluated as part of this study.

Heavy metal leaching from RCA was not evaluated as part of this study. Previous studies from the literature did find some small concentrations of heavy metals to leach under certain scenarios. No examples of RCA use causing groundwater contamination were uncovered in the literature review. The degree to which Florida RCA would leach and migrate into the environment was not specifically assessed as part of this research and thus remains a data gap.

3.0. Appropriate Management of Concrete Grinding Slurry

3.1 Background and Motivation

Over time, Portland cement concrete (PCC) pavement surfaces wear unevenly and can lead to various types of failure. Rather than replacing entire PCC slabs, the surface can be evened out using diamond grinding. The diamond grinding process generates heat and produces a fugitive dust. This dust is controlled with water, which cools the grinding pavement surface and wets the dust to generate slurry. The slurry is then vacuumed into a slurry tanker for management. CGR slurry is also generated during joint cutting operations in new PCC pavement construction. Finally, the FDOT has mandated that all new PCC road surfaces be ground to ensure that the road surface is even. The generated CGR slurry has a relatively high pH, alkalinity, and salt content. The grinding process may also mobilize trace metals that would otherwise remain encapsulated within the concrete. Proper disposal methods for CGR should be used, and the potential for harm to the environment should be studied.

3.2 CGR Fundamentals

CGR is produced from the grinding of PCC, and therefore, is similar in makeup to PCC. Older slabs of PCC that had long exposure to traffic may generate CGR with some trace metals that have been introduced from soil or automobiles. CGR slurry has a solids content that ranges from 5% to 10% by mass, and a particle size that is typically smaller than 53 µm. CGR slurry, due to the fact that it is a product of concrete, has a high pH, which can range from 11.50 to almost 12.50. The presence of calcium hydroxide from interactions with calcium oxide and water in CGR slurry also makes it very alkaline, which will be discussed in further detail in this report.

CGR slurry is managed in several different ways. CGR is often dumped along the roadside or stored in retention ponds. If not handled responsibly, this slurry may pose some environmental concerns related to the potential adverse interactions with the environment.

3.3 Literature Review

3.3.1 Characterization and Analysis of CGR

Concrete often contains various metal oxide compounds. These compounds contribute to the high pH and high alkalinity of the CGR. Typical oxide compounds that are found in CGR slurries include silica, iron oxide, alumina, lime, and magnesia. Results from an analysis of CGR slurries sponsored by the International Grooving and Grinding Association (IGGA) are provided in Table 3.1. Calcium hydroxide is a compound formed when calcium oxide reacts with water. It is a major contributor to high pH and alkalinity in the slurry. CGR slurries with higher concentrations of calcium hydroxide usually have a pH range of 10 to 12.5. The high pH is a concern when deciding how to dispose of CGR slurries. Inappropriate disposal of the slurry can have negative impacts on the environment. The high alkalinity may have negative impacts on flora growth rates and biomass. The resulting increase in acid buffering ability due to high alkalinity may help protect flora and watersheds from acidification.

Table 3.1. Results of CGR samples analyzed for metal oxides, in percent by mass, from an independent laboratory in North Carolina. Samples were taken from grinding projects in Delaware, Pennsylvania, and South Carolina. The project was sponsored by the International Grooving and Grinding Association. (IGGA 1990)

Sample	1	2	3	4	5	6	7
Silica (SiO_2)	15.60	12.95	13.10	16.90	18.10	19.10	16.20
Iron Oxide (Fe_2O_3)	1.40	1.60	1.95	1.65	1.40	1.31	1.29
Alumina (Al_2O_3)	1.80	1.70	1.25	1.65	1.28	1.16	1.40
Lime (CaO)	25.60	24.10	20.90	26.50	30.70	27.10	29.60
Magnesia (MgO)	0.85	0.96	1.10	0.87	0.97	1.20	0.89

Physically, dried CGR is a solid material that can range from silt-sized particles (0.002 mm) to sand sized particles (2 mm). A Nebraska Department of Roads (NDOR) study indicated that particles from 0.002 – 0.02 mm made up between 45 to 60 % of the mass of CGR, particles ranging from 0.02 – 0.2 mm made up 20 to 30 % of the mass of the CGR, and particles ranging from 0.2 – 2 mm made up 15 to 35 % of the mass of the CGR. (Mamo et al., 2015) The particle size distribution of CGR may vary with the type of aggregate used in the parent concrete and with the type of grinding/grooving that is conducted. The grooving and grinding processes use large volumes of water as the CGR is removed from the pavement surface. CGR slurry typically has a moisture content of approximately 90% (Holmes et al., 1997).

The presence of calcium oxide in CGR is considered the main cause of the elevated pH of the slurry. Holmes et al. (1997) found that initial pH of a slurry with a 10% solids content ranged from 9.40 to 11.10. After 24 hours, however, these pH values decreased to a range of 8.23 to 9.63. DeSutter et al. (2010) reported pH values from five samples ranging from 11.6 to 12.5. These samples also showed a high total dissolved solids (TDS) content, ranging from 1420 to 5430 mg/L. Total Solids (TS) analysis was also conducted on the samples. These pH, TDS, and TS values are presented in Table 3.2 (DeSutter et al. 2010). The U.S. Code of Federal Regulation Title 40 Chapter 261 states that a solid waste substance with a pH greater than 12.5 is considered corrosive and must be treated as a hazardous waste. Even though none of the results reported in the literature present a pH greater than 12.5, some samples are relatively close, one being 12.5.

Table 3.2. Physical parameters of the solution phase of concrete grinding slurry from U.S. roadways. Samples were taken from interstate grinding operations in 5 different states. (DeSutter et al. 2010)

Parameter	U.S. roadway identification and location				
	10/CA	94/MN	82/WA	69/MI	75/NE
pH	12.5	11.8	11.6	12.2	11.6
TDS (mg/L)	3040	5430	1420	4100	3580
TS (%)	21.7	15.5	20.3	40.9	48.1

CGR can potentially contain various organic and inorganic compounds. Prior to disposal, it is important to understand the specific constituents of CGR. In a 1997 study by Holmes et al. (1997), six CGR samples were analyzed for volatile organic compounds (VOCs), semi-volatile compounds, and metals. Several samples showed small amounts of benzene, toluene, and petroleum hydrocarbons. Several samples also indicated small amounts of various metals (Holmes et al. 1997). The results from these analyses are in Tables 3.3 through 3.10. Another survey, sponsored by the International Grooving and Grinding Association (IGGA,1990), collected seven samples from Delaware, Pennsylvania, and South Carolina and analyzed them for both organics and inorganics. The analyses were conducted by an independent lab in North Carolina. For all samples, the concentrations of the organic and inorganic constituents were below Environmental Protection Agency (EPA) and Florida Commercial/Industrial Soil Cleanup Target Levels (International 1990). The results of this survey are in Table 3.13. Similar results for CGR composition were found by DeSutter et al. (2011) on five different samples.

Table 3.3. Filtrate analytical results for VOCs and halogenated organics, in mg/L, compared to both Florida groundwater cleanup target levels (GCTL) and U.S. primary drinking water standards. ND indicates not detected. (Holmes et al. 1997)

Sample	Volatile Organic Compounds (VOCs)				Halogenated Organics	
	Benzene	Toluene	Ethylbenzene	Xylene	Pesticides/ PCBs	Chlorinated Herbicides
S001 Filtrate	0.00076	0.00078	ND	ND	ND	ND
S002 Filtrate	ND	0.00057	ND	ND	ND	ND
S003 Filtrate	ND	0.00063	ND	ND	ND	ND
S004 Filtrate	0.00056	ND	ND	ND	ND	ND
S005 Filtrate	ND	0.00071	ND	ND	ND	ND
S006 Filtrate	0.0011	ND	ND	ND	ND	ND
Florida GCTL[1]	0.001	0.040	0.030	0.020	Note 2	Note 2
U.S. Primary Drinking Water Standards	0.005	1	0.7	10	Note 2	Note 2

1. Florida Administrative Code 62-550 (Benzene: FL Primary Drinking Water Standard; Toluene, Ethylbenzene, Xylene: FL Secondary Drinking Water Standards)
2. Regulatory threshold depends on chemical of interest

Table 3.4. Filtrate analytical results for petroleum components and semi-volatile organics, in mg/L, compared to Florida groundwater cleanup target levels (GCTLs) and U.S. primary drinking water standards. ND indicates not detected. None indicates no standard. (Holmes et al. 1997)

Sample	Petroleum Components		Semi-Volatiles	
	Oil & Grease	Total Petroleum Products	Benzoic Acid	Phenanthrene
S001 Filtrate	19.1	29	0.76	ND
S002 Filtrate	6.1	13	0.32	ND
S003 Filtrate	15.5	6.9	0.14	ND
S004 Filtrate	19.4	14	0.27	ND
S005 Filtrate	6.6	9.1	0.065	ND
S006 Filtrate	3.5	7.9	0.12	ND
Florida GCTL	None	None	28	0.21
U.S. Primary Drinking Water Standards	None	None	None	None

Table 3.5. Filtrate analytical results for trace metals, in mg/L, compared to Florida groundwater cleanup target levels (GCTL) and U.S. primary drinking water standards. ND indicates not detected. None indicates no standard. (Holmes et al. 1997)

Sample	Trace Metals																
	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Lead	Mercury	Molybdenum	Nickel	Selenium	Silver	Thallium	Vanadium	Zinc
S001 Filtrate	0.006	0.006	0.1	ND	ND	0.11	ND	0.27	ND	ND	0.05	0.03	0.009	ND	ND	ND	ND
S002 Filtrate	0.009	0.033	4.35	ND	0.0013	0.11	0.04	0.12	0.046	ND	0.04	0.1	0.004	ND	ND	0.11	0.19
S003 Filtrate	ND	ND	0.1	ND	ND	0.05	ND	0.06	ND	ND	0.02	ND	ND	ND	ND	0.03	ND
S004 Filtrate	ND	ND	0.08	ND	ND	0.07	ND	0.06	ND	ND	0.03	ND	ND	ND	ND	0.04	ND
S005 Filtrate	0.004	ND	0.08	ND	ND	0.04	ND	0.002	0.002	ND	0.02	0.02	ND	ND	ND	0.04	ND
S006 Filtrate	ND	ND	0.1	ND	ND	0.07	ND	0.03	0.004	ND	0.04	0.02	ND	ND	ND	0.04	0.03
Florida GCTL[1]	0.006	0.01	2	0.004	0.005	1	0.14	1	0.015	0.002	0.035	0.1	0.05	0.1	0.002	0.049	5
U.S. Primary Drinking Water Standards	0.006	0.010	2	0.004	0.005	0.1	None	1.3[2]	0.015[2]	0.002	None	0.1	0.05	None	0.002	None	None

1. Florida Administrative Code 62-550 (Antimony, Arsenic, Barium, Beryllium, Cadmium, Lead, Mercury, Nickel, Selenium, Thallium: FL Primary Drinking Water Standards; Copper, Silver, Zinc: FL Secondary Drinking Water Standards)
2. U.S. EPA Drinking Water Standards. Copper and lead are regulated by techniques that are used to control corrosiveness in water. These are called action levels, and call for further steps when specified thresholds are reached.

Table 3.6. Filtrate analytical results for other metals and anions, in mg/L, compared to Florida groundwater cleanup target levels (GCTL) and U.S. primary drinking water standards. ND indicates not detected. None indicates no standard. (Holmes et al. 1997)

Sample	Metals					Anions				
	Aluminum	Magnesium	Silica	Iron	Calcium	Chloride	Total Cyanide	Nitrate/Nitrite	Sulfate	Sulfide
S001 Filtrate		0.92	38.1		462	218	0.03	17.5	584	ND
S002 Filtrate	30.2	32.6	65.1	25.5	654	134	0.02	7.2	448	ND
S003 Filtrate	ND	6.59	22.7	0.14	207	135	ND	6.6	376	ND
S004 Filtrate	ND	0.33	32	0.08	335	144	0.02	12.5	611	ND
S005 Filtrate	2	15	27.1	1.72	168	153	0.02	13	475	ND
S006 Filtrate	3.4	12.6	30.7	3.15	212	133	0.02	14.5	435	ND
Florida GCTL[1]	0.2	None	None	0.3	None	None	0.2	10	250	None
U.S. Primary Drinking Water Standards	None	None	None	None	None	None	0.2	10	None	None

1. Florida Administrative Code 62-550 (Total Cyanide, Nitrate/Nitrite: FL Primary Drinking Water Standard; Aluminum, Iron, Chloride, Sulfate: FL Secondary Drinking Water Standards)

Table 3.7. Solids analytical results for VOCs and halogenated organics, in mg/kg, compared to Florida commercial/industrial soil cleanup target levels (SCTLs). ND indicates not detected. None indicates no standard. (Holmes et al. 1997)

Sample	Volatile organics (VOCs)				Halogenated organics	
	Benzene	Toluene	Ethylbenzene	Xylene	Pesticides/PCBs	Chlorinated herbicides
S001 Solids	ND	ND	ND	ND	ND	ND
S002 Solids	ND	ND	ND	ND	ND	ND
S003 Solids	ND	ND	ND	ND	ND	ND
S004 Solids	ND	ND	ND	ND	ND	ND
S005 Solids	ND	ND	ND	ND	ND	ND
S006 Solids	ND	ND	ND	ND	ND	ND
Florida SCTL	1.7	60000	9200	700	2.6	None

Table 3.8. Solids analytical results for petroleum components, semi-volatile organics, and organic lead, in mg/kg, compared to Florida commercial/industrial soil cleanup target levels (SCTLs). ND indicates not detected. None indicates no standard. (Holmes et al. 1997)

Sample	Petroleum components		Semi-volatiles		
	Oil & grease	Total petroleum products	Benzoic acid	Phenanthrene	Organic lead
S001 Solids	14	16	ND	ND	ND
S002 Solids	640	46	ND	ND	ND
S003 Solids	120	41	ND	ND	ND
S004 Solids	54	24	ND	ND	ND
S005 Solids	160	62	ND	ND	ND
S006 Solids	110	29	ND	ND	ND
Florida SCTL	None	None	None	36000	None

Table 3.9. Solids analytical results for trace metals, in mg/kg, compared to Florida commercial/industrial soil cleanup target levels (SCTLs). ND indicates not detected. (Holmes et al. 1997)

Sample	Trace Metals																
	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Lead	Mercury	Molybdenum	Nickel	Selenium	Silver	Thallium	Vanadium	Zinc
S001 Solids	ND	8.4	190	ND	ND	6.8	2.4	15	6.3	ND	ND	7.9	ND	ND	ND	13.8	28.4
S002 Solids	ND	8.4	224	ND	ND	18.2	4.7	27.1	13.5	ND	ND	18.7	ND	ND	ND	21.8	45.9
S003 Solids	ND	9.7	166	ND	ND	10	1.7	22.4	9.9	ND	ND	7.7	ND	ND	ND	14.3	33.9
S004 Solids	ND	8.7	347	ND	ND	18.5	3.2	53.8	11.8	ND	ND	32.5	ND	ND	ND	19.6	37.9
S005 Solids	ND	2.3	51	ND	ND	8	1.4	9.2	3.3	ND	ND	5.3	ND	ND	ND	16.3	33.1
S006 Solids	ND	2.7	66	ND	ND	9.7	2.6	12.6	5.5	ND	ND	6.8	ND	ND	ND	17.8	31.6
Florida SCTL	370	12	130000	1400	1700	470	42000	89000	1400	17	11000	35000	11000	8200	150	10000	630000

Table 3.10. Results of CGR samples analyzed for organic and inorganic constituents for the International Grooving and Grinding Association by an independent laboratory in North Carolina. Samples were taken from locations in Delaware, Pennsylvania, and South Carolina. (International 1990)

Sample	1	2	3	4	5	6	7
	mg/kg (ppm)						
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Barium	0.8	1.1	0.96	2.1	2	1.65	1.8
Cadmium	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Chromium	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Lead	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mercury	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Selenium	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Silver	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Copper	3.10	1.60	1.70	2.60	3.15	2.10	1.85
Zinc	2.60	2.90	1.65	2.65	2.80	1.76	1.90
Aluminum	6570	6900	8210	7420	6840	7250	9130
Benzene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Toluene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethyl Benzene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Xylene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Gasoline	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fuel Oil	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Diesel Fuel	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Lube Oil	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Other Solvents	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

While no leaching data were found for dried CGR, a useful comparison can be made to leachate data from concrete itself. Hillier et al. (1999) conducted two extraction tests, a column test, and a batch/tank test on Portland cement mortar. Two extraction tests were also conducted on PCC samples, one with acetic acid as a leachant, and one with deionized water. Samples were crushed to a fineness of passing through a 150 μm sieve. Atomic absorption spectrometry was used to measure metal content in leachate. For all leachates, antimony, arsenic, beryllium, cadmium, chromium, lead, mercury, nickel, and selenium concentrations were all below detection limits. A solids digestion of the PCC was also conducted to determine the total metals concentrations. Antimony, mercury, cadmium, and selenium were below detection limits. Arsenic, chromium, beryllium, lead, and nickel concentrations were all within the expected limits that were provided by the Portland Cement Association.

Hillier et al. (1999) also conducted an analysis to determine the total concentration of toxic metals in Portland cement. This was done by performing a solids digestion on the cement, followed by atomic absorption spectrometry. The cement samples were the same samples used in the leaching tests. The results of the total metals analyses are in Table 3.11 (Hillier et al. 1999). In this case, the concentration of arsenic exceeds the Florida commercial/industrial soil cleanup target level.

Table 3.11. Metal composition of Portland cement concrete. Solid samples were digested and then run on an atomic absorption spectrometer to find the total metal content with the PCC. (Hillier et al. 1999)

Element	Antimony	Arsenic	Beryllium	Cadmium	Chromium	Lead	Mercury	Nickel	Selenium	Vanadium
Concentration (mg/kg)	Not Detected	19.9 ± 2.4	1.4 ± 0.2	Not Detected	72.7 ± 6.9	75.3 ± 3.2	Not Detected	72.0 ± 4.8	Not Detected	44.1 ± 3.3

The calcium and sodium content of CGR may have implications regarding disposal methods, as high salt levels in soil can be detrimental to plant growth. NDOR conducted an experiment to determine land application guidelines using different loading rates (by mass) of CGR. In the experiment, soil was loaded at 0, 5, 10, 20, and 40 dry tons of CGR per acre at two separate sites and plant growth was surveyed at one month and one year. The amounts of salts applied to the soils are shown in Table 3.12. The application of slurry did not significantly affect vegetation at the one month or at the one-year mark. At the one-month mark, calcium and sodium levels were elevated in the 20 and 40 ton per acre sites, but levels did not persist at the one-year mark (Mamo et al. 2015).

Table 3.12. Average load of potassium, calcium, magnesium, and sodium application load from concrete grinding slurry at the NE State HWY 31 sample sites. CGR slurry was land applied at specified rates, and the total amount of potassium, calcium, magnesium, and sodium were measured. (Mamo et al. 2015)

CGR rate (ton/acre)	Applied load (lbs/acre)			
	K	Ca	Mg	Na
0	0	0	0	0
5	14	1134	28	40
10	27	2268	56	80
20	55	4536	112	160
40	110	9072	224	320

A greenhouse study by DeSutter et al. (2011) was conducted to determine how application of CGR specifically affects smooth brome (*Bromus inermis Leyss*), a species of grass. Two soil beds were used, one containing a silty clay and the other containing a sandy loam. CGR was then applied in each bed at rates of 0%, 8%, and 25% by weight. Twenty smooth brome grass seeds were planted in each treatment. After 100 days of growing, plant shoots were clipped at the soil surface, dried, and weighed. Plant roots were also removed from the soil, dried, and weighed. The shoots and the roots were then analyzed for metal content and for plant biomass. In both soils, the 8% application rate generally increased plant biomass, while 0% and 25% varied. The presence of calcium in the soil due to CGR correlated with an increase in plant growth. This is as expected, since calcium is an essential nutrient for plants (DeSutter et al. 2011).

Another concern regarding CGR is that when applying the slurry to the land, the infiltration rates of the native soil may be altered. In an experiment by DeSutter et al. (2010), CGR was applied to various columns of soil. One column had a 2.5 mm layer of packed CGR at the top of the column, while two other columns had CGR mixed at 8% and at 25% by weight within the top 3 cm of the columns. These three columns were compared to a fourth column containing bare soil and no CGR. Each column had a graduated reservoir upstream, where the infiltrated depth was recorded by the decrease in reservoir level. Once water flow was initiated, the time was recorded at each 5-mm decrease in reservoir level, and the depth of infiltration was plotted with respect to time. The results are shown in Figure 3.1. The loading rate of CGR did have a significant impact on the infiltration rate through the soil tested. The control had the highest infiltration rate, while the column with 25% CGR in the top 3 cm had the lowest (DeSutter et al. 2010).

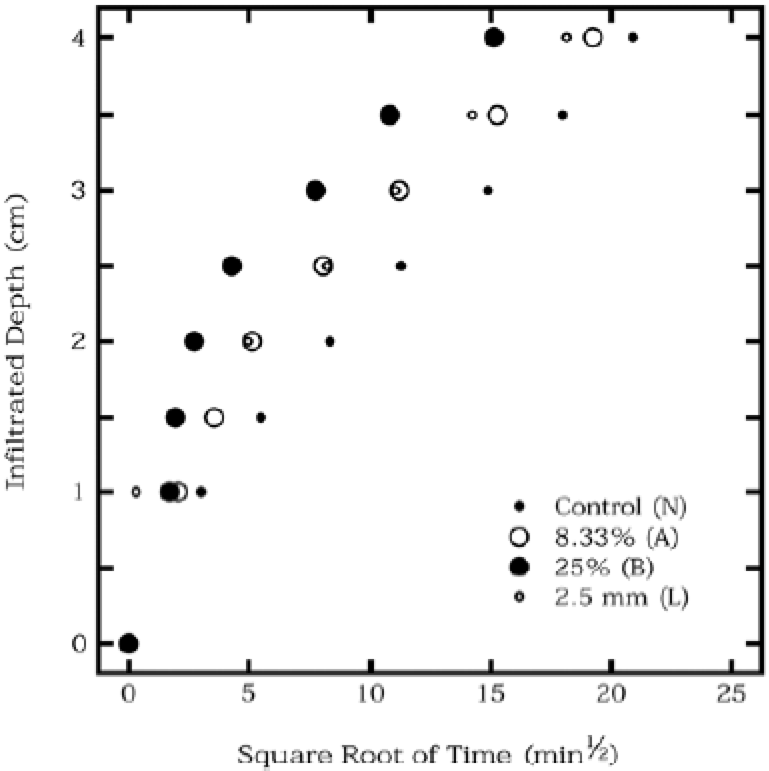


Figure 3.1. Infiltrated depth vs. square root of time for a typical column. Four treatments were used, designated as 8% mix (symbol = A), 25% mix (symbol = B), 2.5 mm layer (symbol = L), and control (symbol = N). Water was allowed to flow down through the column and the time it took for a specified volume to flow was measured. (DeSutter et al. 2010)

3.3.2 Best Management Practices for CGR

Although CGR has not been proven to be significantly detrimental to the environment, it may have adverse environmental consequences because of its high pH. If managed correctly, some evidence suggests that it could be a benefit; certain land application loading rates have been shown to increase plant growth. Mamo et al. (2015) showed that an application of up to 40 tons of dry CGR slurry per acre did not negatively impact vegetative growth. DeSutter et al. (2011) showed that a soil application rate of 8% actually improved plant growth. Water infiltration has also been shown to be affected somewhat by CGR application, but the extent was not determined.

The International Grinding and Grooving Association (IGGA) recommends specific Best Management Practices for the safe disposal of CGR slurry. Three methods of disposal, as well as a pH management plan, are provided below (International Grooving and Grinding Association 2013).

Table 3.13. Best management practices recommended by the International Grooving and Grinding Association. Depending on the location and surroundings of the grinding operation, several options are available. (International 1990)

Method of Slurry Disposal	Preliminary Steps	Methods	Precautions	Monitoring
Slurry spreading in rural areas can occur along vegetated slopes as the grinding operation progresses down the road.	Engineer shall identify nearby wetlands and sensitive areas. Inspections prior to starting the operation shall ensure disposal does not take place in sensitive areas.	Diamond grinding equipment shall be equipped with a vacuum system that is capable of removing all slurry. Vacuumed material shall be spread evenly on the adjacent slopes, beginning at a minimum of 1 foot from the shoulder. With each pass of the grinder, the spreading operation should move further down the slope.	Start and stop point shall be clearly marked. Slurry shall not be spread within 100 feet of natural streams or lakes or within 3 feet of a water filled ditch. At no time will CGR slurry be allowed to enter a closed drainage system.	The pH will be maintained below 12.5 and greater than 2.00. The pH shall be monitored at the start of operations, and the once per hour afterward during operation. After operations have concluded and pH results are consistent, testing frequency may be reduced to 4 tests per day. At no time shall slurry containing a pH outside the acceptable range be discharged to the ground.
In urban areas with closed drainage systems, slurry shall be collected in water-tight haul containers and transported to settlement ponds.		Ponds shall be constructed to allow for the settlement of solids and decanting of water for reuse in grinding. After the operation is completed, the remaining water may be allowed to evaporate or be used in a commercially beneficial manor. After drying, the CGR may be used in commercial application.	Pond may be within or outside the right of way. Once operation has concluded, the pond shall be reclaimed to its original condition and vegetated.	
The slurry may be collected and hauled to a processing plant.	The plant site shall be prepared to control any storm water runoff.	The slurry shall be handled in the same fashion as in the settlement ponds.	The site shall be restored to its original condition after the operation has concluded.	

3.4 Survey of State CGR Management Practices

A survey of other states transportation departments was performed to learn of their experiences and practices related to the management of concrete grooving and grinding wastes. A set of questions was developed by the researchers and distributed by the FDOT to all U.S. states and territories with transportation departments. Responses were received from sixteen states: Arizona, Arkansas, California, Connecticut, Illinois, Iowa, Missouri, Nevada, New Hampshire, Ohio, Pennsylvania, Tennessee, Virginia, Washington, West Virginia, and Wisconsin. Of the states that responded, two did not have answers to the questions: Connecticut and New Hampshire. Connecticut responded that their state operates a very low number of roadway sections that are constructed from PCC, and that they have very limited experience in grinding them. They did, however, express interest in the result of any research. New Hampshire claimed that they operate no PCC pavements.

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Arizona	No specific BMP addressing CGR. Erosion & Pollution Control Manual has specific verbiage stating PCC slurry shall not be allowed to enter storm drains or watercourses.	None	No	No	NA	No
Arkansas	Yes, the Special Provision (SP) "Removal and Disposal of Portland Cement Concrete Pavement Grinding Residue"	The SP requires the contractor to choose a suitable location/method of disposal and obtain necessary permits. Disposal plan must be submitted to the Engineer 30 days prior to grinding operation.	No	There was a complaint that a previous disposal method allowing the contractor to discharge the grinding residue on the highway shoulder in well vegetated areas might cause environmental impacts. This option was removed from the SP.	The Resident Engineer who administers the project is responsible in consultation with AHTD's Environmental Division	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
California	Caltrans Standard Specification requires disposal of concrete grinding residue at a disposal facility which has received a permit from the Regional Water Quality Control Board (RWQCB) or other applicable agency permit. After completing the grooving and grinding operation, receipts and weight tickets for the residue must be submitted. If authorized, offsite drying may be allowed; in that case it must be identified on the Stormwater Pollution Prevention Plan (SWPP) which is subject to RWQCB review.	Submittal of RWQCB or other applicable agency permit.	No	California DOT has been advised by one RWQCB that the permit issued by other agencies may not always allow residue disposal.	Contractors are responsible to comply with management and disposal requirements of the specifications and permit which allows disposal.	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Illinois	For bridge decks the state of Illinois uses 2016 Standard Specification for Road and Bridge Construction Article 503.16(a)(3)(b) pg. 321 of 1225 and Diamond Grinding and Surface Testing of Bridge Sections Special Provision. For PCC (pavements, the texturing of PCC pavements is performed when PCC is in the plastic state. Pavement grinding is minimal to correct isolated locations for smoothness, thus management of CGR is not required. In isolated cases where management is required, a contract specific special provision is inserted to define the grinding requirements. See Profile Specific Grinding of Concrete Pavement Special Provision in Contract 60W56 for an example.	Standard Specification for Road and Bridge Construction Article 202.03 pg. 320 of 1225. It shall be the Contractor's responsibility to have the pH of the material tested to ensure the value is between 6.25 and 9.0, inclusive. A copy of the pH test result shall be provided to the Engineer.	No	No	Contractors are responsible for compliance. District Construction Offices ensure compliance is enforced.	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Iowa	Articles 2531.03.D.3 and 2532.03.D.1.b of Standard Specifications found at http://www.iowadot.gov/erl/index.html	None	No	Yes	Contractor	None in Iowa. Iowa is aware of research being performed by Nebraska Dept. of Roads.
Missouri	Missouri Standard Specifications Section 622.30.3.8	None. Contractor needs Resident Engineer's approval for disposal method.	No	No	Missouri has no central authority. The Resident Engineer needs to approve the disposal method	No
Nevada	No	None	No	Yes, dust.	Resident Engineers.	No
Ohio	Construction and Material Specifications Section 107.19 (general) and 511.17 (Bridge Deck Grooving)	None, other than 107.19	Prequalified for bridge work but not specific to CGR.	No	Contractor	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Pennsylvania	No	There is no permit required if the slurry is collected and impounded at the work site. Waste water needs to be pH 6 to pH 9 and can be used for dust control or other uses that do not include direct discharge into waterways. The solid portion can be treated as a construction waste.	No	No	Contractor	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Tennessee	No	No permitting is required. According to TnDOT's Special Provision 503, residue may be continuously discharged on adjacent roadway slopes or ditches if the Engineer determines that there is sufficient vegetative cover. If there is not sufficient vegetative cover on the adjacent roadway slopes to adequately filter the residue, then the residue shall be collected in approved storage tanks and deposited in settling basins, spread over flat vegetated areas, or filtered by other means approved by the Engineer.	No	No	Project Personnel (those who administer the contract)	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Virginia	Virginia does not have any management system in place relating to residue of grinding operations. The grinding specifications used require the disposal of CGR to be handled in accordance with general materials disposal.					
Washington	Section 5-01.3(11) of WSDOT Standard Specifications	Disposal Site, see WSDOT Standard Specification Section 2-03.3(7)C	No	No	Department of Ecology. WSDOT Staff monitors during construction	Yes, http://btl.bts.gov/lib/56000/56200/56214/FinalReportM335.pdf
West Virginia	No	Specification for Diamond Grinding (Section 508.5) state: "All reside from the pavement surface shall become the responsibility of the Contractor and shall be removed and disposed of legally in a manner and at a location which satisfies environmental regulations."	They must comply with the current environmental regulations.	no	Contractor	No

Table 3.14. CGR management survey results from various state DOT offices. Survey was issued by FDOT and Hinkley Center at University of Florida.

Questions to be answered by state DOT offices.	1. Does your state have or use a specified guidance document or BMP to direct the management of CGR?	2. What type of permitting, if any, do you require of contractors when disposing of CGR?	3. Are the contractors of staff performing the grinding or grooving operations required by your state to have training related to the proper management of CGR?	4. Are you aware of complaints, issues, or problems related to improper management of CGR?	5. Who, in your state, is responsible for compliance with CGR management and/or disposal?	6. Are you aware of recent research on CGR environmental or health and safety issues?
Wisconsin	Section 420.3.4 in WisDOT Standard Specifications	WisDOT does not directly require any permits. Contractor may have to get permits from Wisconsin Department of Natural Resources if applicable.	No direct requirements.	No		No

Of the states that responded to the survey, seven states had some form of management plan in place for disposal of CGR slurry. Some of the management specifications were in place to mitigate CGR slurry from entering bodies of water, however, most included no specifics as how to actually manage any waste. No states required any specific permitting process for CGR slurry, although California does require a Regional Water Quality Control Board (RWQCB) to approve grinding operations. The majority of the states in the survey leave CGR disposal to the discretion of the Engineer or the Contractor on site. No states required any specific training to handle or manage CGR slurry. There were two states that had encountered complaints pertaining to CGR slurry: Arkansas and California. Arkansas encountered a complaint that discharge of reside on the highway shoulder may have environmental impacts. California was advised by a RWQCB that permit issues by other agencies may not always allow reside disposal. Most states held the on-site Engineers and Contractors liable for CGR management compliance, and only two states were aware of any ongoing research involving CGR.

3.5. CGR Samples

In order to better assess the effects of CGR on the environment, CGR samples were collected from several operations in Florida. Two grinding operations on PCC slabs along Interstate 10 in Jacksonville, FL were labeled as Jax10 and Cassat. Both were taken from the bottom drain of the slurry tanker after the diamond grinder had finished resurfacing the respective areas of the PCC slabs. Jax10 samples were from a grinding operation that was resurfacing existing PCC pavement slabs that were being corrected for smoothness. Cassat samples were taken from a grinding operation on new PCC pavement slabs that were part of a lane expansion along the Interstate 10. The Clapboard Creek sample was from a new bridge construction on Heckscher Drive. Samples Tampa 301, Truck #1, JUF, Orlando, Jax, Vero Beach, and Fort Myers/Punta Gorda were all received from the FDOT State Materials Office. Table 3.15 presents the quantity of each sample and where they were obtained.

Table 3.15. CGR slurry samples that were characterized during the study. The first seven samples were received from the FDOT State Materials Office. The Jax10 and Cassat samples were collected during grinding operations directly from the slurry truck. The Jax10 sample was taken from the grinding of existing PCC slabs that were being resurfaced. The Cassat sample was taken from newly poured PCC slabs that were part of a lane expansion. The Clapboard Creek sample was from a new bridge construction on Heckscher Drive.

Sample Name	Quantity of Sample	Location of Sample
Tampa 301	1 Liter	FDOT
Truck #1	1 Liter	FDOT
JUF	1 Liter	FDOT
Orlando	1 Liter	FDOT
Jax	1 Liter	FDOT
Vero Beach	1 Liter	FDOT
Fort Myers/Punta Gorda	1 Liter	FDOT
Jax10	5 5-gallon buckets	I-10 E on bridge overpass at Lane Ave.
Cassat	5 5-gallon buckets	I-10 E lane expansion at Cassat Ave
Clapboard Creek	5 5-gallon buckets	Heckscher Drive Bridge over Clapboard Creek, Jacksonville

3.5.1. Characterization Methodology

Moisture content for all the CGR samples was measured using the same methods as for the RCA samples, using Florida method FM 1-T 255 for coarse and fine aggregates. Duplicate samples were also analyzed from each source for quality assurance. Sieve analysis was performed on 1000 to 1200 g oven-dried samples using a No. 270 sieve (53 µm) in accordance with Florida method FM 1-T027.

EPA LEAF 1316 test guidelines were followed for liquid-solid partitioning between water and CGR at equilibrium. Batch tests were performed using reagent water at L/S of 10, 5, 2, and 1, kept on rotation for 24 hours at 28 ± 2 rpm. Immediately after rotation, pH was measured on each sample to achieve an unfiltered pH value. Solids were separated by decanting after centrifugation at 4000 ± 100 rpm for 15 minutes to clarify the solution.

All extractions were filtered through polypropylene 0.45 µm membrane. Conductivity and pH were measured according to ASTM 1125 and EPA standard procedure 9040 (SW-846), respectively.

Alkalinity was measured to determine the equivalent amount of carbonate species present in CGR leachate and the amount of strong acid required to neutralize it. Standard titration procedure was followed, using 1.6 N sulfuric acid. Acid-neutralization curve was plotted against the amount of acid added, and alkalinity as $CaCO_3$ was calculated on the basis of carbonate equivalence point, which was around 4.5. The method guidelines were followed from the method given in TWRI chapter A6 from Book 9 by USGS (USGS, 2012). Moisture content of the samples was conducted in the same manner as with RCA, using method FM 1-T 255.

A volume of 50 mL of all the filtered CGR samples were digested using an automated block digester. The process uses trace metal grade nitric acid and hydrochloric acid according to EPA method 3010A. The digested samples were made to volume 50 mL by adding deionized water and analyzed for metals concentration on inductively coupled plasma atomic absorption spectrophotometer (ICP) using EPA method 6010B. Solid samples of Jax10, Cassat, Clapboard Creek, and seven different FDOT samples were digested on the automated block digester using EPA method 3050B. The digested samples were then brought to volume using deionized water and analyzed for total metal concentrations on ICP using EPA method 6010B.

3.5.2. CGR Characterization Results

As shown by the initial characterization, CGR slurry has very high moisture content, ranging from 56-95%. The pH ranged from 11.05 to 12.41, and showed noticeable increase with a decrease in L/S ratio. The higher L/S ratios effectively dilute the pH changes in the leachate, in turn lowering pH. Conductivity also increased with a decrease in L/S ratio, which was as expected. Alkalinity did not show a similar trend with regards to L/S ratio. The alkalinity as $CaCO_3$ was calculated for each titration, and ranged from 340 mg/L to 2,210 mg/L.

Table 3.16. Initial characterization of CGR samples. pH, moisture, contents, and alkalinity values were measured for all CGR samples, including various liquid-to-solid ratios (L/S) for the Jax10, Cassat, and Clapboard Creek samples.

Sample	Slurry (Unfiltered) pH	Filtered pH	Moisture Content	Conductivity (µS/cm)	Alkalinity (mg/L as $CaCO_3$)
Tampa 301	11.62	10.95	86%		
Truck #1	12.41	11.66	65%		
JUF	11.08	11.28	56%		
Orlando	12.32	11.58	63%		
Jax	12.25	11.49	59%		
Vero Beach	12.37	11.97	61%		
Fort Myers/Punta Gorda	11.56	11.07	43%		
Jax10 A 10:1	12.02	11.79	95%	8,338	1,165
Jax10 A 5:1	12.09	11.87	95%	11,180	1,577
Jax10 A 2:1	12.14	12.05	95%	13,573	1,910
Jax10 A 1:1	12.22	12.18	95%		2,210
Jax10 B 10:1	11.71	11.63	91%	5,364	671
Jax10 B 5:1	11.96	11.82	91%	10,050	1,431
Jax10 B 2:1	12.06	12.01	91%	13,302	1,685
Jax10 B 1:1	12.17	12.17	91%		2,090
Cassat A 10:1	11.25	11.18	70%	1,470	368
Cassat A 5:1	11.30	11.90	70%	1,475	410
Cassat A 2:1	11.83	12.10	70%	3,375	621
Cassat A 1:1	11.85	12.34	70%		601
Cassat B 10:1	11.11	11.05	75%	1,654	474
Cassat B 5:1	11.30	11.91	75%	1,229	440
Cassat B 2:1	11.73	12.10	75%	3,396	661
Cassat B 1:1	11.80	12.29	75%	4,712	921
Clapboard Creek A 10:1	11.70	11.72	63%	1,672	340
Clapboard Creek A 5:1	11.87	11.87	63%	2,430	500
Clapboard Creek A 2:1	12.03	12.03	63%	3,656	673
Clapboard Creek A 1:1	12.28	12.26	63%	5,166	1,089
Clapboard Creek B 10:1	11.72	11.76	56%	1,762	360
Clapboard Creek B 5:1	11.82	11.83	56%	2,429	420
Clapboard Creek B 2:1	12.05	12.04	56%	3,649	665
Clapboard Creek B 1:1	12.22	12.23	56%	5,144	1,037

The pH of the samples collected were plotted with respect to the L/S ratio. This is to show how dilution effects within the slurry can lower the pH of what would normally be relatively basic. The pH drop was fairly significant, reaching as low as 11.63, a 0.55 drop from the more concentrated L/S of 1/1. The pH was taken on both filtered and unfiltered samples to see if removing suspended particulate had any impact on the results. The presence of suspended particles seemed to have some effect on individual values, however it had no effect on overall trend.

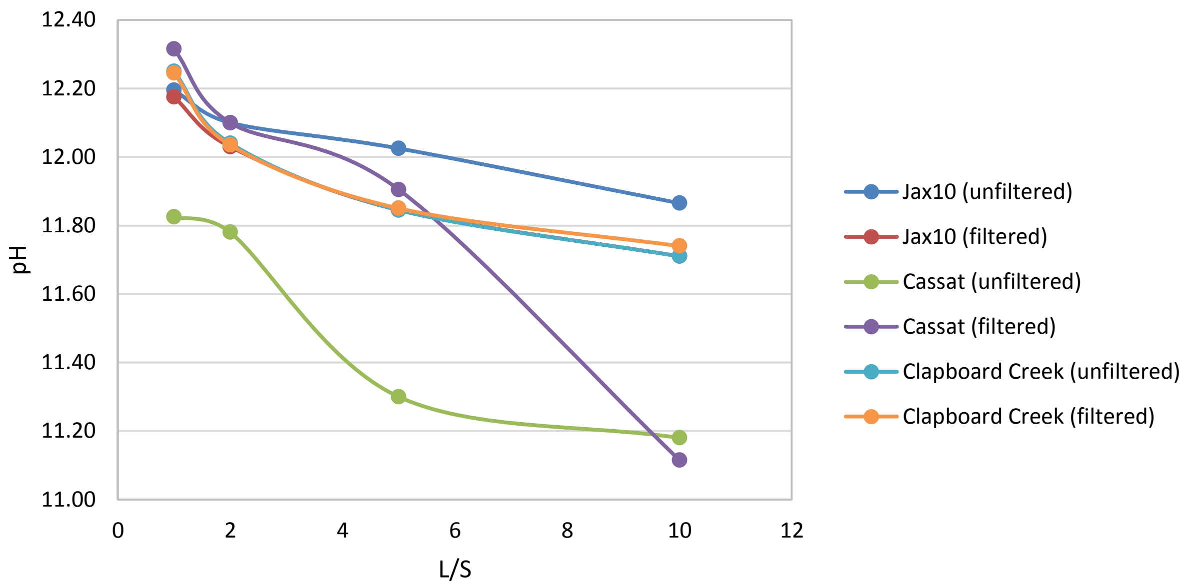


Figure 3.2. CGR pH as a function of L/S Ratio. CGR samples were mixed in batches with water to achieve liquid-to-solid ratios of 10/1, 5/1, 2/1, and 1/1. After 24 hours of end-over-end rotation, the unfiltered pH was measured for each sample. The samples were filtered, and the pH was measured again. Data shows the average pH for duplicates of each sample.

The conductivity results of the various L/S ratios of CGR were plotted similarly to the pH results. The presence of dissolved solids in the CGR slurry was expected to be high, and this was shown by the high conductivity values. With the effects of dilution, the values were able to be reduced by almost half. This trend may be of importance if there are concerns with CGR slurry discharge into the environment. By increasing the amount of water in the slurry, the CGR can be effectively "washed" of the ions responsible for its high conductivity.

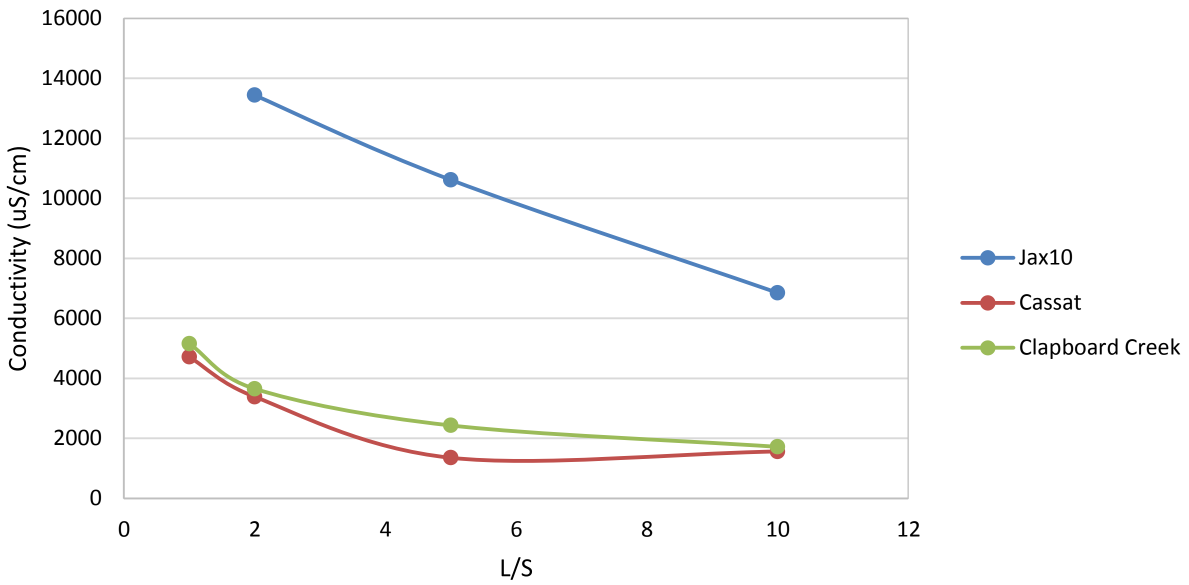


Figure 3.3. CGR conductivity as a function of L/S ratio. CGR samples were mixed in batches with water to achieve liquid-to-solid ratios of 10/1, 5/1, 2/1, and 1/1. After 24 hours of end-over-end rotation, the conductivity of each sample was measured. Data shows the average conductivities for duplicates of each sample.

Figures 3.4 to 3.9 compare the alkalinity titrations of each L/S ratio of CGR. For both samples A and B, T01 indicates a L/S of 10, T02 indicates a L/S of 5, T03 indicates a L/S ratio of 2, and T04 indicates a L/S of 1. All samples show significant acid neutralization capacity, indicated by the zero or nearly zero slope on the respective figures. There was some variation in the amount of neutralization capacity between various L/S ratios, however there was not a clear trend as to which were better at neutralizing acidity. In both the A and B replicates of the Jax10 sample, the L/S of 1 was able to neutralize the most of the acid before showing severe drop in pH, while the other L/S ratios varied somewhat. The Cassat A sample showed the highest acid neutralization ability in the batch with L/S of 2. The Cassat B and both Clapboard Creek samples showed the highest acid neutralization ability in the batches with L/S of 1.

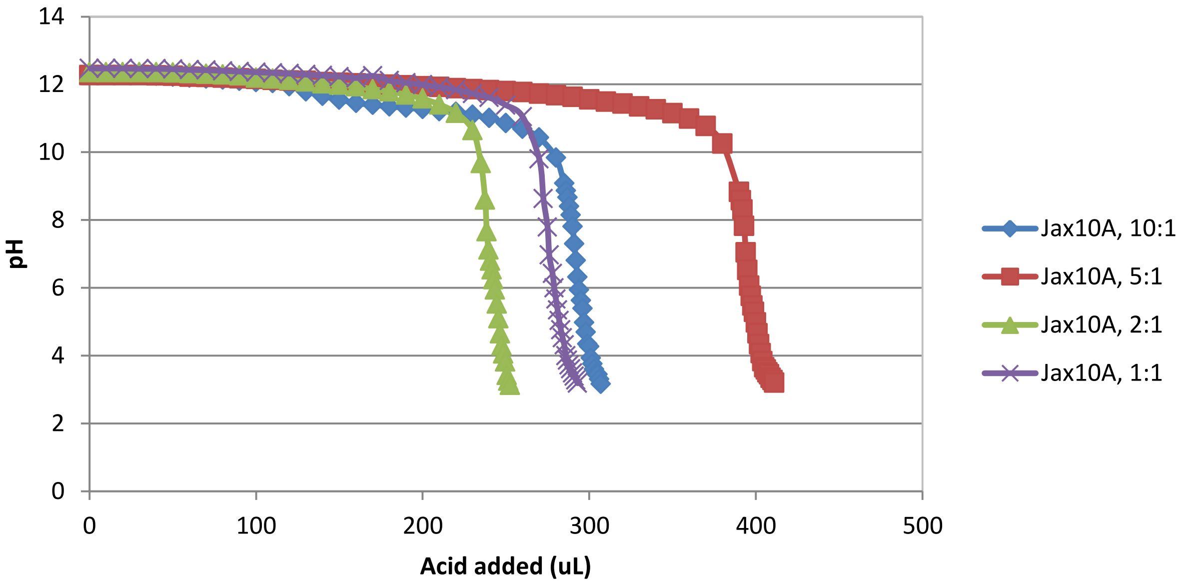


Figure 3.4. Sample Jax10 A pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

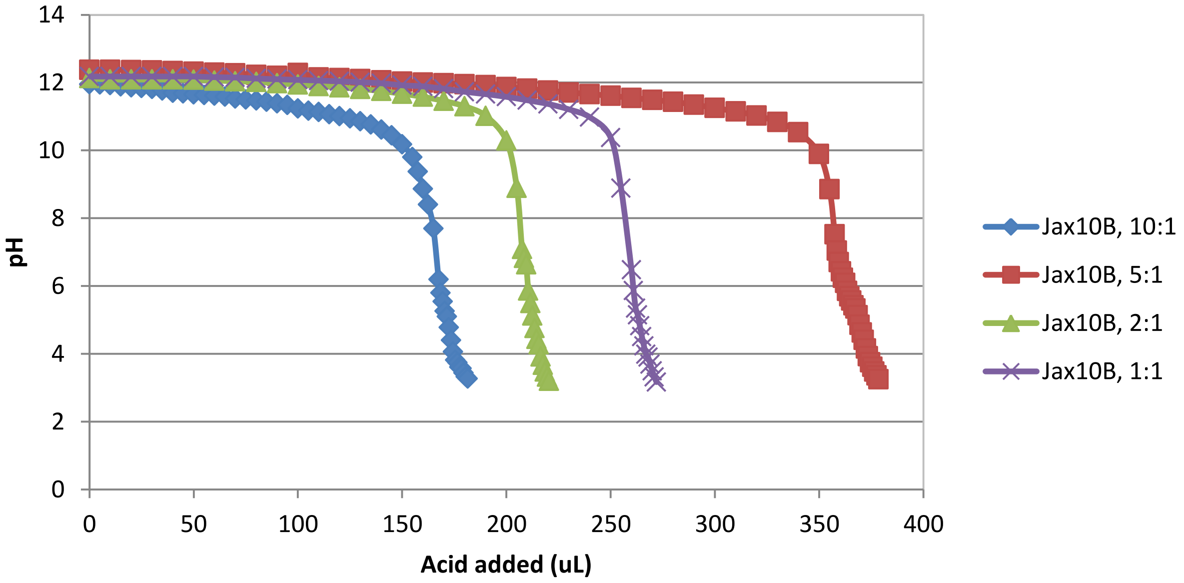


Figure 3.5. Sample Jax10 B pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

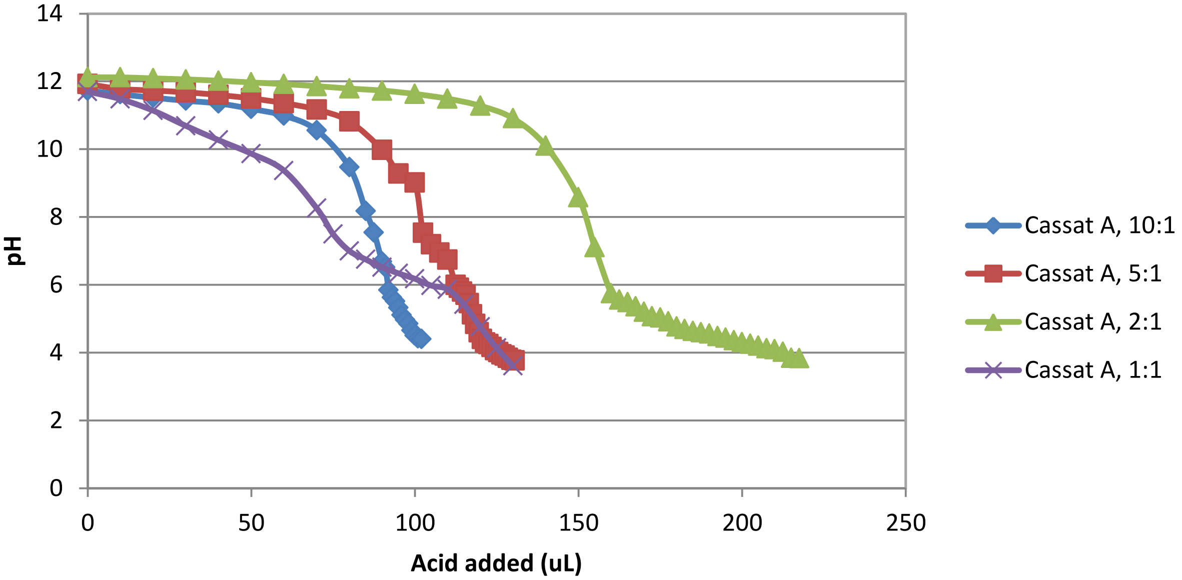


Figure 3.6 Sample Cassat A pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

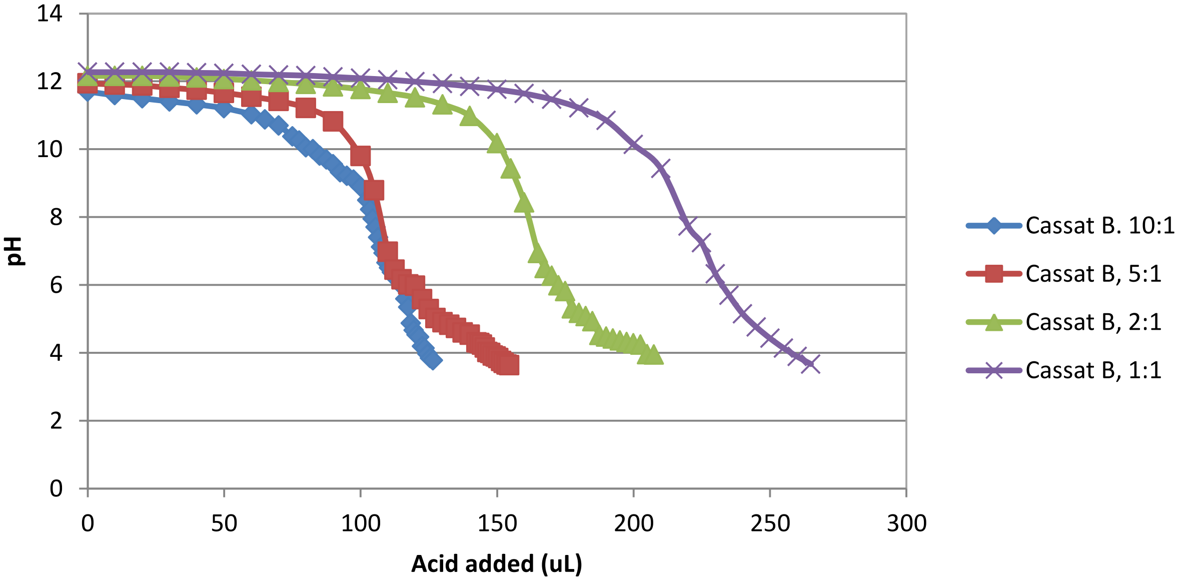


Figure 3.7 Sample Cassat B pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

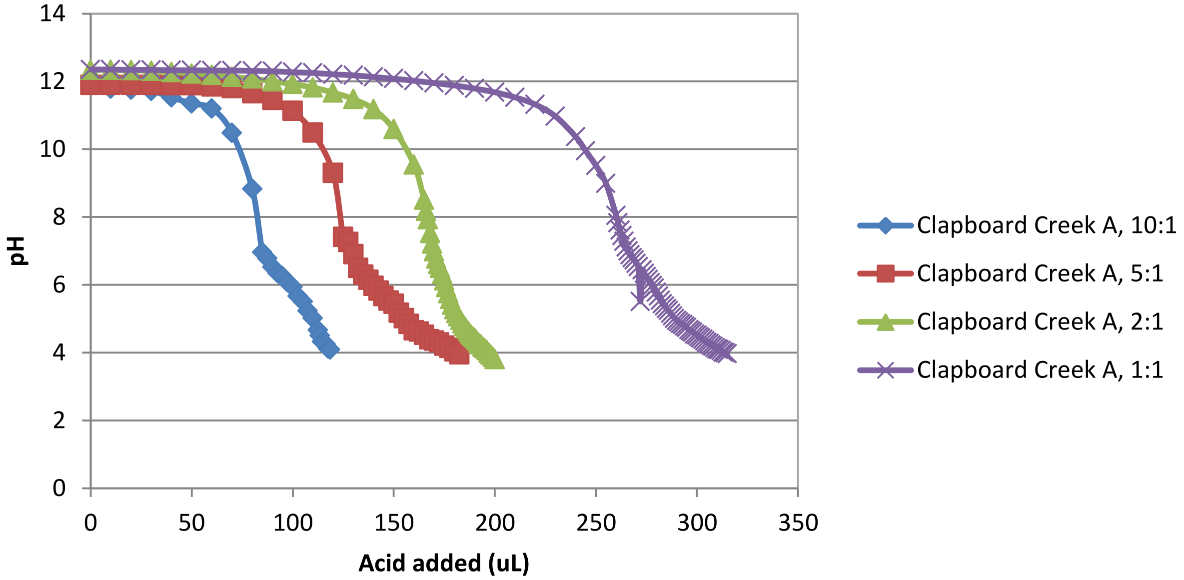


Figure 3.8 Sample Clapboard Creek A pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

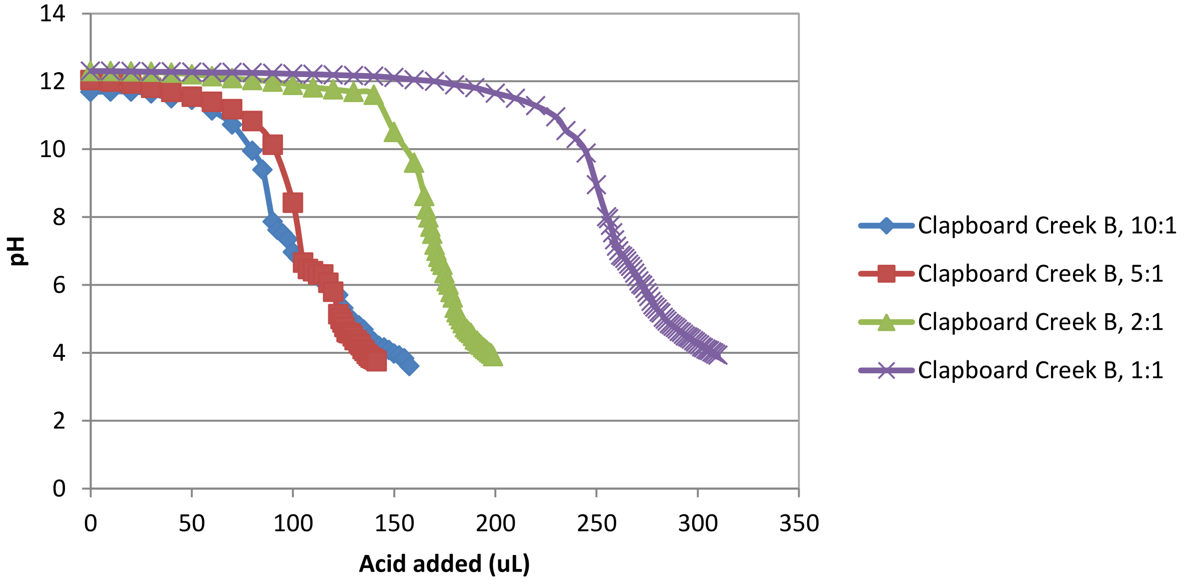


Figure 3.9 Sample Clapboard Creek B pH vs. volume of acid added. Alkalinity titrations were performed using 1.6 Normal Sulfuric Acid. Titrations were performed on each liquid-to-solid ratio to compare the effect of dilution on neutralization capacity. T01 indicates a L/S of 10/1. T02 indicates a L/S of 5/1. T03 indicates a L/S of 2/1. T04 indicates a L/S of 1/1.

The point on the plots where there is the largest change in pH per change in total volume is used to calculate the actual alkalinity as $CaCO_3$. This point would be where each sample's respective line becomes the steepest. The alkalinity of each sample shows a similarly increasing trend with decreasing L/S ratio.

Table 3.17. The calculated alkalinity for each CGR sample. The alkalinity, which is based on the largest change in pH per change in total volume, shows an increasing trend with decreasing L/S ratio.

Sample, Replicate, and L/S	Alkalinity as $CaCO_3$ (mg/L)
Jax10 A 10:1	1,165
Jax10 A 5:1	1,577
Jax10 A 2:1	1,910
Jax10 A 1:1	2,210
Jax10 B 10:1	671
Jax10 B 5:1	1,431
Jax10 B 2:1	1,685
Jax10 B 1:1	2,090
Cassat A 10:1	368
Cassat A 5:1	410
Cassat A 2:1	621
Cassat A 1:1	601
Cassat B 10:1	474
Cassat B 5:1	440
Cassat B 2:1	661
Cassat B 1:1	921
Clapboard Creek A 10:1	340
Clapboard Creek A 5:1	500
Clapboard Creek A 2:1	673
Clapboard Creek A 1:1	1,089
Clapboard Creek B 10:1	360
Clapboard Creek B 5:1	420
Clapboard Creek B 2:1	665
Clapboard Creek B 1:1	1,037

Liquid digestions of the Jax10, Cassat, and Clapboard Creek samples that were analyzed on the ICP were tested for a suite of metals, including aluminum, arsenic, boron, barium, beryllium, calcium, cadmium, chromium, copper, iron, magnesium, manganese, molybdenum, sodium, nickel, lead, antimony, selenium, tin, strontium, vanadium, and zinc. Results were then compared to the Florida Groundwater Cleanup Target Levels, (GCTLs), where GCTLs applied. All samples exceeded the Florida GCTLs for aluminum, two exceeded the GCTLs for chromium, one exceeded for sodium, and seven exceeded the limits for strontium. All samples tested also exhibited relatively high levels of calcium, which was as expected. These samples are representative to what would leach from CGR material as various volumes of water were able to interact with them. Results of the analysis are presented in Appendix I.

CGR samples obtained from operations along Interstate 10, Heckscher Drive, and from the FDOT State Materials Office were tested on the ICP for total metal content. The metals that were tested for include aluminum, arsenic, boron, barium, beryllium, calcium, cadmium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, molybdenum, sodium, nickel, lead, tin, selenium, strontium, titanium, vanadium, and zinc. These results were then compared to the Florida commercial soil cleanup target levels. For all samples, including the samples received from FDOT, none were higher than the Florida SCTLs.

Six of the FDOT samples, from districts 2, 4, 5, and 7, were collected to determine if the waste was characteristically hazardous according to 40 CFR 261.24. Several labs conducted the toxicity characteristic leaching procedure (TCLP) to produce leachate for analysis. The process involves the extraction of waste material using acetic acid and analyzing the concentrations of eight toxic characteristics elements in the leachate. All six samples tested for toxicity characteristic (TC) hazardous waste met the federal regulatory TC limits according to 40 CFR 261.24. Results of the TCLP analysis are presented in Table 3.18.

Table 3.18. TCLP results from six CGR samples collected by FDOT. Samples were analyzed in triplicate and compared to the TC limits, in mg/L. The analyses were performed at various labs, which are provided in the table.

Date	Location	District	Contaminant	As	Ba	Cd	Cr	Pb	Se	Ag	Hg	lab
			TC limit	5.0	100.0	1.0	5.0	5.0	1.0	5.0	0.2	
			Sample#	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
1/9/2015	Orlando: I-95/I-4 interchange	5	1	U	0.14 I	U	0.545	U	U	U	U	ENCO
			2	U	0.131 I	U	0.536	U	U	U	U	
			3	U	0.184 I	U	0.466	U	U	U	U	
2/3/2015	Tampa: Veteran's expressway	7	1	0.049 I	0.353	U	0.0093 I	U	U	U	U	Spectrum Analytical
			2	U	0.107	U	0.0112 I	U	U	U	U	
			3	U	0.114	U	0.0138 I	U	U	U	U	
2/24/2015	Orlando: SR-50/West Colonial Dr.	5	1	U	0.974	U	0.0558 I	U	U	U	U	ENCO
			2	U	0.061 I	U	0.200	U	U	U	U	
			3	U	0.511	U	0.0725 I	U	U	0.0138 I	U	
4/9/2015	Vero Beach: US 1	4	1	U	0.30	U	0.50	0.00059 I	0.0030 I	U	U	Jupiter Env Labs Inc
			2	U	0.33	U	0.52	0.00080 I	0.0026 I	U	U	
			3	U	0.39	U	0.53	0.0012 I	0.0033 I	U	U	
4/30/2015	Tampa: US 301	7	1	U	0.68	U	0.020 I	0.029 I	0.029 I	U	U	Millennium Labs
			2	0.021 I	0.98	U	0.03	0.036 I	0.019 I	U	U	
			3	U	0.30	U	0.037	U	0.023 I	U	U	
9/3/2015	Jacksonville: Arlington River Bridge	2	1	U	0.47	U	U	U	U	U	U	ENCO
			2	U	0.474	U	U	U	U	U	U	
			3	U	0.493	U	U	U	U	U	U	
U:	indicates that the compound was analyzed for but not detected											
I:	the reported value is between the laboratory method detection limit (MDL) and the practical quantitation limit (PQL)											

3.6. Recommended Management Practices for CGR in Florida

CGR samples have shown elevated pH levels, but none were higher than 12.5. Metal analysis of the samples via ICP has shown that no concentration of metals higher than the Florida commercial SCTLs was found. Some samples, however, contained arsenic in concentrations greater than the Florida residential SCTL. Leaching tests performed on the CGR samples indicated that some metals leach in concentrations that exceed the Florida GCTLs. These leached metals include aluminum, chromium, iron, molybdenum, sodium, and strontium. Based on available literature and the analyses that were performed in this study, CGR was not determined to be a "hazardous waste" under the Federal Resource Conservation and Recovery Act (RCRA) and does not need to be treated as a "hazardous waste". Currently, grinding operations that produce CGR in Florida do not use specific guidelines for managing CGR. Investigations have shown that there is no standard method of managing and disposing of CGR. In most cases, the contractor has been responsible for the disposal arrangements of the CGR, and the method of disposal seems to vary according to the location of generation. In areas where grinding takes place in close proximity to surface waters or storm water collection systems, CGR slurry is typically hauled off-site via a tanker truck. Transported CGR slurry has been disposed of in open pits on private sites, in Class II landfills, and in some cases, at concrete recycling centers. In areas where grinding operations are remote from water bodies and storm water collection systems, and in areas with available space, the slurry has been spread on the road embankment or dumped into pits for drying. Once the CGR slurry has dried, it is mixed into the soil.

Even though CGR is not a hazardous waste under RCRA, the potential environmental effects from high pH and high salt content should be recognized, and it should be handled appropriately. CGR could very easily be managed using practices that are used for managing concrete washout from concrete trucks. Concrete recycling centers often accept concrete truck washout, a material similar in characteristics to CGR. In rural areas, it may still be appropriate to dispose of CGR on vegetated road embankment, provided that there are no nearby water bodies or at-risk areas and the disposal meets appropriate soil loading guidelines. Current management practices that are recommended by the IGGA and that are in place by other states require that CGR shall not be discharged within 100 ft of water bodies or within 3 ft of any water filled ditch. There may be some benefit in establishing a beneficial commercial use for CGR, since surface grinding on all new PCC pavement slabs is required per FDOT Specifications Workbook Section 352. Our recommendation for best management practices are provided in Table 3.19.

Table 3.19 Best Management Practices for Concrete Grinding Residue Slurry

Location of CGR generation	Close proximity (within 100 ft.) to surface waters or storm water collection
Precautions	• Use vacuum apparatus to collect CGR slurry from grinding rig • Use tanker truck or equivalent to collect CGR slurry during operation • Do not allow CGR slurry to flow across traffic lanes • Do not allow CGR slurry to flow into any nearby surface waters, stormwater collection systems, or infiltrate into the ground within 100 ft of any nearby water bodies
Disposal	• Must be hauled off site for disposal • May be managed in the same manner as concrete truck washout • An open pit or container may be used to dry the material • Container or liner must have hydraulic conductivity no greater than 10^{-7} cm/sec. Research has shown that even highly acidic soils have only a limited ability to reduce the pH of alkaline water. Introduction of high pH slurry water into natural water bodies should be minimized. • Dried material may be disposed of in a Class II landfill • Dried material may be reused in the production of new PCC • Dried material may be used beneficially in a commercial manor • If material is to be beneficially used, it must be in accordance with a Beneficial Use Permit
Monitoring	• If material is stored in a container for drying, visual leak inspections should be performed at least on a weekly basis • If precipitation is expected to cause an overflow in either container or pit while CGR material is present, precautions should be made to either prevent precipitation from infiltrating the container, or there should be adequate volume to prevent overflow • Anytime CGR material is present in its slurry form, pH reading should be taken at least daily. This is to ensure that the pH is, at no point, greater than 12.5. A pH of 12.5 constitutes a hazardous material, and the material would have to be handled as such.

Table 3.19 Best Management Practices for Concrete Grinding Residue Slurry

Location of CGR generation	Rural areas not in close proximity (further than 100 ft.) to surface waters or storm water collection
Precautions	• Use vacuum apparatus to collect CGR slurry from grinding rig • Use tanker truck or equivalent to collect CGR slurry during operation • Do not allow CGR slurry to flow across traffic lanes • Do not allow CGR slurry to flow into any nearby surface waters, stormwater collection systems, or infiltrate into the ground within 100 ft of any nearby water bodies
Disposal	• When land area permits, CGR slurry may be spread along the side of the road embankment or right of way. CGR slurry that is disposed of in this manor must be spread evenly and at a constant rate to ensure that no single area becomes overburden with CGR material and the high pH of the slurry water. The material that is spread in this manor should be done on to vegetated areas. If the area is not vegetated, efforts should be made to mix the material in with the existing soil. • CGR slurry may be hauled off site • May be managed in the same manner as concrete truck washout • An open pit or container may be used to dry the material • Container or liner must have hydraulic conductivity no greater than 10^{-7} cm/sec. Research has shown that even highly acidic soils have only a limited ability to reduce the pH of alkaline water. Introduction of high pH slurry water into natural water bodies should be minimized. • Dried material may be disposed of in a Class II landfill • Dried material may be reused in the production of new PCC • Dried material may be used beneficially in a commercial manor • If material is to be beneficially used, it must be in accordance with a Beneficial Use Permit

Table 3.19 Best Management Practices for Concrete Grinding Residue Slurry

Monitoring	• If the option to dispose of CGR slurry on site is chosen, the pH of the slurry water must be taken first. The pH must be less than 12.5 to ensure that the material is not a hazardous material. • If material is stored in a container for drying, visual leak inspections should be performed at least on a weekly basis • If precipitation is expected to cause an overflow in either container or pit while CGR material is present, precautions should be made to either prevent precipitation from infiltrating the container, or there should be adequate volume to prevent overflow • Anytime CGR material is present in its slurry form, pH reading should be taken at least daily. This is to ensure that the pH is, at no point, greater than 12.5. A pH of 12.5 constitutes a hazardous material, and the material would have to be handled as such.

4.0. Summary of Project Results

The research conducted and presented in this report examined two distinct but related issues. First was the possible impact of recycled concrete aggregate (RCA) used as road base on the subsurface environment as a result of the water coming into contact with the RCA road base. Second was the management of concrete grinding residuals (CGR) resulting from grooving and grinding operations for Portland cement concrete pavements. This section summarizes the major findings from this work.

With regard to the RCA work, the following findings and comments should be of interest to FDOT.

- Road construction contractors commonly utilize RCA as a base course material for paved roads in many locations in the U.S., and this practice will likely increase in the future in Florida because of the broadened scope of materials feasible for utilization as road base application.
- A number of past investigations explored the possible environmental concerns that might result from chemicals leached from RCA through contact with water, and the two most commonly identified issues have been heavy metals and elevated pH.
- No known groundwater contamination events as a result of RCA used as road base course in practice were identified as part of a review of existing literature.
- Trace amounts of heavy metals occur in Portland cement concrete as a result of their presence in natural and waste byproduct ingredients (both cement and aggregates) and because of exposure to chemicals during the concrete's usage; these trace elements are thus encountered in RCA.
- Past studies where RCA samples were leached in laboratory tests found most heavy metals to occur at concentrations below regulatory drinking water standards, though some results have reported concentrations of arsenic, chromium, and lead greater than the regulatory threshold. Heavy metal leaching from RCA depends upon on the concrete source and the leaching conditions (e.g., pH).
- Water coming into contact with RCA does become elevated in pH. This results from the hydrolysis of calcium oxide present in concrete. pH levels as high as 12.3 have been reported. Several concerns have been raised in the literature over the possible effect of high-pH leachate from RCA entering the environment, including impact on aquatic life, increased corrosion to metal conduit, and adverse effects on underlying groundwater.
- Leachate produced by creating intimate contact between water and samples of RCA collected from Florida concrete recycling facilities was found with average pH values of 11.8 at L/S = 0.5 and 11.2 at L/S = 10. As the water to RCA ratio (L/S) increased, the pH decreased, though the resulting pH was still elevated compared to natural water conditions.

- A number of factors will act to reduce the pH of RCA leachate in the environment, including carbonation (reaction with carbon dioxide), neutralization by soil acidity, and dilution with natural water sources (e.g., groundwater).
- Natural soil acidity (resulting from hydrogen ions and aluminum complexes) will lower the pH of RCA leachate as the leachate travels through the soil, but the extent of neutralization will depend on the amount of soil, the soil acidity level, and the extent of the mixing between the soil and the leachate, as well as the initial pH of the RCA leachate. Equilibrium calculations found that pH levels decreased as the L/S ratio decreased and as the acidity levels increased. Soil acidity, particularly the acidity due to exchangeable aluminum will be expended over time, and therefore, the neutralization capacity of the soil will correspondingly decrease.
- Carbon dioxide will react with the hydroxide ions in the leachate to reduce the pH of the leachate. Equilibrium calculations indicated that the degree of neutralization resulting from the carbon dioxide in the in the soil porosity under an RCA road base would be small if the carbon dioxide was not replenished by simultaneous biodegradation of organic matter in deeper regions of the soil. The effect of carbonation resulting from CO_2 produced by biological activity in the soil could not be quantified, but might possibly be substantial.
- RCA leachate passing through a soil column and entering underlying groundwater will increase the pH of the groundwater, but the degree of this increase will depend on the degree of dilution, the pH of the RCA leachate and the groundwater, and the acidity of groundwater.
- Laboratory tests indicated that soil columns will neutralize the alkaline RCA leachate passing through it, to a limited extent, but over time, pH of the effluent would return to its original value.
- Based on a review of the literature and previous experience of the authors on the subject of beneficial use of waste materials, heavy metal migration from RCA to groundwater will likely be limited. Heavy metal testing of Florida RCA and pollutant attenuation modeling specific to Florida environments is required to fully address this issue.
- Results from previous laboratory testing and from new experimental work on Florida RCA suggest that some degree of pH elevation will occur in the soil underneath an RCA road base. Though some degree of pH reduction was demonstrated through laboratory testing and chemical modeling, the influence of transient conditions and carbonation as a result of microbial respiration could not be accounted for in the research performed thus far, and additional testing is required.

With regard to the CGR work, the following findings and comments should be of interest to FDOT.

- The process of concrete grinding generates a low-solids wastewater that is elevated in pH.
- A number of state agencies, including the FDOT, have recognized the need to manage CGR in an appropriate manner to prevent environmental degradation as a result of discharging high pH material to the environment.
- Previous FDOT testing on CGR in Florida has found that the CGR is not a hazardous waste.
- CGR pH was measured over a range of L/S ratios, and at different times during sampling and analysis. The pH ranged from 11.0 to 12.4 depending on the amount of liquid present. The pH was measurably higher in samples that contained less amounts of water, and were more neutral in samples with high L/S ratios.
- Total elemental analysis of CGR found arsenic and barium to exceed Florida soil cleanup target levels for residential use, but these elements were well under commercial use thresholds, suggesting that land application of CGR as an amendment should have limited concern as long as application rates are limited.
- Currently, in Florida, CGR disposal is handled at the discretion of the contractor. The contractor is responsible for making contact with the concrete recycling center or processing plant that is used in the disposal process and ensuring proper transportation is available
- Best management practices for CGR have been developed by the concrete grinding industry, and several State DOTs recognize and require implementation of such requirements. Management of CGR in a similar approach as concrete truck washout is a common practice that should provide appropriate protection. If CGR is discharged adjacent to roadways, this should only be conducted in a manner protective of adjacent aquatic ecosystems.

5.0. Research Plan for Needed RCA Characterization

Based on the results of the research effort presented herein and the data gaps identified, the investigators believe additional research is required to fully examine whether limitations on the use of RCA as road base are warranted because of concerns over elevated pH and heavy metals, and if so, what these limitations should be (e.g., distance to groundwater, soil types, metal conduit presence). The following research plan is proposed.

The samples of RCA collected for the current effort should be characterized for total (mg/kg) and leachable (mg/L) heavy metal content using standardized EPA leaching procedures. Standardized leaching tests to be conducted would include similar tests as performed for the study on pH leaching (EPA method 1316) in addition to EPA method 1313 (metal leaching as a function of pH). A conclusion resulting from the literature review was that pH does change as the RCA ages in the environment, and that changes in pH can dramatically affect leached metal concentrations. The batch leaching tests will provide a broad characterization of heavy metal leaching of Florida RCA, a sense of how Florida RCA compares to other sources as reported in the literature, and a measure of the variation among RCA sources throughout Florida. Based on the literature review, arsenic, chromium, and lead should be target metals for analysis, but other metals should be included for completeness (those with risk-based target levels in FAC 62-777).

Larger-scale one-dimensional flow through experiments (e.g., column experiments) should then be conducted to better evaluate the mobility of RCA leachate in the environment under conditions similar to those encountered in practice. A conceptual schematic of the experimental setup is presented in Figure 5.1. The experimental apparatus portrayed in Figure 5.1 is a downward flowing leaching column (often referred to as a lysimeter); an alternative approach would be to construct a vault or box that would provide a larger area. A layer of compacted RCA will be placed at the surface of the lysimeter. RCA sources for the lysimeter experiments will be selected based on the results from the batch leaching tests outlined above; a representative RCA or a blend of RCA sources will be used to best position the research outcomes to address target objectives. Below the compacted RCA, a soil column that has been characterized with respect to typical soil quality characteristics (including acidity) will be included. Synthetic rainwater will be added to the surface of the compacted RCA and liquid samples would be collected at different depths within the column (e.g., at the base of the RCA, in the middle of the soil column, and at the termination of the soil column). Multiple columns will be constructed to control three primary variables: soil type, soil depth and infiltration rate. Several control lysimeters without RCA (substituted with limerock) will be constructed and operated in the same fashion.

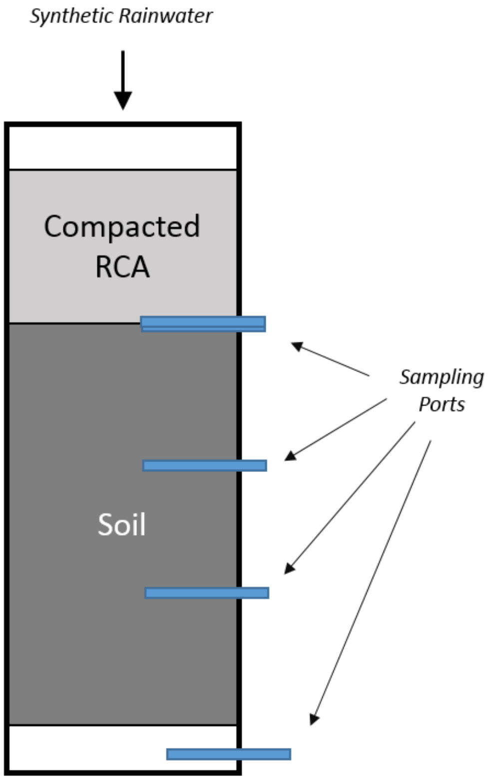


Figure 5.1. Conceptual illustration of experimental lysimeter

During installation, coupons representative of the types of metal conduit likely to be present under roadways constructed with RCA will be placed within the columns. The columns will be operated for 12 months. The infiltration rates tested will represent a range of conditions likely to be encountered with paved roadways in Florida. Leachate collected from the bottom of the lysimeters (passing through the complete soil column) will be monitored weekly for pH, heavy metal content, and other pertinent water quality parameters. Leachate will be withdrawn from the sampling ports to test for pH weekly and heavy metals monthly. Measurements of carbon dioxide in the soil pore space will be monitored in both the control and RCA columns; an objective of the experimental design will be to simulate true soil biotic conditions that result in CO_2 respiration. If sufficient CO_2 concentrations in the columns cannot be reproduced, additional CO_2 will be added. At the end of the experiments, the soil columns will be dismantled and the soil depth profiles will be tested for pH and total heavy metal content. Metals coupons will be collected and tested for appropriate characteristics (i.e., corrosion); these will be compared to control coupons placed in the columns.

The results of the leaching and soil concentration data will be used to develop parameters that can be incorporated into models of chemical mobility from RCA over a range of typical roadway conditions encountered in Florida. A combination of the experimental and modeling results will be used to provide FDOT with opinions regarding whether a need to exists to place limitations (e.g., soil depth, soil type) on the use of RCA as road base, and if so, what those limitations should be.

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Appendices

Appendix A: Moisture Content Data of RCA Samples

Calculation of the moisture content for RCA samples is calculated as follows.

$$MC = \frac{W1 - W2}{W1 - W_c} \times 100$$

Where, MC = moisture content of sample
W1 = mass of container and moist sample (g.)
W2 = mass of container and oven-dried sample (g.)
W_c = mass of container (g.)

Solids content is found as follows:

$$Solids\ contents = 100 - moisture\ content\ (\%)$$

Table A. 1. Moisture and solid contents of recycled concrete aggregate samples collected from

Sample	Solids Content	Moisture Content
ECR1	91.55%	8.45%
ECR2	93.15%	6.85%
ER1	85.53%	14.47%
ER2	85.19%	14.81%
MR1	90.24%	9.76%
MR2	89.49%	10.51%
PJ1	92.93%	7.07%
PJ2	91.14%	8.86%
RRF1	91.14%	8.86%
RRF2	93.59%	6.41%
SG1	92.75%	7.25%
SG2	92.36%	7.64%
TS1	86.96%	13.04%
TS2	84.51%	15.49%
WS1	90.49%	9.51%
WS2	89.09%	10.91%

eight recycling facilities in Florida

Appendix B: Percent Passing of RCA at Various Sieves

Sieve analysis was performed on approximately 1000 g oven-dried samples using sieves of 50 mm, 19.1 mm, 9.52 mm, 4.75 mm, 2 mm, 0.3 mm, and 0.075 mm, in accordance with Florida method FM 1-T027. Weight of RCA sample retained on each sieve was measured and percent passing was calculated as follows.

Percent passing of sample through nth sieve is calculated as follows:

$$Percent\ retained\ on\ n^{th}\ sieve = \frac{Mass\ retained\ on\ n^{th}\ sieve}{Total\ mass\ of\ sample\ analyzed} \times 100$$

$$Percent\ Passing\ from\ from\ n^{th}\ sieve$$
$$= Percent\ passing\ from\ (n-1)^{th}\ sieve - Percent\ retained\ on\ n^{th}\ \text{sieve}$$

Table A. 2. Particle size distribution of recycled concrete aggregate samples collected from eight recycling facilities in Florida

Weights Retained on the sieve for respective samples (g)							
Sieve Size	2"	3/4"	3/8"	No 4	No 10	No 50	No 200
ECR1	0.0	35.7	153.4	114.1	114.2	361.5	177.0
ECR2	0.0	107.8	183.4	102.7	98.5	297.8	177.6
ER1	0.0	291.0	199.9	127.2	94.0	139.0	69.5
ER2	0.0	181.3	141.1	160.1	148.3	217.9	88.8
MR1	0.0	122.0	204.0	194.0	180.0	341.5	163.0
MR2	0.0	183.0	221.5	185.0	176.0	341.5	177.5
PJ1	0.0	169.9	141.1	133.2	128.8	242.7	143.6
PJ2	0.0	171.8	169.7	123.9	112.7	224.9	134.8
RRF1	0.0	101.5	315.8	195.8	150.7	257.6	253.8
RRF2	0.0	332.2	333.5	163.4	121.7	216.3	231.7
SG1	0.0	474.0	375.5	145.5	70.0	103.5	123.0
SG2	0.0	541.0	385.5	84.5	38.0	98.0	115.5
TS1	0.0	134.9	188.6	114.9	106.4	286.6	130.7
TS2	0.0	66.5	236.0	118.7	106.0	283.8	122.5
WS1	0.0	174.5	328.5	230.5	133.5	204.0	63.0
WS2	0.0	86.5	254.0	262.5	190.5	304.0	86.0

Table A. 3. Particle size distribution (Percent passing) of recycled concrete aggregate samples collected from eight recycling facilities in Florida compared to FDOT requirements for a certified product for use as road base, called as a B12 product in FDOT language

Percent passing of RCA sample from specific sieve size (%)							
Sieve Size	2"	3/4"	3/8"	No 4	No 10	No 50	No 200
ECR1	100.0	96.3	80.4	68.5	56.7	19.2	0.8
ECR2	100.0	89.0	70.2	59.7	49.6	19.2	1.0
ER1	100.0	68.7	47.2	33.5	23.4	8.5	1.0
ER2	100.0	80.8	65.9	49.0	33.3	10.2	0.8
MR1	100.0	90.0	73.3	57.4	42.7	14.7	1.4
MR2	100.0	86.0	69.1	55.0	41.5	15.4	1.9
PJ1	100.0	82.5	68.0	54.2	41.0	16.0	1.2
PJ2	100.0	81.9	64.0	50.9	39.0	15.3	1.0
RRF1	100.0	92.1	67.7	52.5	40.9	20.9	1.3
RRF2	100.0	76.5	53.0	41.4	32.8	17.6	1.2
SG1	100.0	63.8	35.1	24.0	18.7	10.8	1.4
SG2	100.0	57.7	27.6	21.0	18.0	10.4	1.4
TS1	100.0	86.2	66.9	55.1	44.2	14.8	1.5
TS2	100.0	93.0	68.2	55.7	44.5	14.7	1.8
WS1	100.0	84.8	56.1	36.0	24.3	6.5	1.0
WS2	100.0	92.8	71.6	49.7	33.8	8.5	1.3
Minimum	100.0	65.0	40.0	25.0	20.0	5.0	0.0
Maximum	100.0	95.0	85.0	65.0	50.0	25.0	10.0

Appendix C: pH and Conductivity of RCA Leachate Generated from RCA Samples at Various L/S

EPA LEAF 1316 test guidelines were followed to run liquid-solid partitioning between water and RCA materials under equilibrium conditions. Five parallel batch tests per sample were performed using reagent water at L/S of 10, 5, 2, 1, and 0.5. Samples were mixed by rotation for 24 hours at 28 ± 2 rpm. The vessels were centrifuged at 4000 ± 100 rpm for 15 minutes to clarify the solution. Conductivity and pH were measured for all the extractions after filtration through polypropylene 0.45 µm membrane following EPA standard procedure 9040 found in SW-846 and ASTM 1125 respectively.

Table A. 4. pH of leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

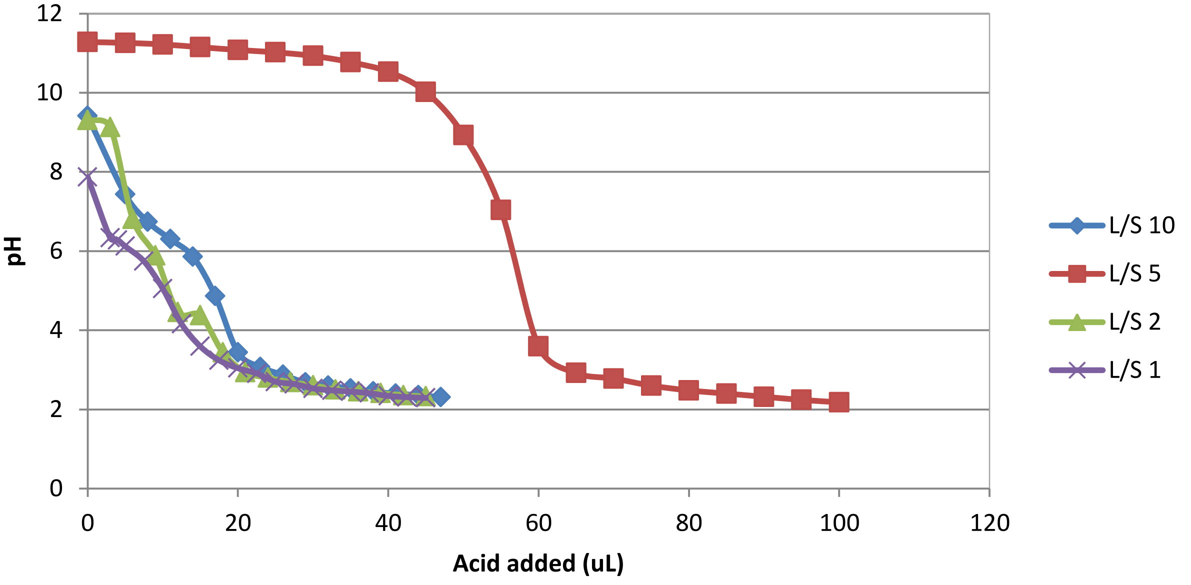
Samples	pH of RCA leachate generated from RCA samples at various L/S				
L/S	10	5	2	1	0.5
ECR1	10.7	10.82	10.94	11.05	11.93
ECR2	10.58	10.98	11.4	11.55	11.56
ER1	11.86	11.97	11.98	12.15	12.18
ER2	11.65	11.72	11.88	11.95	12.05
MR1	11.15	11.43	11.37	11.95	12.01
MR2	11.28	11.56	11.36	11.89	11.93
PJ1	10.96	11.06	11.28	11.43	11.5
PJ2	11.08	11.13	11.29	11.38	11.44
RRF1	11.04	11.13	11.31	11.4	11.57
RRF2	10.93	11.34	11.43	11.38	11.58
SG1	11.47	11.6	11.49	11.6	11.94
SG2	11.31	11.32	11.66	11.21	11.43
TS1	11.1	11.42	12.1	12.14	12.1
TS2	11.34	11.44	11.79	11.91	11.93
WS1	11.64	11.38	11.82	11.41	12.07
WS2	11.36	11.35	12.26	11.72	12.26
Limerock 1	8.72	8.4	8.04	7.9	7.56
Limerock 2	8.88	8.5	7.98	7.75	7.42

Table A. 5. Conductivity of leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

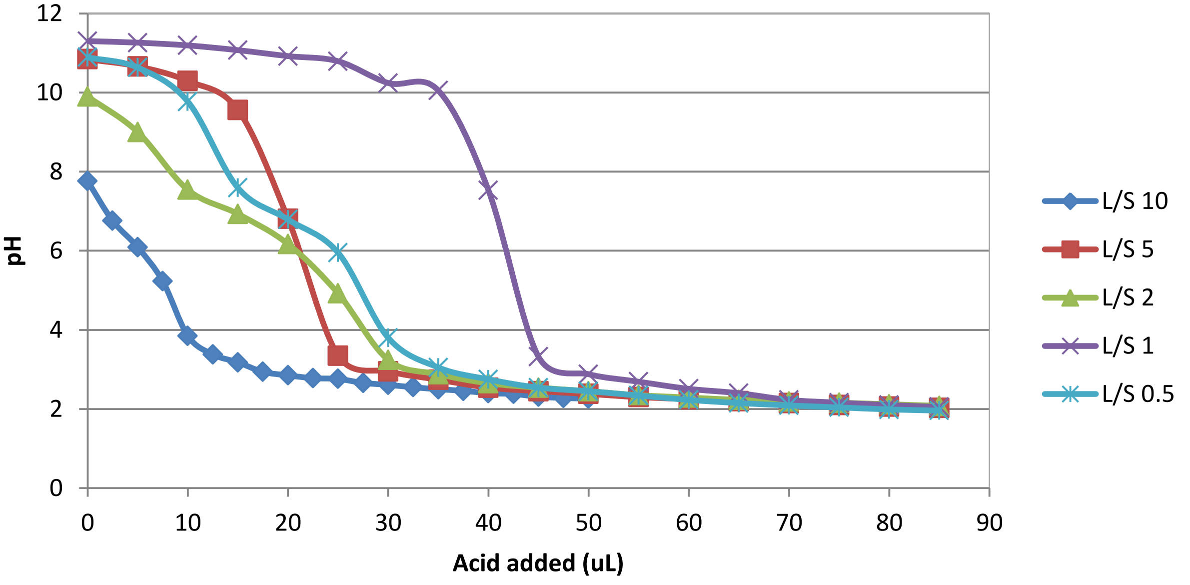
Samples	Hydraulic Conductivity (µS/cm) of RCA leachate generated from RCA samples at various L/S				
L/S	10	5	2	1	0.5
ECR1	672	716	792	823	
ECR2	680	730	757	834	
ER1	6227	6797	7336	8432	
ER2	6326	6848	7595	7772	
MR1	1464	1858	2272	3132	3526
MR2	1506	1994	2288	3336	3665
PJ1	2246	3051	3211	3463	
PJ2	2036	3200	3238	6156	
RRF1	1893	2490	3230	4685	1157
RRF2	1920	2085	2347	2625	
SG1	1232	1521	2253	1987	3780
SG2	1216	1899	2240	3128	6328
TS1	1412	1854	2624	3358	
TS2	1460	1860	2720	3070	
WS1	3128	5274	5889	8286	8038
WS2	3562	4890	6445	8167	7692
Limerock 1	76	102	183	256	377
Limerock 2	93	112	177	253	387

Appendix D: Alkalinity of RCA Leachate

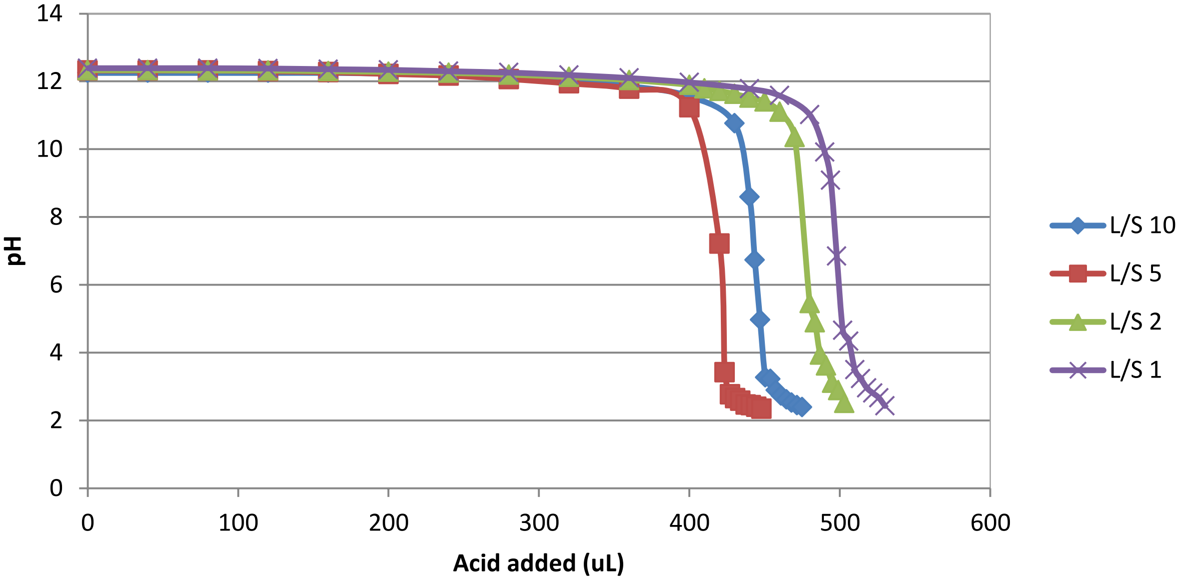
To calculate alkalinity of RCA leachates, sample was titrated by adding small increments of 1.6 N sulfuric acid, and pH was plotted against every acid addition.



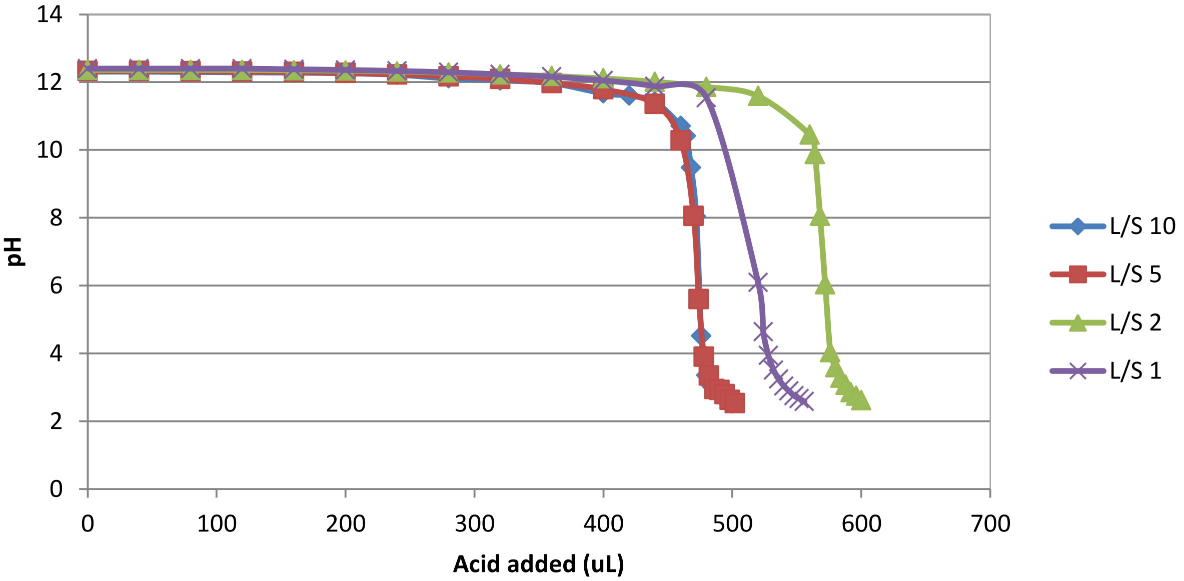
pH vs acid added for alkalinity analysis a: RCA sample ECR 1



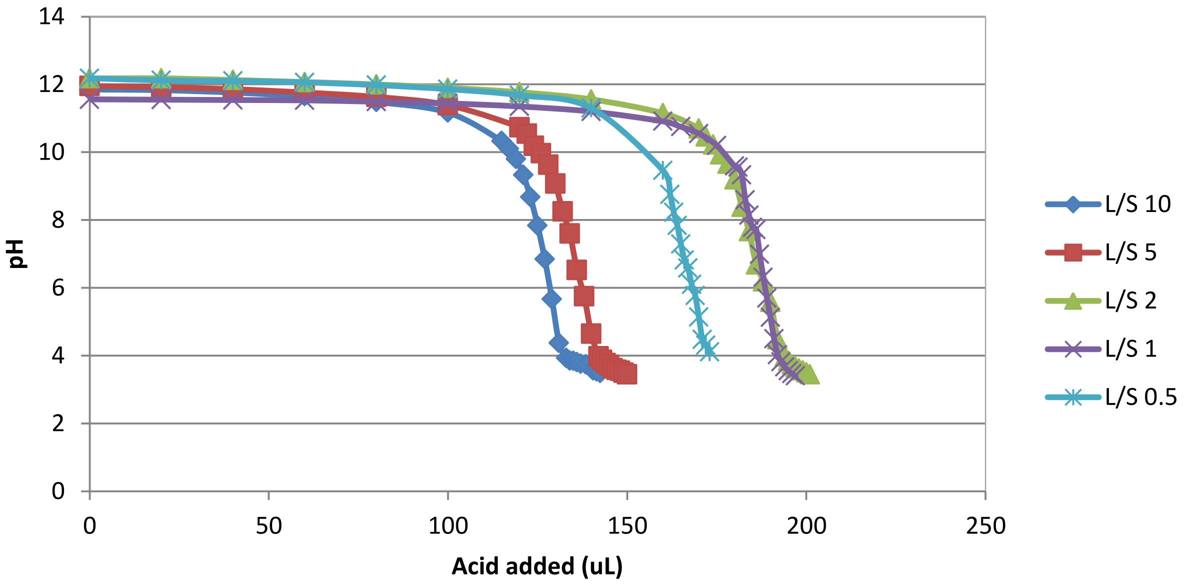
pH vs acid added for alkalinity analysis b: RCA sample ECR 2



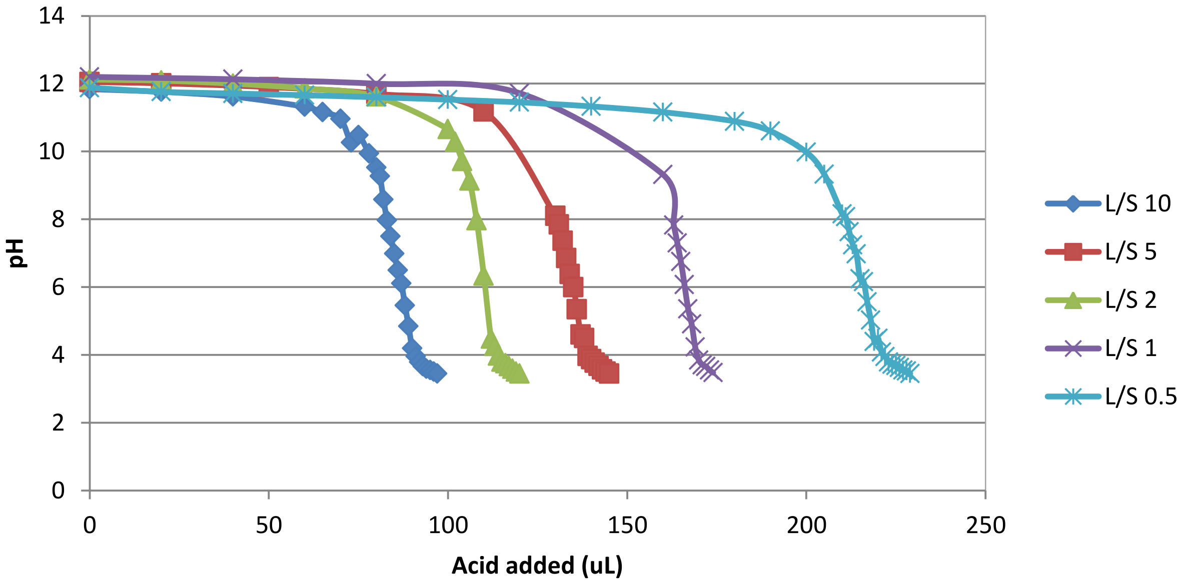
pH vs acid added for alkalinity analysis c: RCA sample ER 1



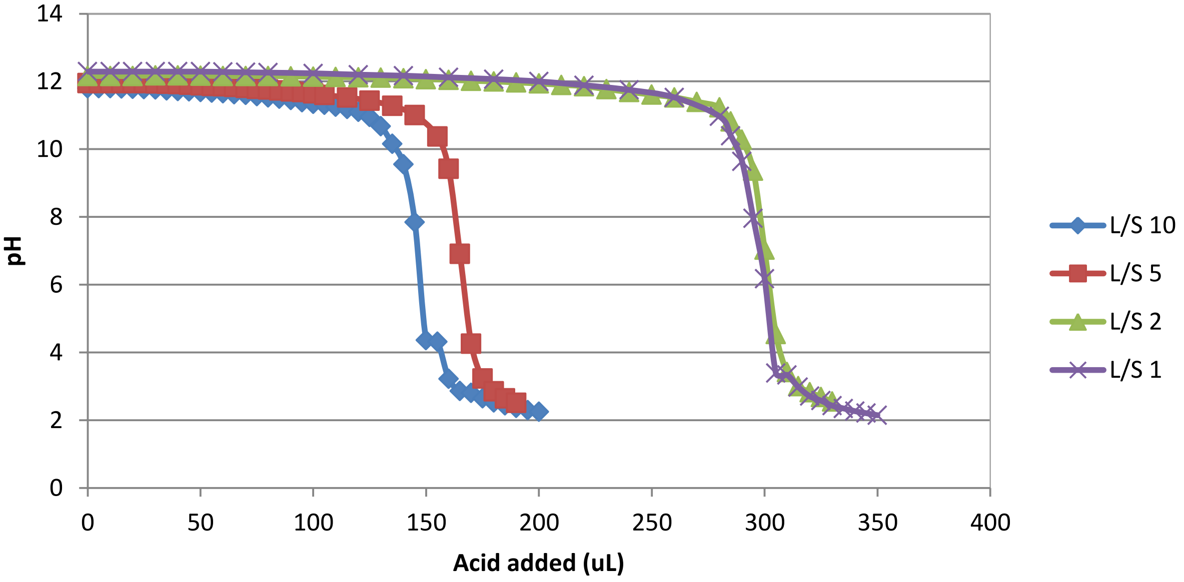
pH vs acid added for alkalinity analysis d: RCA sample ER 2



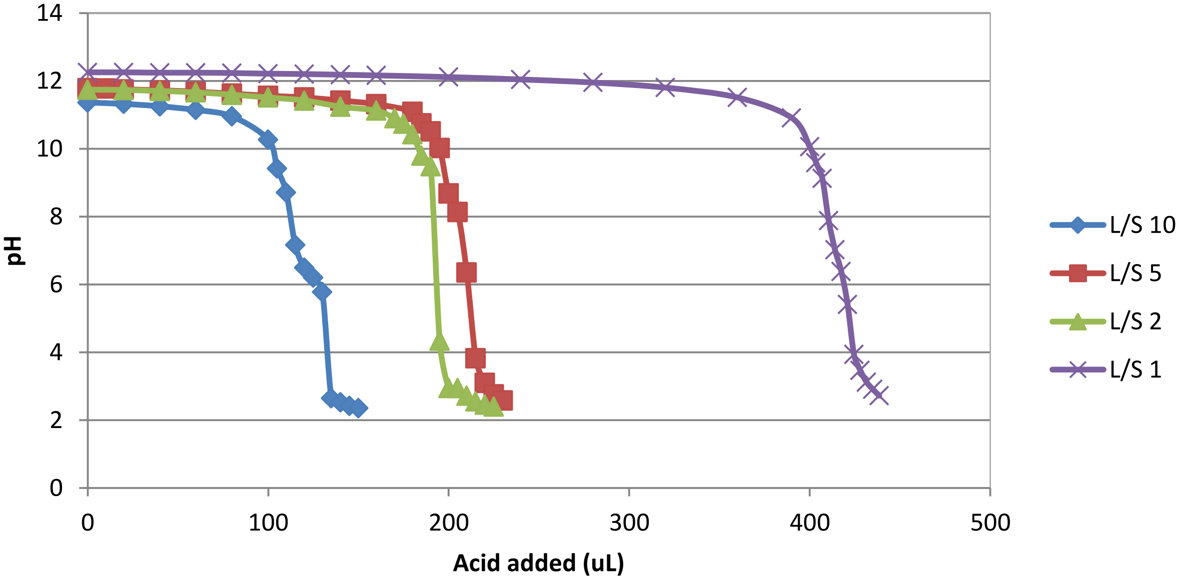
pH vs acid added for alkalinity analysis e: RCA sample MR 1



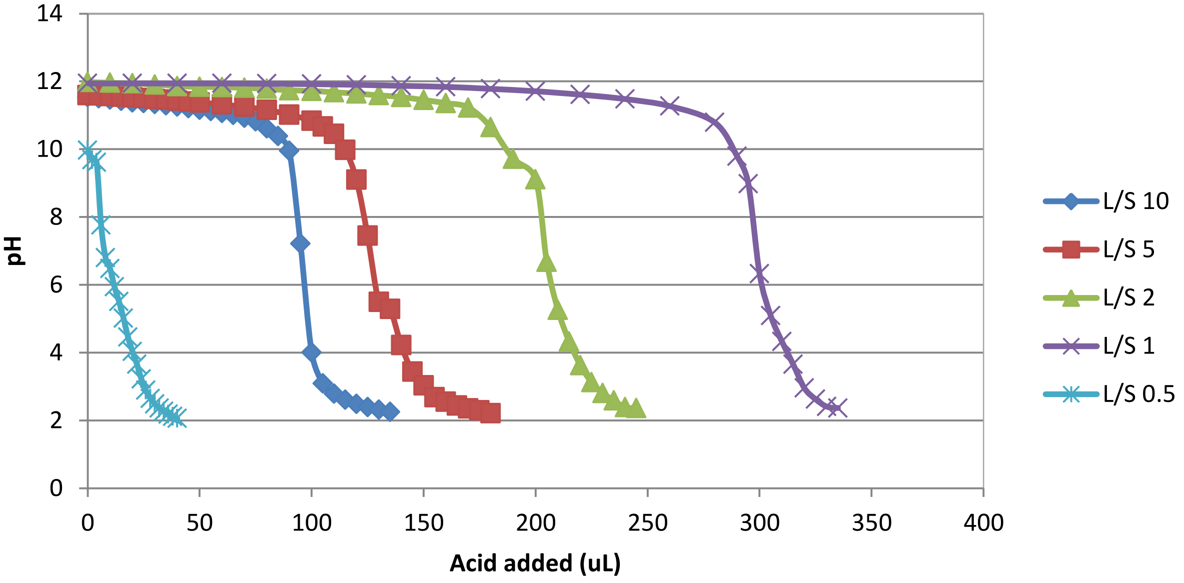
pH vs acid added for alkalinity analysis f: RCA sample MR 2



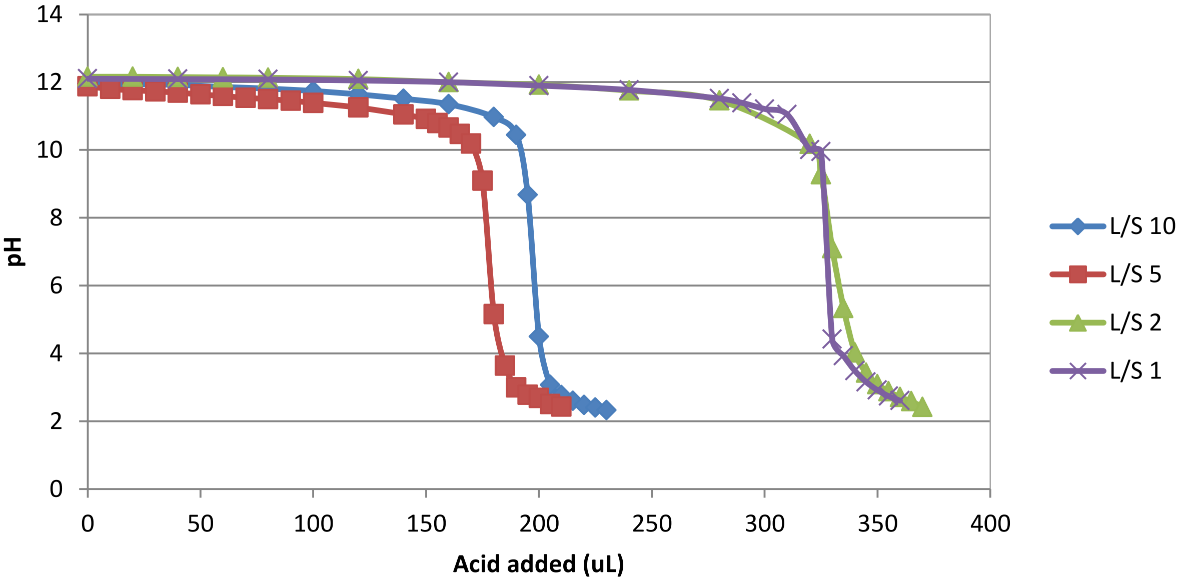
pH vs acid added for alkalinity analysis g: RCA sample PJ 1



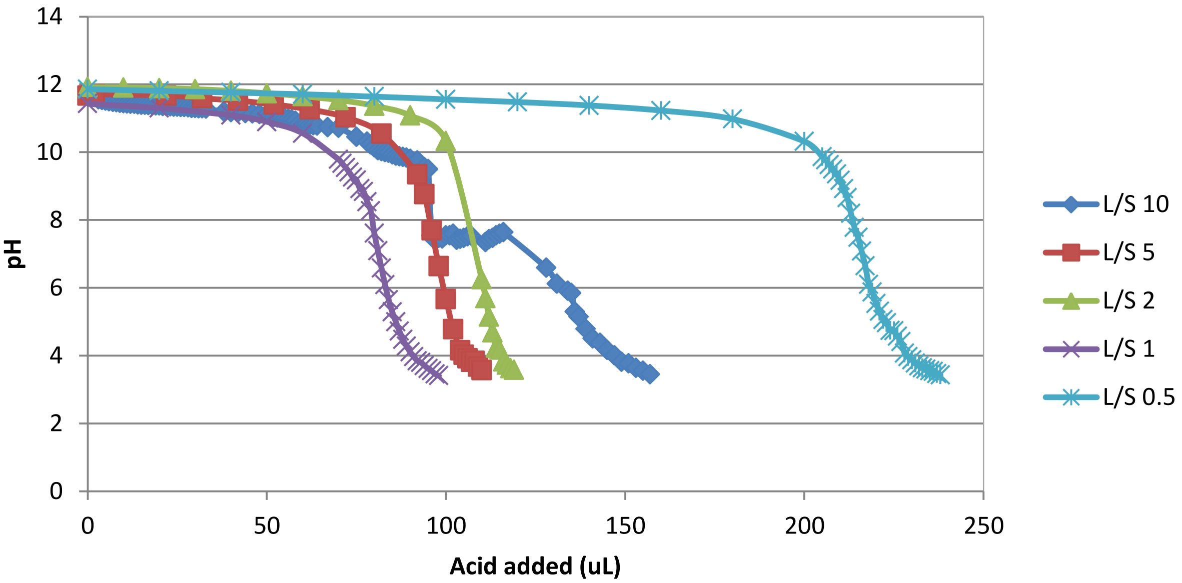
pH vs acid added for alkalinity analysis h: RCA sample PJ2



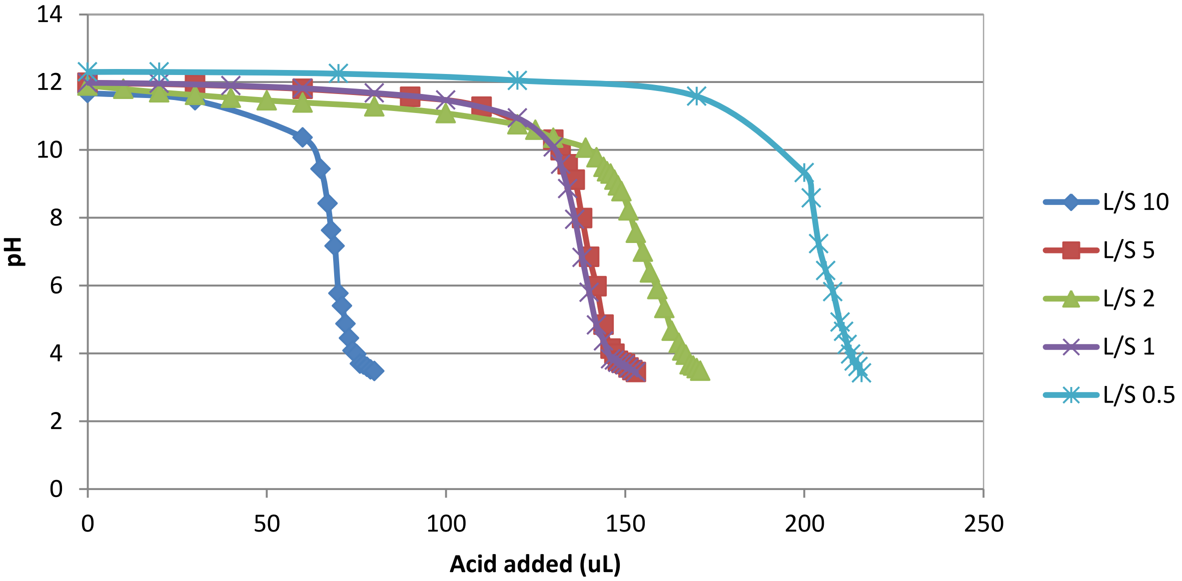
pH vs acid added for alkalinity analysis i: RCA sample RRF 1



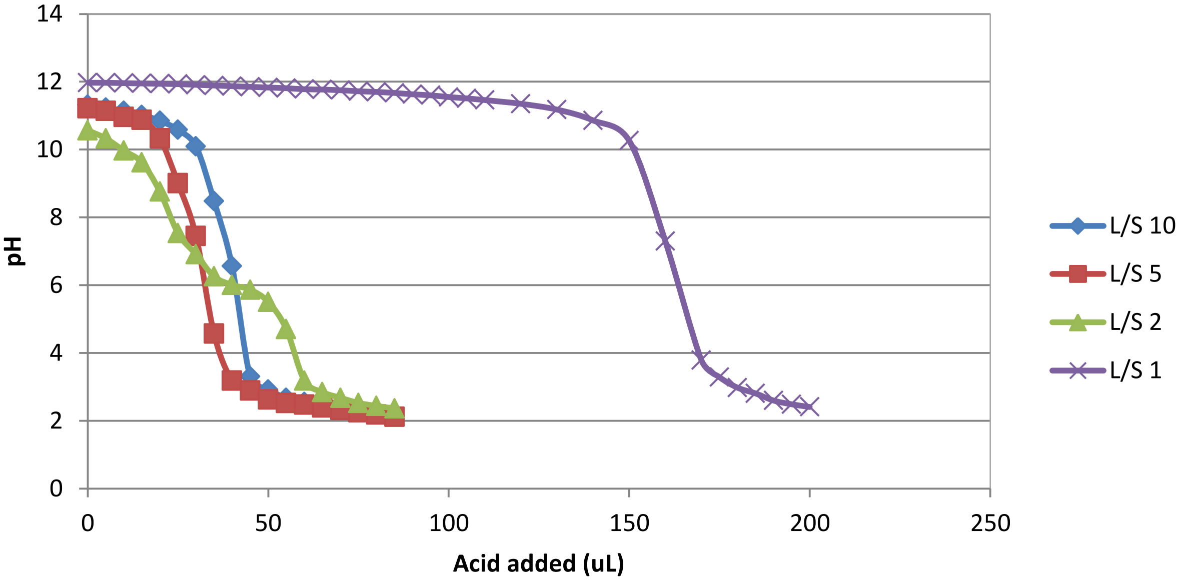
pH vs acid added for alkalinity analysis j: RCA sample RRF 2



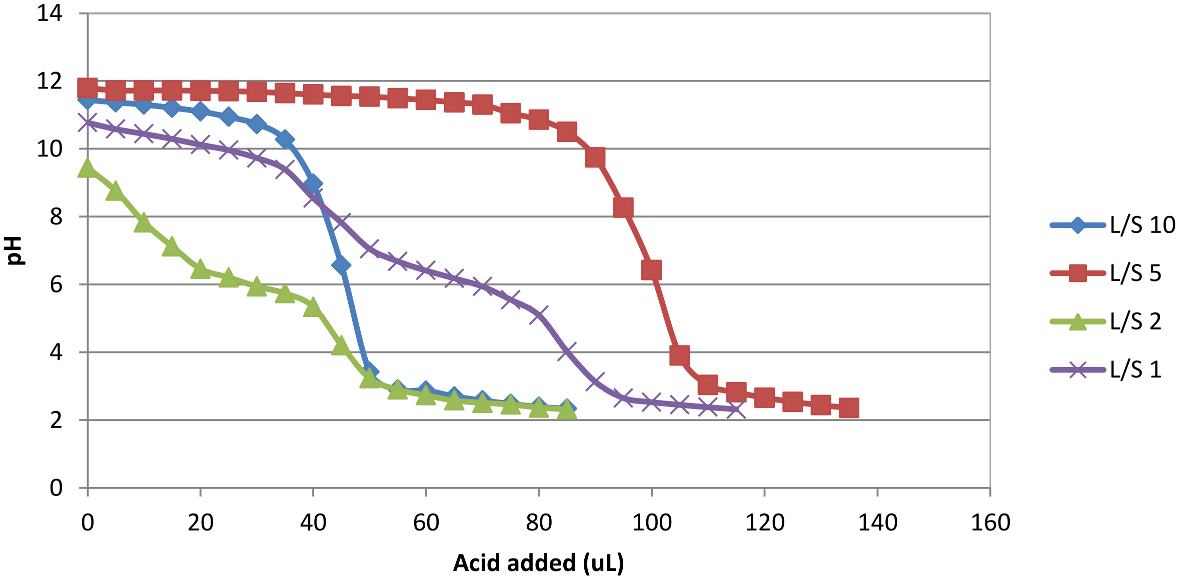
pH vs acid added for alkalinity analysis k: RCA sample SG 1



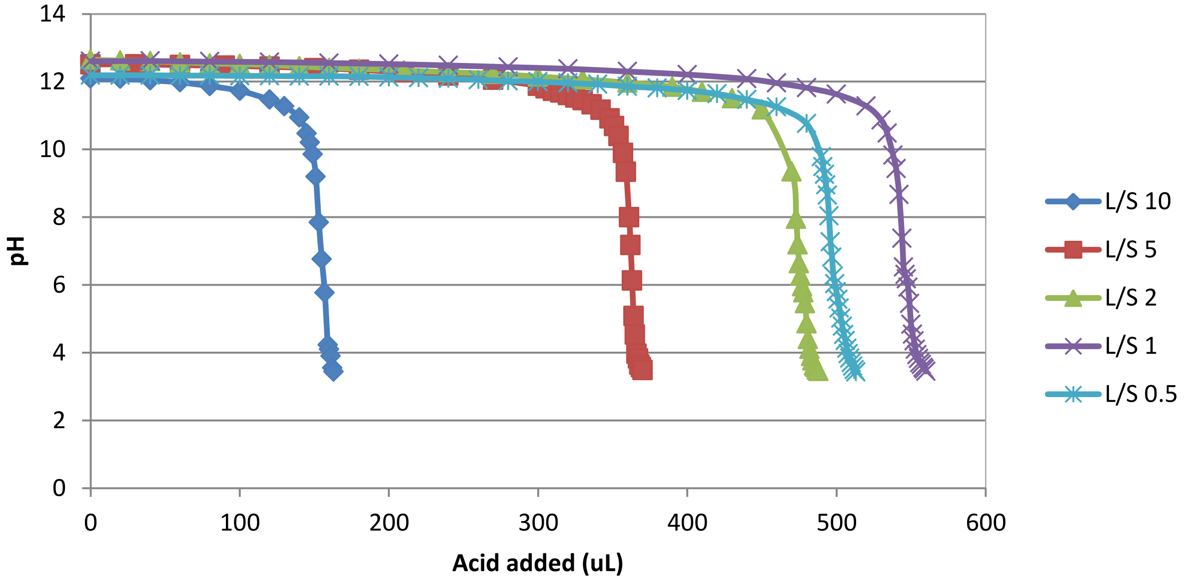
pH vs acid added for alkalinity analysis l: RCA sample SG 2



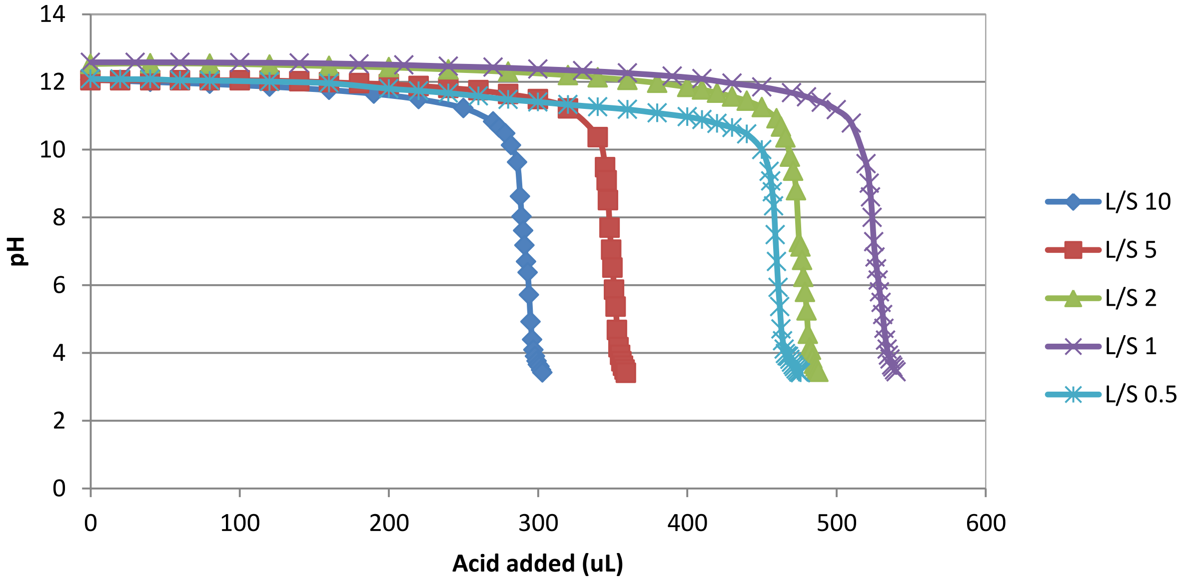
pH vs acid added for alkalinity analysis m: RCA sample TS 1



pH vs acid added for alkalinity analysis n: RCA sample TS 2



pH vs acid added for alkalinity analysis o: RCA sample WS 1



pH vs acid added for alkalinity analysis p: RCA sample WS 2

Amount of sulfuric acid added till the carbonate equivalence point of approximately pH near 4.5 was noted. Alkalinity is calculated following the guidelines from USGS TWRI book 9, chapter A6.

$$Alk = \frac{B \times C_a \times CF}{V_s} \times 1000$$

$$Alk\ (\frac{mg}{L} as\ CaCO_3) = Alk \times \frac{1\ mmol\ CaCO_3}{2\ meq} \times \frac{100.087\ mg\ CaCO_3}{1mmol\ CaCO_3}$$

Where,
Alk is the alkalinity of the sample (meq/L)
B is the volume of titrant added from initial pH to bicarbonate equivalent point (near pH 4.5), in milliliters
C_a is the concentration of acid titrant (C_a = 1.6 N)
CF is the correction factor (CF = 1)
V_s is the volume of sample titrated, in milliliters

Alkalinity for all the samples are given in following table

Table A. 6. Alkalinity of leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

RCA Sample used for extraction	L/S used for extraction	Volume of titrant added (B), in mL	Volume of sample (Vs), in mL	Alkalinity (Alk), in meq/L	Alkalinity as $CaCO_3$, in mg/L
ECR1	10	0.02	21.5	1.27	63.3
ECR1	5	0.06	19	5.05	252.9
ECR1	2	0.01	20.5	0.94	46.9
ECR1	1	0.01	16.5	1.21	60.7
ECR2	10	0.02	22	1.09	54.6
ECR2	5	0.03	20	2	100.1
ECR2	2	0.03	20	2	100.1
ECR2	1	0.05	16.5	4.36	218.4
ECR2	0.5	0.03	12.5	3.84	192.2
ER1	10	0.45	21	34.06	1704.3
ER1	5	0.42	21	32.27	1614.7
ER1	2	0.49	20.5	38.1	1902.1
ER1	1	0.5	20.5	39.18	1960.7
ER2	10	0.48	20	38.08	1905.7
ER2	5	0.48	20	38.24	1913.7
ER2	2	0.58	23.5	39.22	1962.6

Table A. 6. Alkalinity of leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

RCA Sample used for extraction	L/S used for extraction	Volume of titrant added (B), in mL	Volume of sample (Vs), in mL	Alkalinity (Alk), in meq/L	Alkalinity as $CaCO_3$, in mg/L
ER2	1	0.52	20	41.92	2097.8
MR1	10	0.13	30	6.99	349.6
MR1	5	0.14	26	8.62	431.1
MR1	2	0.19	29	10.59	530.1
MR1	1	0.19	24	12.73	637.2
MR1	0.5	0.17	18	15.2	760.7
MR2	10	0.09	20	7.12	356.3
MR2	5	0.14	25	8.77	438.8
MR2	2	0.11	17	10.54	527.5
MR2	1	0.17	20	13.68	684.6
MR2	0.5	0.22	24	14.6	730.6
PJ1	10	0.15	21	11.43	571.9
PJ1	5	0.17	20	13.6	680.6
PJ1	2	0.31	21	23.24	1162.9
PJ1	1	0.31	15	30.5	1526.3
PJ2	10	0.13	15	13.87	693.9
PJ2	5	0.22	20	17.2	860.7
PJ2	2	0.2	20	15.6	780.7
PJ2	1	0.42	20	33.96	1699.5
RRF1	10	0.1	20	8	400.3
RRF1	5	0.14	20	11.2	560.5
RRF1	2	0.22	20	17.2	860.7
RRF1	1	0.31	20	24.8	1241.1
RRF1	0.5	0.02	7.5	3.84	192.2
RRF2	10	0.2	19	16.84	842.8
RRF2	5	0.18	19.5	14.77	739.1
RRF2	2	0.34	20	27.2	1361.2
RRF2	1	0.33	20	26.4	1321.1
SG1	10	0.1	27	5.69	284.7
SG1	5	0.1	27	6.04	302.5
SG1	2	0.11	19	9.52	476.2
SG1	1	0.09	25	5.57	278.6
SG1	0.5	0.22	25	13.95	698.2
SG2	10	0.07	23	4.87	243.7
SG2	5	0.14	27	8.53	427
SG2	2	0.16	28	9.31	466.1

Table A. 6. Alkalinity of leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

RCA Sample used for extraction	L/S used for extraction	Volume of titrant added (B), in mL	Volume of sample (Vs), in mL	Alkalinity (Alk), in meq/L	Alkalinity as $CaCO_3$, in mg/L
SG2	1	0.14	19	11.96	598.4
SG2	0.5	0.12	12	28.27	1414.6
TS1	10	0.05	20.5	3.51	175.8
TS1	5	0.04	20	2.8	140.1
TS1	2	0.06	21	4.57	228.8
TS1	1	0.17	20	13.6	680.6
TS2	10	0.05	20	4	200.2
TS2	5	0.11	19	8.84	442.5
TS2	2	0.05	19	3.79	189.6
TS2	1	0.09	20	6.8	340.3
WS1	10	0.16	20	12.72	636.6
WS1	5	0.36	25	23.3	1165.8
WS1	2	0.48	25	30.72	1537.3
WS1	1	0.55	23	38.26	1914.7
WS1	0.5	0.51	26	31.08	1555.2
WS2	10	0.3	26	18.15	908.5
WS2	5	0.35	25	22.59	1130.6
WS2	2	0.48	25	30.78	1540.5
WS2	1	0.53	20	42.56	2129.9
WS2	0.5	0.46	22	33.67	1685.1

Appendix E: Calcium Leaching from RCA

A volume of 50mL of all the filtered RCA samples were digested using an automated block digester. The process uses trace metal grade nitric acid and hydrochloric acid according to EPA method 3010A. The digested samples were made to volume 50 mL, by adding deionized water and analyzed for calcium concentration on inductively coupled plasma atomic absorption spectrophotometer (ICP) using EPA method 6010B. The results are given in table below.

Table A. 7. Amount of calcium present in leachate generated from recycled concrete aggregate (RCA) samples at various liquid-to-solid ratios for environmental assessment of RCA as road base

Samples	Calcium concentration in leachate generated from RCA samples at various L/S (mg/L)				
L/S	10	5	2	1	0.5
ECR1	89.39	114	133.51	144.86	150.47
ECR2	84.18	101.88	181.76	145.06	159.62
ER1	694.87	726.7	684.48	560.28	264.23
ER2	665.02	695.53	689.1	586.34	183.08
MR1	134.24	152.43	147.39	170.79	142.55
MR2	137.61	176.15	140.09	166.73	121.18
PJ1	255.65		504.04	340.59	584.53
PJ2	217.22	334.82	430.15	596.57	498.1
RRF1	240.48	284.18	410.03	485.07	491.01
RRF2	345.54	346.69	502.89	495.96	425.86
SG1	124.51	148.23	313.14	251.23	247.49
SG2	121.03	179.4	186.71	220.51	479.54
TS1	165.43	183.57	257.13	241.63	151.71
TS2	175	170.87	217.71	191.49	102.61
WS1	296.73	451.43	538.85	581.91	516.59
WS2	328.74	428.68	628.24	-	540.64

Appendix F: High Acidity Soil interaction with RCA leachate

Chemical analysis of effluent samples from high acidity soil columns are given in tables below. The chemical analysis included measurement of pH, conductivity and redox potential.

Table A. 8. Change in pH of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of high acidity soil and effluent samples were collected at different L/S ratio. Initial pH of RCA leachate was 11.96.

pH of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0.2	6.3	6.9	6.9	6.7	0.3	6.6
0.5	6.2	6.1	6.1	6.1	0.0	6.3
1	4.0	3.9	4.0	4.0	0.0	6.1
1.5	4.2	4.4	4.3	4.3	0.1	6.5
2	5.0	8.1	6.5	6.5	1.6	7.2
4.5	11.9	12.0	12.2	12.0	0.2	6.5
5	11.9	11.9	12.0	11.9	0.0	6.4
9.5	11.7	12.0	12.1	11.9	0.2	6.4
10	11.7	12.0	12.1	11.9	0.2	6.6

Table A. 9. Change in ORP of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of high acidity soil and effluent samples were collected at different L/S ratio.

ORP (mV) of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0.2	52.3	52.0	62.0	55.4	5.7	54.0
0.5	55.6	57.0	56.7	56.4	0.7	59.0
1	168.0	162.0	154.0	161.3	7.0	63.0
1.5	179.0	185.0	169.0	177.7	8.1	60.7
2	120.4	47.0	66.2	77.9	38.1	57.0
4.5	8.7	-7.5	-21.2	-6.7	15.0	67.8
5	-28.0	-26.3	-32.9	-29.1	3.4	68.3
9.5	-12.5	-20.0	-29.0	-20.5	8.3	52.0
10	-25.0	-27.0	-31.0	-27.7	3.1	50.0

Table A. 10. Change in conductivity of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of high acidity soil and effluent samples were collected at different L/S ratio.

Conductivity (µS/cm) of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0.2	40	40	52	44.0	6.9	6.9
0.5	38	40	37	38.3	1.5	1.5
1	110	145	153	136.0	22.9	22.9
1.5	225	337	305	289.0	57.7	57.7
2	390	946	763	699.7	283.4	283.4
4.5	4993	6856	6578	6142.3	1005.0	1005.0
5	8114	8123	8154	8130.3	21.0	21.0
9.5	8699	8541	8507	8582.3	102.5	102.5
10	8612	8593	8603	8602.7	9.5	9.5

Appendix G: Low Acidity Soil interaction with RCA leachate

Chemical analysis of effluent samples from low acidity soil columns are given in tables below. The chemical analysis included measurement of pH, conductivity and redox potential.

Table A. 11. Change in pH of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of low acidity soil and effluent samples were collected at different L/S ratio. Initial pH of RCA leachate was 11.96.

pH of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0	7.0	7.0	7.0	7.0	0.0	7.0
0.2	7.2	7.2	7.2	7.2	0.0	7.0
0.5	8.5	9.0	9.0	8.8	0.3	7.3
1	9.1	9.5	9.3	9.3	0.2	7.3
1.5	9.9	10.2	10.1	10.1	0.2	7.4
2	11.7	11.9	12.0	11.9	0.2	7.5
4.5	12.1	12.1	12.1	12.1	0.0	8.0
5	11.4	12.1	11.8	11.8	0.3	8.1
8.5	12.1	12.1	12.1	12.1	0.0	7.0
9	12.1	12.1	12.2	12.1	0.0	7.3

Table A. 12. Change in ORP of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of low acidity soil and effluent samples were collected at different L/S ratio.

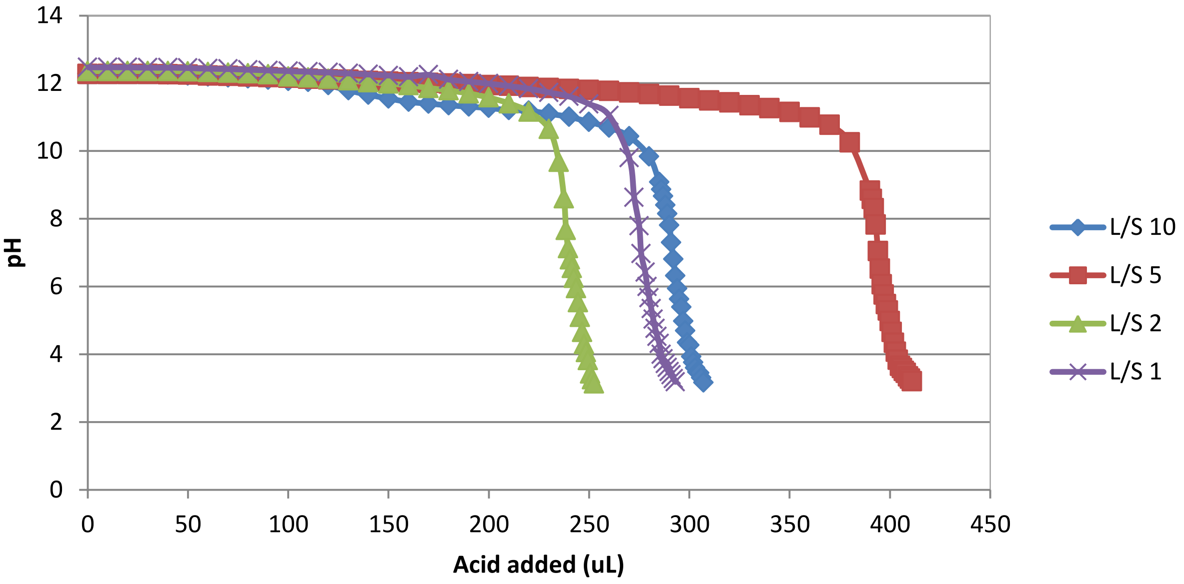
ORP (mV) of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0.2	55.0	60.0	60.0	58.3	2.9	65.0
0.5	40.0	25.0	25.0	30.0	8.7	50.0
1	40.0	25.0	25.0	30.0	8.7	50.0
1.5	40.0	25.0	25.0	30.0	8.7	50.0
2	-30.0	-60.0	-65.0	-51.7	18.9	80.0
4.5	24.0	16.0	4.4	14.8	7.7	54.3
5	-	-22.1	-44.4	-33.3	15.8	69.0
8.5	-30.0	-30.0	-40.0	-33.3	5.8	42.0
9	-30.0	-45.0	-50.0	-41.7	10.4	40.0

Table A. 13. Change in conductivity of effluent as a function of cumulative L/S. Recycled concrete aggregate (RCA) leachate was passed through soil column of high acidity soil and effluent samples were collected at different L/S ratio.

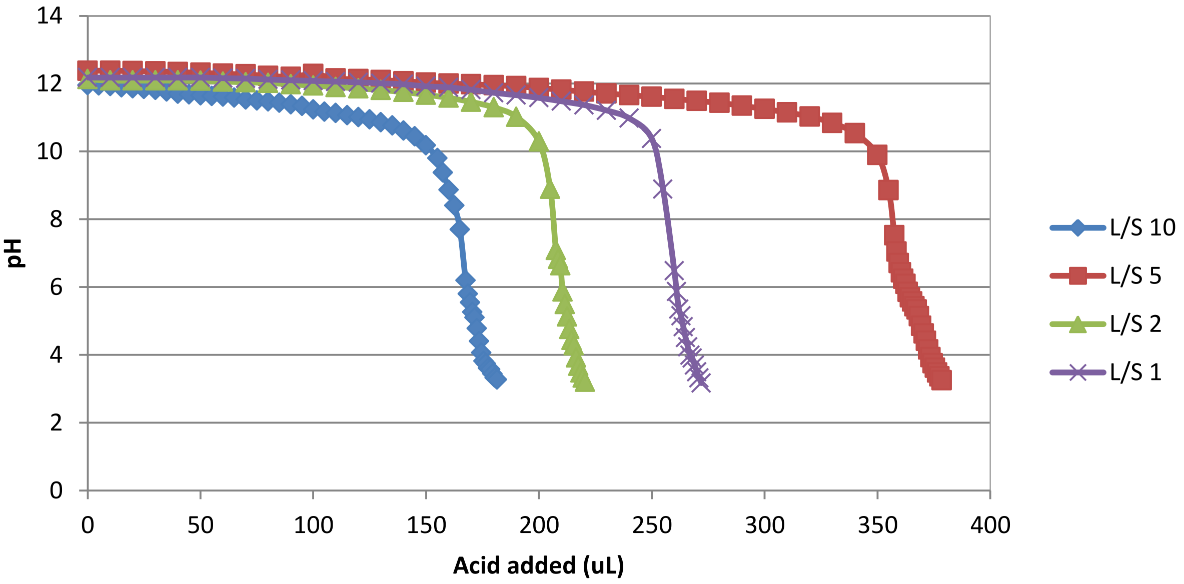
Conductivity (µS/cm) of effluent from triplicate soil columns and control vs L/S						
L/S	A	B	C	Average	Standard Deviation	Control
0.2	83	77	82	80.7	3.2	60
0.5	220	338	313	290.3	62.2	57
1	590	891	1012	831.0	217.3	50
1.5	980	1374	1347	1233.7	220.1	55
2	2245	2806	3289	2780.0	522.5	41
4.5	3390	3613	3243	3415.3	186.3	36
5	-	3667	2283	2975.0	978.6	28
8.5	2380	2837	2699	2638.7	234.4	33
9	2414	2903	2714	2677.0	246.6	30

Appendix H: Alkalinity of CGR Leachate

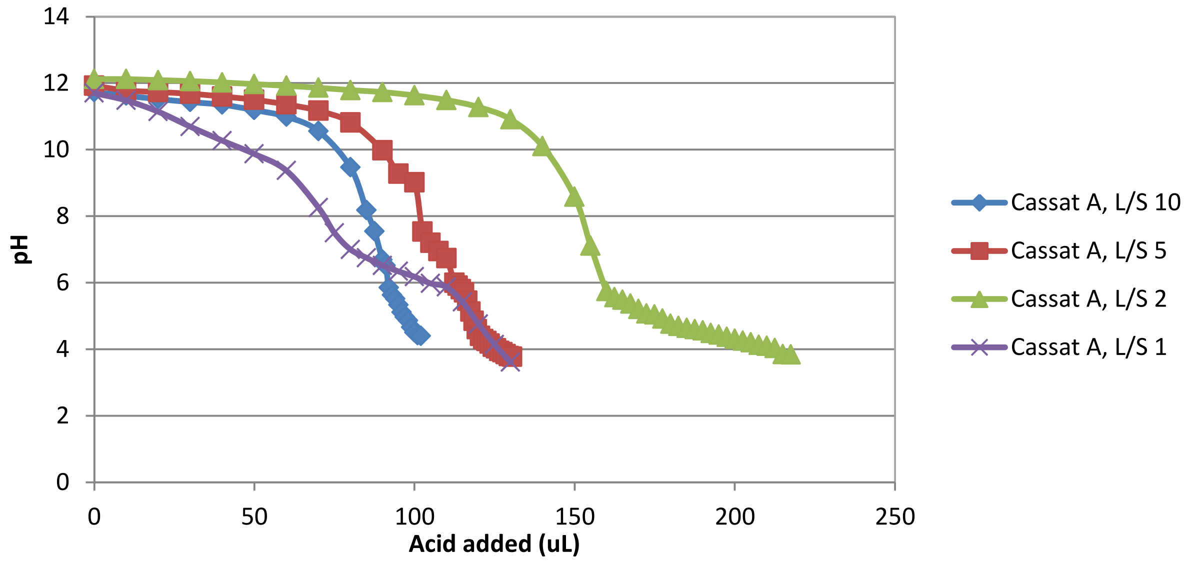
To calculate alkalinity of CGR leachates, sample was titrated by adding small increments of 1.6 N sulfuric acid, and pH was plotted against every acid addition.



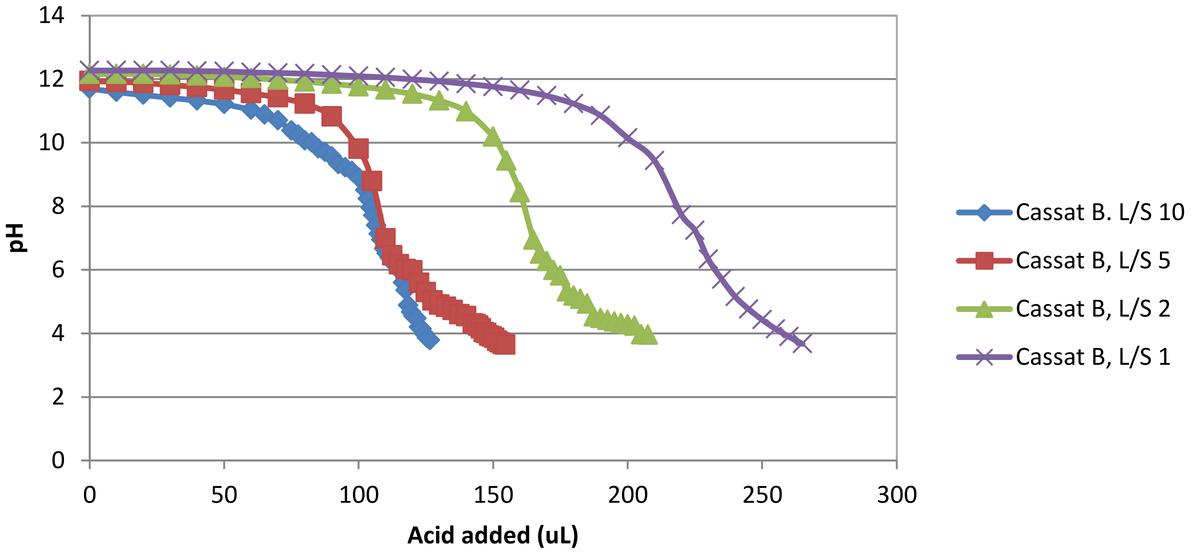
pH vs acid added for alkalinity analysis q. CGR sample Jax 10 A



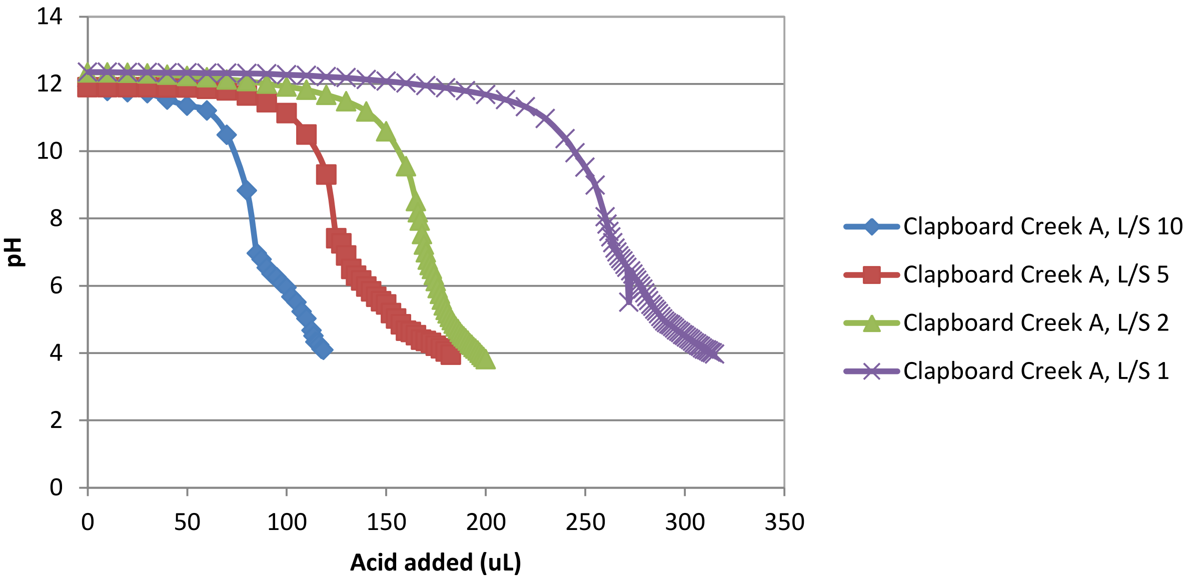
pH vs acid added for alkalinity analysis r. CGR sample Jax 10 B



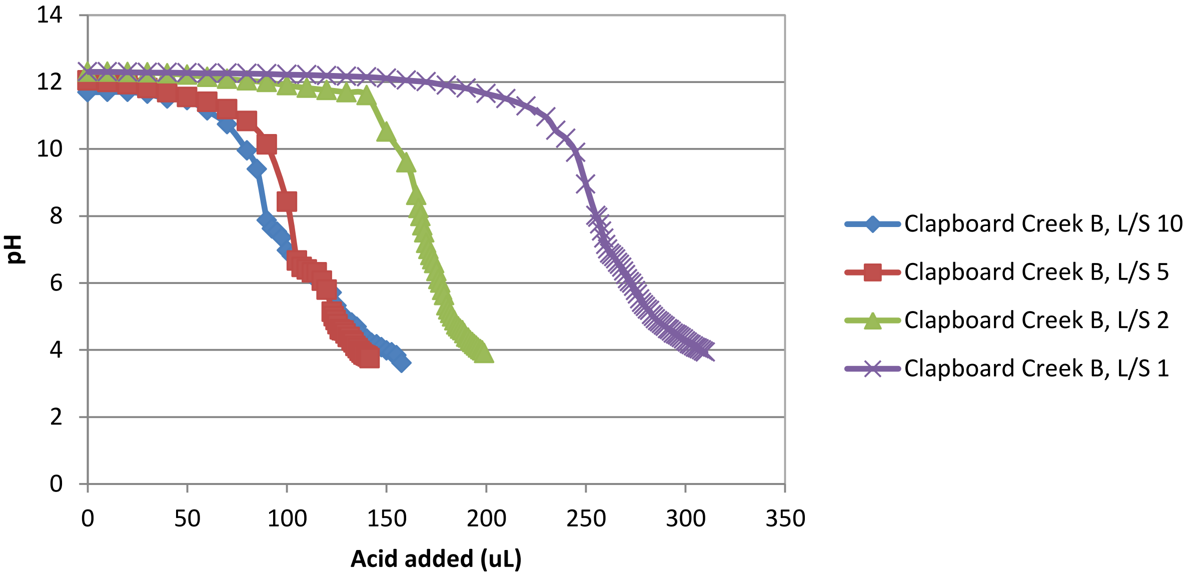
pH vs acid added for alkalinity analysis s. CGR sample Cassat A



pH vs acid added for alkalinity analysis t. CGR sample Cassat B



pH vs acid added for alkalinity analysis u. CGR sample Clapboard Creek A



pH vs acid added for alkalinity analysis v. CGR sample Clapboard Creek B

Amount of sulfuric acid added till the carbonate equivalence point of approximately pH near 4.5 was noted. Alkalinity is calculated following the guidelines from USGS TWRI book 9, chapter A6.

$$Alk = \frac{B \times C_a \times CF}{V_s} \times 1000$$

$$Alk\,(\frac{mg}{L} as\ CaCO_3) = Alk \times \frac{1\ mmol\ CaCO_3}{2\ meq} \times \frac{100.087\ mg\ CaCO_3}{1 mmol\ CaCO_3}$$

Where,
Alk is the alkalinity of the sample (meq/L)
B is the volume of titrant added from initial pH to bicarbonate equivalent point (near pH 4.5), in milliliters
Ca is the concentration of acid titrant (Normal)
CF is the correction factor (equal to 1)
Vs is the volume of sample titrated, in milliliters
Note: 1.6N Sulfuric Acid was used as a titrant

Table A. 14. The calculated alkalinity for each CGR sample. The alkalinity, which is based on the largest change in pH per change in total volume.

CGR Sample used for extraction	L/S used for extraction	Volume of titrant added (B), in mL	Volume of sample (Vs), in mL	Alkalinity (Alk), in meq/L	Alkalinity, expressed as mg/L of $CaCO_3$
Jax 10 A	10	0.35	20	28.0	1401.2
Jax 10 A	5	0.40	20	32.1	1605.4
Jax 10 A	2	0.25	10	39.4	1973.7
Jax 10 A	1	0.28	10	45.4	2273.9
Jax 10 B	10	0.17	20	13.9	694.6
Jax 10 B	5	0.37	20	29.3	1467.3
Jax 10 B	2	0.21	10	34.3	1717.5
Jax 10 B	1	0.26	10	42.4	2121.8
Cassat A	10	0.09	20	7.4	368.3
Cassat A	5	0.10	20	8.2	410.4
Cassat A	2	0.16	20	12.4	620.5
Cassat A	1	0.08	10	12.0	600.5
Cassat B	10	0.12	20	9.5	474.4
Cassat B	5	0.11	20	8.8	440.4
Cassat B	2	0.17	20	13.2	660.6
Cassat B	1	0.23	20	18.4	920.8
Clapboard Creek A	10	0.09	20	6.8	340.3
Clapboard Creek A	5	0.13	20	10	500.4
Clapboard Creek A	2	0.17	20	13.4	672.6
Clapboard Creek A	1	0.27	20	21.8	1088.9
Clapboard Creek B	10	0.09	20	7.2	360.3
Clapboard Creek B	5	0.11	20	8.4	420.4
Clapboard Creek B	2	0.17	20	13.3	664.6
Clapboard Creek B	1	0.26	20	20.7	1036.9

Appendix I: Concentration of Leached Elements (Those Exceeded at Least Once) from CGR Slurry

A volume of 50 mL of all the filtered Jax10 samples were digested using an automated block digester. The process uses trace metal grade nitric acid and hydrochloric acid according to EPA method 3010A. The digested samples were made to volume 50 mL by adding deionized water and analyzed for metals concentration on inductively coupled plasma atomic absorption spectrophotometer (ICP) using EPA method 6010B. Aluminum, chromium, iron, molybdenum, sodium, and strontium were found to exceed their respective Florida groundwater cleanup target levels for some samples, as given in table below.

Table A. 15. Concentration of leached elements from CGR slurry. Only the elements which exceeded at least once over different L/S ratio are presented in the table below.

Element->		**Al**	**Cr**	**Fe**	**Mo**	**Na**	**Sr**
GCTL (mg/L)	**L/S**	**0.2**	**0.1**	**0.3**	**0.035**	**160**	**4.2**
JAX 10 A, T01	10	**1.06**	0.09	0.08	0.02	36.57	**5.38**
JAX 10 A, T02	5	**0.61**	0.07	0.13	0.02	68.96	**9.77**
JAX 10 A, T03	2	**0.45**	0.08	0.06	0.02	148.84	**13.01**
JAX 10 A, T04	1	**0.22**	0.05	0.04	0.01	142.57	**4.63**
JAX 10 B, T01	10	**2.62**	**0.16**	0.10	0.02	42.52	3.05
JAX 10 B, T02	5	**0.60**	**0.11**	0.13	0.02	60.10	**7.94**
JAX 10 B, T03	2	**0.49**	0.09	0.00	0.02	**172.03**	**11.07**
JAX 10 B, T04	1	**0.30**	0.05	0.06	0.01	138.18	**6.16**
Cassat A, T01	10	**5.83**	**0.22**	0.10	**0.16**	57.20	1.08
Cassat A, T02	5	**7.02**	**0.39**	0.22	**0.31**	95.03	0.67
Cassat A, T03	2	**9.89**	**0.97**	**0.49**	**0.75**	**214.34**	0.59
Cassat A, T04	1	**12.44**	**1.54**	**0.90**	**1.35**	**350.35**	0.61
Cassat B, T01	10	**6.00**	**0.18**	0.12	**0.15**	37.52	1.25
Cassat B, T02	5	**6.99**	**0.45**	0.21	**0.32**	64.46	0.83
Cassat B, T03	2	**9.21**	**0.73**	**0.40**	**0.60**	**170.14**	0.81
Cassat B, T04	1	**13.30**	**1.74**	**0.95**	**1.40**	**245.86**	0.52
Clapboard Creek A, T01	10	**2.45**	**0.16**	0.11	**0.05**	21.13	0.47
Clapboard Creek A, T02	5	**3.42**	**0.20**	0.23	**0.09**	0.00	0.00
Clapboard Creek A, T03	2	**6.95**	**0.56**	**0.77**	**0.21**	**162.63**	0.67
Clapboard Creek A, T04	1	**4.90**	**0.36**	**1.15**	**0.18**	**165.41**	0.97
Clapboard Creek B, T01	10	**3.09**	**0.16**	0.11	**0.05**	34.97	0.46
Clapboard Creek B, T02	5	**4.56**	**0.28**	0.24	**0.09**	61.01	0.79
Clapboard Creek B, T03	2	**4.14**	**0.37**	**0.64**	**0.14**	115.27	0.84
Clapboard Creek B, T04	1	**3.80**	**0.18**	**0.60**	**0.10**	0.00	0.00
# of exceedance		24	18	8	16	7	7

Appendix J: Total Concentration of Metals in CGR Samples

Solid samples of Jax 10, Cassat, Clapboard Creek and seven different FDOT samples were digested on the automated block digester using EPA method 3050B. The digested samples were then brought to volume using deionized water and analyzed for total metal concentrations on ICP using EPA method 6010B. Total elemental concentration of metals found are given in the table below; with comparison of Florida soil cleanup residential as well as commercial target levels.

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Vero 1	Vero 2	Vero 3
Aluminum	80000	N/A	6490.92	5736.04	6315.15
Arsenic	2.1	12	4.65	4.13	4.48
Boron	17000	430000	28.63	26.11	28.52
Barium	120	130000	54.23	49.45	53.83
Beryllium	120	1400	0.75	0.68	0.74
Calcium	N/A	N/A	137739.30	123777.00	135301.8
Cadmium	82	1700	0.49	0.44	0.47
Cobalt	1700	42000	7.95	7.39	7.88
Chromium	210	470	53.39	49.17	52.99
Copper	150	89000	48.85	43.88	47.99
Iron	53000	N/A	5155.40	4780.04	5142.23
Potassium	N/A	N/A	1159.97	1034.24	1101
Magnesium	N/A	N/A	1688.60	1524.84	1674.41
Manganese	3500	43000	46.65	42.41	46.29
Molybdenum	440	11000	7.03	6.40	7.03
Sodium	N/A	N/A	580.51	522.01	552.03
Nickel	340	35000	9.93	9.21	9.86
Lead	400	1400	39.57	36.14	39.58
Antimony	27	370	1.06	0.92	0.91
Selenium	440	11000	0.98	1.13	1.04
Tin	47000	880000	8.91	8.41	9.15
Strontium	52000	N/A	302.62	276.86	299.18
Titanium	N/A	N/A	292.77	268.04	291.54
Vanadium	67	10000	21.86	19.66	21.62
Zinc	26000	630000	426.47	394.67	428.88

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Orlando 1	Orlando 2	Orlando 3
Aluminum	80000	N/A	4753.82	5331.84	6096.03
Arsenic	2.1	12	8.1	8.71	10.2
Boron	17000	430000	43.58	47.94	55.8
Barium	120	130000	127.21	154.17	193.19
Beryllium	120	1400	0.42	0.45	0.52
Calcium	N/A	N/A	108097.2	107971.9	125174.2
Cadmium	82	1700	0.61	0.7	0.81
Cobalt	1700	42000	18.53	14.78	12.61
Chromium	210	470	16.04	14.98	17.3
Copper	150	89000	39.04	45.47	53.02
Iron	53000	N/A	4248.71	4688.63	5859.06
Potassium	N/A	N/A	396.86	438.52	449.01
Magnesium	N/A	N/A	1153.69	1182.88	1369.61
Manganese	3500	43000	32.02	34.59	41.7
Molybdenum	440	11000	11.36	11.93	14.02
Sodium	N/A	N/A	179.69	212.79	230.03
Nickel	340	35000	8.48	8.5	10.05
Lead	400	1400	8.6	9.05	10.66
Antimony	27	370	0.25	0.47	0.53
Selenium	440	11000	0.9	0.68	0.18
Tin	47000	880000	3.23	3.28	4.11
Strontium	52000	N/A	135.76	135.52	160.72
Titanium	N/A	N/A	244.35	256.76	303.51
Vanadium	67	10000	27.49	30.14	35.32
Zinc	26000	630000	83.82	86.01	102.52

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	JUF 1	JUF 2	JUF 3
Aluminum	80000	N/A	8951.11	9896.5	17464.11
Arsenic	2.1	12	3.82	4.54	7.53
Boron	17000	430000	14.52	15.31	41.48
Barium	120	130000	64.29	75.86	286.39
Beryllium	120	1400	0.8	0.93	1.66
Calcium	N/A	N/A	124235.9	141607.8	175502.6
Cadmium	82	1700	0.24	0.3	0.6
Cobalt	1700	42000	2.9	3.22	26
Chromium	210	470	10.42	10.96	21.22
Copper	150	89000	29.83	35.22	62.34
Iron	53000	N/A	2392.07	2725.38	5515.53
Potassium	N/A	N/A	776.2	792.84	1261.5
Magnesium	N/A	N/A	3655.58	4188.91	4887.86
Manganese	3500	43000	176.98	205.12	224.98
Molybdenum	440	11000	5.3	5.93	10.42
Sodium	N/A	N/A	254.96	252.51	442.45
Nickel	340	35000	4.12	4.35	8.81
Lead	400	1400	4.04	5	10.76
Antimony	27	370	0.55	0.46	1.19
Selenium	440	11000	0.82	0.71	1.28
Tin	47000	880000	1.35	1.38	2.54
Strontium	52000	N/A	176.47	197.72	285.65
Titanium	N/A	N/A	336.16	377.92	639.37
Vanadium	67	10000	8.54	9.88	24.37
Zinc	26000	630000	37.69	44.03	74.09

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Tampa301 1	Tampa301 2	Tampa301 3
Aluminum	80000	N/A	14101.24	18068.67	5130.59
Arsenic	2.1	12	5.7	7.84	3.6
Boron	17000	430000	33.53	42.87	36.81
Barium	120	130000	235.31	295.99	29.51
Beryllium	120	1400	1.35	1.71	0.43
Calcium	N/A	N/A	142001.6	182720.8	136552.6
Cadmium	82	1700	0.48	0.65	0.43
Cobalt	1700	42000	21.11	26.8	7.06
Chromium	210	470	17.16	21.45	34.97
Copper	150	89000	50.11	64.45	43.11
Iron	53000	N/A	4524.38	5627.5	4871.14
Potassium	N/A	N/A	1004.56	1297.18	1901.87
Magnesium	N/A	N/A	3983.63	4944.04	1664.43
Manganese	3500	43000	183.27	232.06	50.01
Molybdenum	440	11000	8.18	10.59	8.82
Sodium	N/A	N/A	355.06	454.88	654.39
Nickel	340	35000	7.18	9.02	17.27
Lead	400	1400	8.74	10.84	21.1
Antimony	27	370	0.89	0.92	0.61
Selenium	440	11000	0.87	1.17	1.15
Tin	47000	880000	1.93	2.58	5.92
Strontium	52000	N/A	232.07	294.89	271.89
Titanium	N/A	N/A	507.39	650.33	222.05
Vanadium	67	10000	19.82	25.07	18.62
Zinc	26000	630000	60.89	77.18	229.26

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Truck#1 1	Truck#1 2	Truck#1 3
Aluminum	80000	N/A	5514.63	6264.65	2174.59
Arsenic	2.1	12	3.7	4.18	0.88
Boron	17000	430000	39.09	44.41	6.56
Barium	120	130000	31.68	36.32	16.66
Beryllium	120	1400	0.46	0.54	0.11
Calcium	N/A	N/A	144401.8	156832.6	91638.79
Cadmium	82	1700	0.47	0.56	0.11
Cobalt	1700	42000	7.45	7.33	1.52
Chromium	210	470	36.58	40.05	4.63
Copper	150	89000	46.41	50.47	2.68
Iron	53000	N/A	5171.24	6146.88	1477.38
Potassium	N/A	N/A	2138.26	1657.49	404.22
Magnesium	N/A	N/A	1769.8	1921.65	2117.31
Manganese	3500	43000	52.9	62.11	8.61
Molybdenum	440	11000	9.38	10.5	0.62
Sodium	N/A	N/A	726.75	607.77	254.69
Nickel	340	35000	17.88	16.93	4.76
Lead	400	1400	22.13	25.6	0
Antimony	27	370	0.81	0.69	0.2
Selenium	440	11000	0.92	0.59	0.25
Tin	47000	880000	6.13	7.22	0.12
Strontium	52000	N/A	289.96	304.68	1471.14
Titanium	N/A	N/A	236.45	272.94	78.24
Vanadium	67	10000	19.81	22.52	6.15
Zinc	26000	630000	238.75	280.99	5.18

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Fort Myers/Punta Gorda 1	Fort Myers/Punta Gorda 2	Fort Myers/Punta Gorda 3
Aluminum	80000	N/A	2138.25	6242.42	6449.84
Arsenic	2.1	12	0.77	1.61	1.58
Boron	17000	430000	6.47	8.76	9.01
Barium	120	130000	16.8	41.65	43.15
Beryllium	120	1400	0.11	0.63	0.65
Calcium	N/A	N/A	86902.66	68678.88	70058.55
Cadmium	82	1700	0.11	0.14	0.15
Cobalt	1700	42000	1.58	2.91	2.95
Chromium	210	470	4.41	6.19	6.53
Copper	150	89000	2.79	19.24	20.14
Iron	53000	N/A	1524.91	1531.06	1584.66
Potassium	N/A	N/A	398.59	311.43	301.36
Magnesium	N/A	N/A	2147.48	2533.34	2584.8
Manganese	3500	43000	8.44	94.24	97.44
Molybdenum	440	11000	0.6	4.74	5.08
Sodium	N/A	N/A	254.41	162.62	157.28
Nickel	340	35000	5.04	2.99	2.95
Lead	400	1400	0	1.84	1.72
Antimony	27	370	0.13	0.4	0.2
Selenium	440	11000	0.14	0.81	0.19
Tin	47000	880000	0.21	0.94	0.85
Strontium	52000	N/A	1505.64	102.76	104.46
Titanium	N/A	N/A	80.88	232.31	239.44
Vanadium	67	10000	6.4	5.51	5.48
Zinc	26000	630000	5.22	19.92	20.57

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Jax 1	Jax 2	Jax 3
Aluminum	80000	N/A	5923.94	4151.07	4087.66
Arsenic	2.1	12	1.47	1.27	1.56
Boron	17000	430000	8.18	12.24	12.03
Barium	120	130000	39.72	30.36	29.06
Beryllium	120	1400	0.59	0.29	0.29
Calcium	N/A	N/A	64867.56	91566.84	90812.73
Cadmium	82	1700	0.14	0.28	0.29
Cobalt	1700	42000	2.84	2.56	2.48
Chromium	210	470	5.81	10.76	10.61
Copper	150	89000	18.98	10.6	10.42
Iron	53000	N/A	1444.89	2973.96	2931.02
Potassium	N/A	N/A	300.36	488.76	347.37
Magnesium	N/A	N/A	2383.57	1043.37	1042.44
Manganese	3500	43000	88.91	31.54	30.81
Molybdenum	440	11000	4.65	1.5	1.47
Sodium	N/A	N/A	154.28	226.77	179.12
Nickel	340	35000	2.79	9.08	8.92
Lead	400	1400	1.53	0.97	0.89
Antimony	27	370	0.23	0.25	0.29
Selenium	440	11000	0.36	0.68	0.49
Tin	47000	880000	0.84	0.64	0.49
Strontium	52000	N/A	96.54	154.99	146.55
Titanium	N/A	N/A	219.41	177.81	173.63
Vanadium	67	10000	5.22	9.17	8.48
Zinc	26000	630000	18.87	11.81	12.72

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Jax10 1	Jax10 2	Jax10 3
Aluminum	80000	N/A	4246.98	6480.92	5736.04
Arsenic	2.1	12	1.3	4.65	4.13
Boron	17000	430000	12.58	28.63	26.11
Barium	120	130000	29.96	54.23	49.45
Beryllium	120	1400	0.3	0.75	0.68
Calcium	N/A	N/A	94294.39	137739.3	123777
Cadmium	82	1700	0.29	0.49	0.44
Cobalt	1700	42000	2.65	7.95	7.39
Chromium	210	470	11.16	53.39	49.17
Copper	150	89000	10.76	48.85	43.88
Iron	53000	N/A	3080.12	5155.4	4780.04
Potassium	N/A	N/A	420.22	1159.97	1034.24
Magnesium	N/A	N/A	1072.32	1688.6	1524.84
Manganese	3500	43000	32.05	46.65	42.41
Molybdenum	440	11000	1.57	7.03	6.4
Sodium	N/A	N/A	209.18	580.51	522.02
Nickel	340	35000	9.35	9.93	9.21
Lead	400	1400	1.1	39.57	36.14
Antimony	27	370	0.5	1.06	0.92
Selenium	440	11000	0.52	0.98	1.13
Tin	47000	880000	0.6	8.91	8.41
Strontium	52000	N/A	151.64	302.62	276.86
Titanium	N/A	N/A	181.75	292.77	268.04
Vanadium	67	10000	8.86	21.86	19.66
Zinc	26000	630000	11.03	426.47	394.67

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Cassat A	Cassat B
Aluminum	80000	N/A	2186.04	1638.72
Arsenic	2.1	12	1.18	1.01
Boron	17000	430000	24.61	23.86
Barium	120	130000	31.06	24.32
Beryllium	120	1400	0.24	0.21
Calcium	N/A	N/A	50524.40	38449.77
Cadmium	82	1700	0.27	0.15
Cobalt	1700	42000	2.83	2.11
Chromium	210	470	8.36	7.32
Copper	150	89000	6.66	5.88
Iron	53000	N/A	0.00	3169.62
Potassium	N/A	N/A	603.01	456.58
Magnesium	N/A	N/A	668.61	505.94
Manganese	3500	43000	0.00	23.23
Molybdenum	440	11000	2.17	1.74
Sodium	N/A	N/A	211.43	154.17
Nickel	340	35000	8.65	6.58
Lead	400	1400	2.03	1.36
Antimony	27	370	0.00	0.17
Selenium	440	11000	1.78	0.78
Tin	47000	880000	0.02	0.18
Strontium	52000	N/A	0.00	128.45
Titanium	N/A	N/A	0.00	121.21
Vanadium	67	10000	5.90	4.92
Zinc	26000	630000	12.17	9.39

Table A. 16. Total Concentration of Metals in CGR Samples compared with Florida residential and commercial risk based threshold values.

All sample and SCTL concentrations are in mg/kg	Florida Residential SCTL	Florida Commercial SCTL	Clapboard A	Clapboard B
Aluminum	80000	N/A	2278.52	1882.54
Arsenic	2.1	12	1.49	0.97
Boron	17000	430000	13.42	12.07
Barium	120	130000	27.92	23.74
Beryllium	120	1400	0.23	0.21
Calcium	N/A	N/A	49185.90	41901.03
Cadmium	82	1700	0.15	0.15
Cobalt	1700	42000	2.20	1.96
Chromium	210	470	8.87	7.44
Copper	150	89000	7.29	6.48
Iron	53000	N/A	3389.95	2840.99
Potassium	N/A	N/A	482.85	293.35
Magnesium	N/A	N/A	660.53	554.52
Manganese	3500	43000	31.14	26.72
Molybdenum	440	11000	1.24	1.14
Sodium	N/A	N/A	70.59	0.06
Nickel	340	35000	7.39	6.61
Lead	400	1400	1.23	0.83
Antimony	27	370	0.12	0.40
Selenium	440	11000	1.03	1.28
Tin	47000	880000	0.45	0.31
Strontium	52000	N/A	146.82	125.92
Titanium	N/A	N/A	148.81	119.91
Vanadium	67	10000	4.87	5.14
Zinc	26000	630000	9.93	8.76