BEE02: NEXTGEN Concrete - Tests of the Future: Chloride and Sulfate Durability

Deliverable #6: Final Report

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16. Abstract

To enhance the durability of newly constructed structural elements, FDOT is seeking concrete mixes that are designed and approved based on element type and service conditions. As one of the most important concerns on concrete, the durability of concrete needs to be robustly assessed with a series of screening tests. Specifically, the chloride and sulfate durability need to be further evaluated. FDOT has elected to move forward with the surface resistivity (SR) test method based on AASHTO T358 and bulk resistivity (BR) test method based on AASHTO TP119 for chloride durability assessment. For the sulfate durability assessment, FDOT elected to move forward with the rapid sulfate permeability test method based on a modified ASTM C1202 test method for Rapid Sulfate Permeability Test (RSPT). In order to widely deploy these test methods for chloride and sulfate durability, we need to choose appropriate thresholds. In addition, to fully assess the durability of concrete mixes with Supplementary Cementitious Materials (SCM), 56-day result need to be obtained and its correlation with 28-day result need to be studied. The research team has performed SR, BR, RSPT, and length change test (ASTM C1012) for 31 selected concrete mixes and the thresholds were selected and proposed for SR, BR, and RSPT tests. A series of prediction equations were also developed to predict the 56-day result based on 28-day testing result.

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EXECUTIVE SUMMARY

To enhance the durability of newly constructed structural elements, FDOT is seeking concrete mixes that are designed and approved based on element type and service conditions. Thus, assessing the performances of different concrete mixes for shrinkage, creep, chloride, and sulfate resistance is extremely important. This assessment needs to adapt to various issues associated with concrete's constituent ingredients including physical, chemical, and market. As one of the most important concerns on concrete, the durability of concrete needs to be robustly assessed with a series of screening tests. Specifically, the chloride and sulfate durability need to be further evaluated.

To ensure wide deployment and safe execution of durability tests, there are five important criteria for the development of testing methods was considered in this research:

(1) Easy: The tests should be simple enough for a high school graduate to run.
(2) Affordable: The cost of the equipment should be low enough to support a wide deployment.
(3) Safe: The tests should avoid the use of hazardous materials.
(4) Quick: The tests should take no longer than 56 days to complete. We need to develop specification thresholds to use when screening a mix for particular use on FDOT projects.
(5) Repeatability: The test results should be reliable with an acceptable coefficient of variation when performed by various technicians.

The FDOT-funded project BDV31-977-136 investigated existing tests that may meet FDOT's needs as-is or with some modification. Based on their recommendations, FDOT has elected to move forward with the surface resistivity (SR) test method based on AASHTO T358 and bulk resistivity (BR) test method based on AASHTO TP119 for chloride durability assessment. Since supplementary cementitious materials (SCMs) generally delay the hydration of concrete, the concrete needs more time to develop resistance to permeation. The 56-day results are considered necessary to adequately assess the mix with SCMs. Thus, the research team established the correlation between the 56-day results with 28- day results so that 56-day SR and BR results can be predicted using 28-day result.

For the sulfate durability assessment, FDOT elected to move forward with the rapid sulfate electrochemical test method based on a modified ASTM C1202 test method for Rapid Sulfate Permeability Test (RSPT). The research team has conducted the RSPT for all 31 selected mixes and derived the correlation between 28-day and 56-day results.

The research team has performed a comprehensive literature view that consists of:

(1) Review of the analysis and recommendations of BDV31-977-136 related to chloride and sulfate durability testing.
(2) Review State Material Office (SMO) and other available databases that indicate the distribution of Florida soil and water test results for 1) chlorides, 2) sulfates, 3) pH, and 4) resistivity.
(3) Review and collect the data in the literature that related to the threshold SR/BR value and sulfate durability threshold appropriate for concrete in an extremely aggressive environment for 75- and 100-year designs.
(4) Review and analyze the data for 4x8 inch cylinders at 28 days and 56 days of curing for SR/BR tests and RSPT tests.
(5) Review the SR data available from the Department's mix design database.

Based on the literature review and the data collected from it, the research team has developed and executed a comprehensive testing plan for both chloride and sulfate durability tests. Since this project aims at finding appropriate thresholds to use for chloride and sulfate durability tests for a concrete mix designed for an extremely aggressive environment. A group of 31 design mixes that have been already approved for use in an extremely aggressive environment has been selected to establish 28- and 56- day SR and BR thresholds. Samples from the same batch were tested at 28- and 56-days. The research team has analyzed the test results, formulated conclusions, and developed initial recommendations. Particularly, based on the data collected various tests, the research team developed a procedure to correlate concrete resistivity and chloride diffusion coefficient because the chloride diffusion coefficient is the parameter that directly affects the service life of the reinforced concrete structure. Based on data analysis results, the research team has recommended the appropriate thresholds to be used for SR, BR, and RSPT for a concrete mix designed for an extremely aggressive environment. Moreover, the research team also prediction equations for 56-day SR, BR, and RSPT results based on correlations between 56-day and 28-day results. The prediction equations considered various parameters including water to cement (w/c) ratio and percentage of different SCMs.

RESEARCH OBJECTIVES

The two objectives of this project are the following:

1. Investigate and recommend the appropriate thresholds to use for bulk (TP 119) and surface (T 358) resistivity for a concrete mix designed for an extremely aggressive chloride environment.
2. Investigate and recommend the appropriate thresholds to use for RSPT for a concrete mix designed for an extremely aggressive sulfate environment.

CONCLUSIONS AND RECOMMENDATIONS

In order to achieve the objective of this project, the research team conducted a series of tests for selected 31 mix designs for both 28-days and 56-days curing conditions and the following conclusions and recommendations are drawn. It is worth noting that to choose the appropriate thresholds for chloride resistivity, experimental results from a companion project BED32: Chloride Diffusion were used to correlate between resistivity and concrete service life.

In order to choose thresholds for SR and BR tests, the research team first investigated the correlation between concrete resistivity and chloride diffusion coefficient because the chloride diffusion coefficient is the parameter that directly affects the service life of the reinforced concrete structure. Since both conductivity and resistivity results show good correlation with apparent diffusion coefficients, the correlation between conductivity and apparent diffusion coefficients were used to predict the SR and BR thresholds for a service life of 75 years. The SR thresholds at 28 days for End Bent, Piers in contract with water, Piers not in contact with water, Retaining walls, and Pier cap and intermediate bent are 55 kΩ-cm, 42 kΩ-cm, 55 kΩ-cm, 106 kΩ-cm, and 55 kΩ-cm, respectively. The BR thresholds at 28 days for End Bent, Piers in contract with water, Piers not in contact with water, Retaining walls, and Pier cap and intermediate bent are 21 kΩ-cm, 17 kΩ-cm, 21 kΩ-cm, 31 kΩ-cm, and 21 kΩ-cm, respectively.

Previous studies indicate that sulfates react with the Ca (OH)2 and the calcium aluminate hydrates, thus causing expansive reactions which may result in spalling and cracking, and the loss of bond strength between the cement paste and aggregate. Thus, percentage of expansion is a direct indicator of sulfate attack to concrete structure. In this study, the research team used *ASTM C1012 Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution* to measure the expansion of concrete due to sulfate attack. To choose an appropriate threshold for the RSPT test, we need to establish the correlation between the length change test data according to ASTM C1012 and the RSPT test results. Based on the previous research and current code specifications, the research team proposes to use 0.1% expansion at 18 months (72 weeks) as the criteria for an extremely aggressive environment. Due to lack of available testing results at 18 months (72 weeks), the linear regression prediction equation developed based on length change test data were used to predict the 18 months (72 weeks) length change results except for four mixes with available 18 months results. Based on linear correlation between percentage of expansion and RSPT results, the RSPT threshold for a 0.1% expansion is 2153 coulomb.

The research team also proposed a series of prediction equations to predict the SR, BR, and RSPT results at 56-day based on 28-day results.

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1 INTRODUCTION

1.1 Research Problem and Background

To enhance the durability of newly constructed structural elements, FDOT is seeking concrete mixes that are designed and approved based on element type and service conditions. Thus, assessing the performances of different concrete mixes for shrinkage, creep, chloride, and sulfate resistance is extremely important. This assessment needs to adapt to various issues associated with concrete's constituent ingredients including physical, chemical, and market. As one of the most important concerns on concrete, the durability of concrete needs to be robustly assessed with a series of screening tests. Specifically, the chloride and sulfate durability need to be further evaluated.

To ensure wide deployment and safe execution of durability tests, there are five important criteria for the development of testing methods considered in this research:

(1) Easy: The tests should be simple enough for a high school graduate to run.
(2) Affordable: The cost of the equipment should be low enough to support a wide deployment.
(3) Safe: The tests should avoid the use of hazardous materials.
(4) Quick: The tests should take no longer than 56 days to complete. We need to develop specification thresholds to use when screening a mix for particular use on FDOT projects.
(5) Repeatability: The test results should be reliable with an acceptable coefficient of variation when performed by various technicians.

For chloride durability, FDOT has elected to move forward with the surface resistivity (SR) test method based on AASHTO T358 and bulk resistivity (BR) test method based on AASHTO TP119 for chloride durability assessment. For the sulfate durability assessment, FDOT elected to move forward with the rapid sulfate permeability test (RSPT) method based on a modified ASTM C1202 test method. Thus, the research team has performed these tests for 31 mixes that were approved by FDOT. These 31 mixes use different supplementary cementitious materials (SCM) including fly ash, slag, silica fume, and metakaolin. In addition, concrete expansion was also tested based on ASTM C1012, and the results were used to correlate with the RSPT results.

Since supplementary cementitious materials (SCMs) generally delay the hydration of concrete, the concrete needs more time to develop resistance to permeation. Thus, 56-day results were also collected from SR, BR, and RSPT tests. Based on 28-day and 56-day testing results, the research team established their correlation and developed predication equations so that the durability at 56-day can be evaluated.

1.2 Research Objectives

The two objectives of this project are the following:

1. Investigate and recommend the appropriate thresholds to use for bulk (TP 119) and surface (T 358) resistivity for a concrete mix designed for an extremely aggressive chloride environment.
2. Investigate and recommend the appropriate thresholds to use for RSPT test for a concrete mix designed for an extremely aggressive sulfate environment.

In order to achieve these objectives, the research team has performed a comprehensive literature review, developed a detailed testing plan, executed the testing plan and obtained the results from different tests, performed an in-depth data analysis, and finally, the thresholds were proposed for SR, BR, and RSPT tests.

2 LITERATURE REVIEW

The research team reviewed the analysis and recommendations of BDV31-977-136 related to chloride and sulfate durability testing. The research team also investigated State Material Office (SMO) and other available databases that indicate the distribution of Florida soil and water test results for 1) chlorides, 2) sulfates, 3) pH, and 4) resistivity. The research team particularly investigated the relationship of environments classified as extremely aggressive for chlorides and sulfates uniquely, and those that are extremely aggressive for both.

The research team reviewed and collected data in the literature that is related to the thresholds of surface resistivity (SR) and bulk resistivity (BR) appropriate for concrete in an extremely aggressive environment for 75- and 100-year designs. The research team also reviewed and analyzed the values for 4x8 inch cylinders at 28 days and 56 days of curing. Regarding the rapid sulfate electrochemical test, the research team reviewed and analyzed the values for 4x8 inch cylinders at 28 days and 56 days of curing.

This task is divided into five main subtasks consisting of:

a) review of the analysis and recommendations of BDV31-977-136 related to chloride and sulfate durability testing.

b) review SMO and other available databases that indicate the distribution of Florida soil and water test results for 1) chlorides, 2) sulfates, 3) pH, and 4) resistivity.

c) review and collect the data in the literature that related to the threshold of SR/BR value and sulfate durability threshold appropriate for concrete in an extremely aggressive environment for 75- and 100-year designs.

d) review and analyze the data for 4x8 inch cylinders at 28 days and 56 days of curing for SR/BR tests and rapid sulfate permeability test (RSPT).

e) review the SR data available from the Department’s mix design database.

2.1 REVIEW OF THE ANALYSIS AND RECOMMENDATIONS OF BDV31-977-136 RELATED TO CHLORIDE AND SULFATE DURABILITY TESTING

In BDV31-977-136, Ferraro et. al (2021) investigated various standard testing methods for chloride durability including ASTM C1202/ AASHTO T 277, NT Build 492, AASHTO T 358, and AASHTO TP 119. The findings of BDV31-977-136 related to chloride durability testing are summarized in Table 1. They concluded that the chloride durability testing methods require further evaluation and development prior to being accepted with FDOT criteria with the largest obstacle is the 30-day requirement in combination with the ability to test concrete mixes with supplementary cementitious materials. However, they also recommended AASHTO T 358 and AASHTO TP 119 for further investigation. Since the department has elected to move forward with AASHTO T 358 and AASHTO TP 119, the research team also used these two methods for chloride durability testing.

Table 1. Available testing methods for chloride durability based on BDV31-977-136

Testing Method	**≤ 30 days**	**≤ $30,000**	**Uncomplicated**	**No Hazards**	**Drawbacks**
ASTM C1202/ AASHTO T 277	No	Yes	Yes	Yes	- Depends on the chemistry of the pore solution - Overestimate permeability
NT Build 492	No	Yes	Yes	No	- Hazard materials and hazardous waste disposal
AASHTO T 358	No	Yes	Yes	Yes	- Accelerated moist-curing in the test vs. standard moist-curing in the field
AASHTO TP 119	No	Yes	Yes	Yes	Same as AASHTO T 358

Ferraro et. al (2021) also investigated various testing methods for sulfate durability including the United States Bureau of Reclamation (USBR) 4908, (Mulenga-Nobst-Stark) MNS Test (Mulenga et al., 1999), Soaking and Drying Test (de Almeida, 1991), Rapid Sulfate Electrochemical Test (Tumidajski and Turc, 1995), Partial Immersion, and Complete Immersion method. Similar to chloride durability testing, they concluded that the largest barrier to acceptance is the 30-day requirement in combination with the ability to test concrete mixes with supplementary cementitious materials. Similar to chloride durability testing, the research team used Rapid Sulfate Electrochemical Test described in section 4.3.4 of BDV31-977-136 for sulfate durability testing.

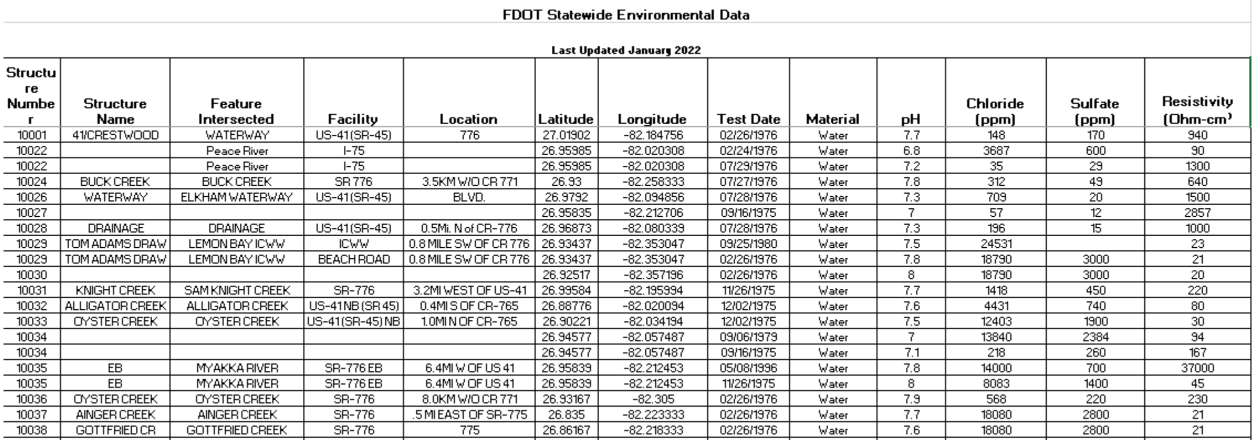
Table 2. Available testing methods for sulfate durability based on BDV31-977-136

Testing Method	**≤ 30 days**	**≤ \$30,000**	**Uncomplicated**	**No Hazards**	**Drawbacks**
USBR 4908	No	Yes	Yes	Yes	- Require 1 to 2 years minimum - Cost might exceed \$30,000
MNS Test	No	Yes	Yes	Yes	- Testing time at 28 days and temperature at 20°C - 3-4 months of testing time - Sample size too small for concrete
Soaking and Drying Test	No	Yes	Yes	Yes	- 28 days of room temperature curing which will not allow pozzolanic materials to reach adequate maturity - 28 weeks of testing time - 2” sample size
Rapid Sulfate Electrochemical Test	No	Yes	Yes	Yes	Same as AASHTO C1202
Partial Immersion	No	Yes	Yes	Yes	The length required to indicate concrete performance when exposed to sulfate solutions.
Complete Immersion	No	Yes	Yes	Yes	- 9 months testing time - Chemical disposal

2.2 REVIEW STATE MATERIAL OFFICE (SMO) AND OTHER AVAILABLE DATABASES THAT INDICATE THE DISTRIBUTION OF FLORIDA SOIL AND WATER TEST RESULTS

The research team has reviewed the State Material Office (SMO) database including soil and water data for chlorides, sulfates, pH, and resistivity. Then the research team conducted a thorough analysis of the data. The results and insights from these data give the research team the information to better define an extremely aggressive environment.

Figure 1 shows a sample of most recent bridge environment data from the SMO. Comparing with the data set from 2016 (Figure 2), field results on resistivity and pH were not reported.

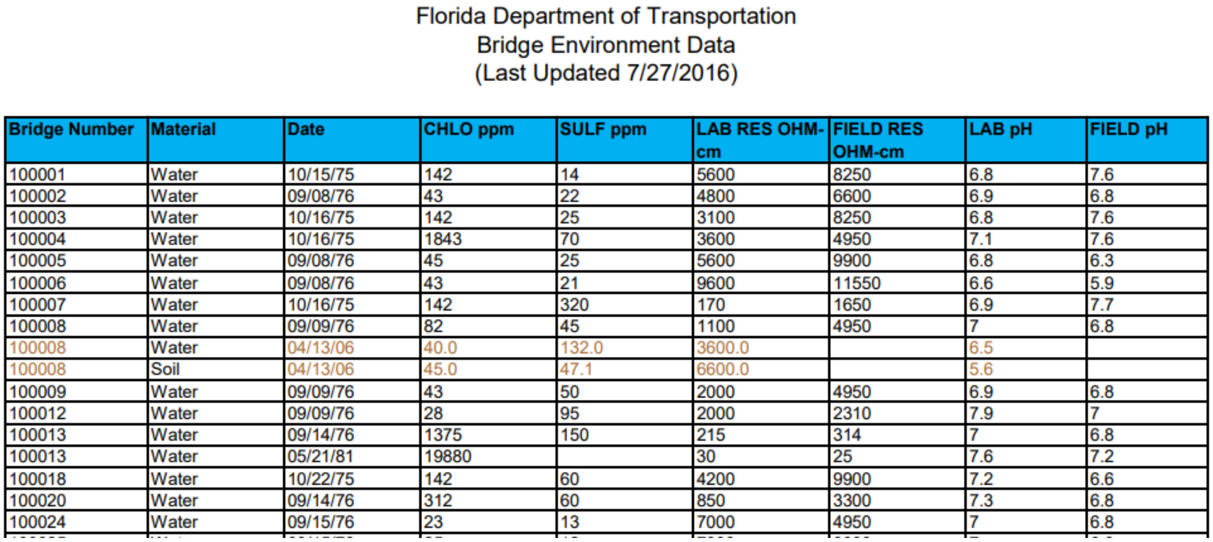


FDOT Statewide Environmental Data

Last Updated January 2022

Structure Number	Structure Name	Feature Intersected	Facility	Location	Latitude	Longitude	Test Date	Material	pH	Chloride (ppm)	Sulfate (ppm)	Resistivity (Ohm-cm)
10001	41/CRESTWOOD	WATERWAY	US-41(SR-45)	776	27.01902	-82.184756	02/26/1976	Water	7.7	148	170	940
10022		Peace River	I-75		26.95985	-82.020308	02/24/1976	Water	6.8	3687	600	90
10022		Peace River	I-75		26.95985	-82.020308	07/29/1976	Water	7.2	35	29	1300
10024	BUCK CREEK	BUCK CREEK	SR 776	3.5KM W/O CR 771	26.93	-82.258333	07/27/1976	Water	7.8	312	49	640
10026	WATERWAY	ELKHAM WATERWAY	US-41(SR-45)	BLVD.	26.9792	-82.094856	07/28/1976	Water	7.3	709	20	1500
10027					26.95835	-82.212706	09/16/1975	Water	7	57	12	2857
10028	DRAINAGE	DRAINAGE	US-41(SR-45)	0.5Mi. N of CR-776	26.96873	-82.080339	07/28/1976	Water	7.3	196	15	1000
10029	TOM ADAMS DRAW	LEMON BAY ICWW	ICWW	0.8 MILE SW OF CR 776	26.93437	-82.353047	09/25/1980	Water	7.5	24531		23
10029	TOM ADAMS DRAW	LEMON BAY ICWW	BEACH ROAD	0.8 MILE SW OF CR 776	26.93437	-82.353047	02/26/1976	Water	7.8	18790	3000	21
10030					26.92517	-82.357196	02/26/1976	Water	8	18790	3000	20
10031	KNIGHT CREEK	SAM KNIGHT CREEK	SR-776	3.2MI WEST OF US-41	26.99584	-82.195994	11/26/1975	Water	7.7	1418	450	220
10032	ALLIGATOR CREEK	ALLIGATOR CREEK	US-41NB (SR 45)	0.4MI S OF CR-765	26.88776	-82.020094	12/02/1975	Water	7.6	4431	740	80
10033	OYSTER CREEK	OYSTER CREEK	US-41(SR-45) NB	1.0MI N OF CR-765	26.90221	-82.034194	12/02/1975	Water	7.5	12403	1900	30
10034					26.94577	-82.057487	09/06/1979	Water	7	13840	2384	94
10034					26.94577	-82.057487	09/16/1975	Water	7.1	218	260	167
10035	EB	MYAKKA RIVER	SR-776 EB	6.4MI W OF US 41	26.95839	-82.212453	05/08/1996	Water	7.8	14000	700	37000
10035	EB	MYAKKA RIVER	SR-776 EB	6.4MI W OF US 41	26.95839	-82.212453	11/26/1975	Water	8	8083	1400	45
10036	OYSTER CREEK	OYSTER CREEK	SR-776	8.0KM W/O CR 771	26.93167	-82.305	02/26/1976	Water	7.9	568	220	230
10037	AINGER CREEK	AINGER CREEK	SR-776	.5 MI EAST OF SR-775	26.835	-82.223333	02/26/1976	Water	7.7	18080	2800	21
10038	GOTTFRIED CR	GOTTFRIED CREEK	SR-776	775	26.86167	-82.218333	02/26/1976	Water	7.6	18080	2800	21

Figure 1. FDOT bridge environment data (last updated January 2022)



Florida Department of Transportation
Bridge Environment Data
(Last Updated 7/27/2016)

Bridge Number	Material	Date	CHLO ppm	SULF ppm	LAB RES OHM-cm	FIELD RES OHM-cm	LAB pH	FIELD pH
100001	Water	10/15/75	142	14	5600	8250	6.8	7.6
100002	Water	09/08/76	43	22	4800	6600	6.9	6.8
100003	Water	10/16/75	142	25	3100	8250	6.8	7.6
100004	Water	10/16/75	1843	70	3600	4950	7.1	7.6
100005	Water	09/08/76	45	25	5600	9900	6.8	6.3
100006	Water	09/08/76	43	21	9600	11550	6.6	5.9
100007	Water	10/16/75	142	320	170	1650	6.9	7.7
100008	Water	09/09/76	82	45	1100	4950	7	6.8
100008	Water	04/13/06	40.0	132.0	3600.0		6.5	
100008	Soil	04/13/06	45.0	47.1	6600.0		5.6	
100009	Water	09/09/76	43	50	2000	4950	6.9	6.8
100012	Water	09/09/76	28	95	2000	2310	7.9	7
100013	Water	09/14/76	1375	150	215	314	7	6.8
100013	Water	05/21/81	19880		30	25	7.6	7.2
100018	Water	10/22/75	142	60	4200	9900	7.2	6.6
100020	Water	09/14/76	312	60	850	3300	7.3	6.8
100024	Water	09/15/76	23	13	7000	4950	7	6.8

Figure 2. FDOT bridge environment data (last updated 7/27/2016)

The following sub-sections show the analysis that the research team performed and results that have been obtained.

2.2.1 FDOT Testing Methods

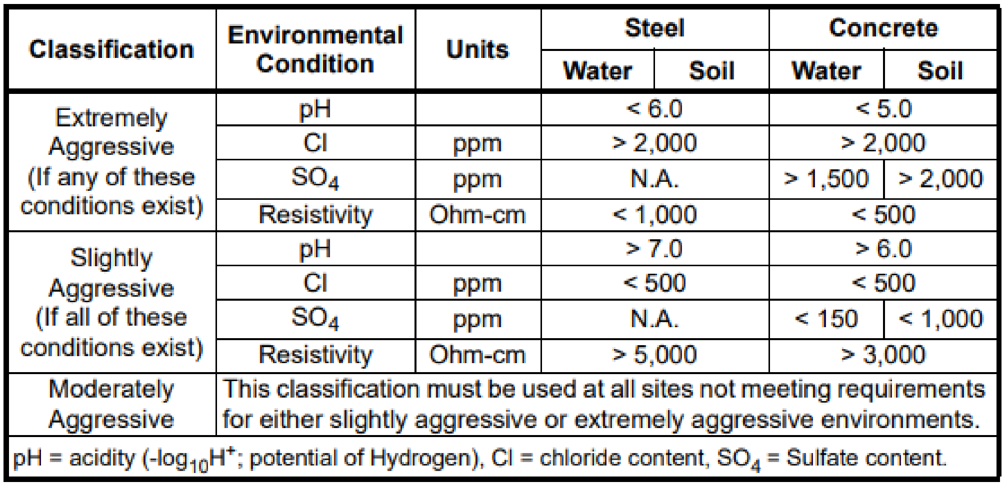
Environmental bridge data was acquired from the FDOT SMO, there were two sets of data used in this project. The first was Environmental Bridge Data updated January 2022 and the second was historical data updated March 2022. FDOT conducted the tests for pH, resistivity, sulfate and chloride as per the respective Florida Sampling and Testing Methods (FSTM):

- Florida Method of Test for pH of Soil and Water (FM-550)
- Florida Method of Test for Minimum Resistivity of Soil and Water (FM 5-551)
- Florida Method of Test for Chloride in Soil and Water (FM-552)
- Florida Method of Test for Sulfate in Soil and Water (FM-553)

All four methods can be used for determining the levels of pH, resistivity, sulfate and chloride of fine and coarse aggregates with adjustments made for the properties for the aggregate types. Steps for procuring water and soil samples are identical across all four methods. FM 552 and 553 provide 3 different test methods. One is outlined with the FM and two are based off of Section 4000 of Standard Methods for the Examination of Water and Wastewater (SMEWW). The team was unable to determine which testing methods of FM 552 and 553 were utilized for the tests result provided by the SMO. As there is no indicator but the consistency of sample procurement across all FM provides insight into providing high accuracy for test results of all four methods. All four FMs provided a precision and Bias section that provided Acceptable ranges of deviation and expected bias. From the bias section of FM 5-552, it can be concluded that temperature correction for a range of 21 to 23 degrees Celsius is important to providing result with lower biases. Criteria listed in Table 3 was used to determine the environmental classification for a bridge site.

The data provided by the FDOT SMO followed an updated guideline compared to Figure 2. Field tests are no longer reported, and pH and resistivity tests are no longer conducted in-field.

Table 3. Criteria for substructure environmental classifications (FDOT, 2023)



Classification	Environmental Condition	Units	Steel		Concrete	
			Water	Soil	Water	Soil
Extremely Aggressive (If any of these conditions exist)	pH		< 6.0		< 5.0	
	Cl	ppm	> 2,000		> 2,000	
	SO_4	ppm	N.A.		> 1,500	> 2,000
	Resistivity	Ohm-cm	< 1,000		< 500	
Slightly Aggressive (If all of these conditions exist)	pH		> 7.0		> 6.0	
	Cl	ppm	< 500		< 500	
	SO_4	ppm	N.A.		< 150	< 1,000
	Resistivity	Ohm-cm	> 5,000		> 3,000	
Moderately Aggressive	This classification must be used at all sites not meeting requirements for either slightly aggressive or extremely aggressive environments.					
pH = acidity ($-\log_{10}H^+$; potential of Hydrogen), Cl = chloride content, SO_4 = Sulfate content.						

2.2.2 Water Results

Table 4 shows a summary of the water test results consolidated from the FDOT Statewide Environmental Dataset. There are total of 627 bridges with an extremely aggressive environmental condition. The data first went through a screening and preparation procedure outlined in Appendix A. Then the data was analyzed for various criteria.

Table 4. Summary of water results

Number of water test results	8340
Previous entries with all four test results	4634
Number of bridge structures with test results	3357
% of bridges tested (out of 12982*)	25.86%
Bridges with extreme environmental condition	627

*12982 is the collective number of bridge structures from the National Bridge Inventory (NBI) and the FDOT bridge shapefile

Table 5 shows the cases with either extreme sulfate or chloride aggressive environmental conditions. Please note that resistivity criteria are not considered in this Table. For 627 bridges that are identified under extremely aggressive environmental conditions, there are 247 of them are sulfate aggressive and 446 are chloride aggressive. When we further analyze the data, we found out that 238 or 96.3% of the bridges with sulfate aggressive condition are also chloride aggressive while less than 4% of the bridges with sulfate aggressive condition are only sulfate aggressive but not chloride aggressive. On the other hand, among the bridges with chloride aggressive condition, only 238 or 53.4% are also sulfate aggressive.

Table 5. Summary of cases with extremely aggressive environmental conditions based on water results

Case Criteria	Count	Percentage of Extreme Cases
Sulfate Aggressive	247	39.39%
Chloride Aggressive	446	71.13%
Both Chloride & Sulfate Aggressive	238	72.57%
Only Sulfate Aggressive	9	1.44%
Only Chloride Aggressive	208	33.17%

Figure 3 shows the break-down of chloride and sulfate aggressive cases. It clearly showed that we can assume if a bridge site is sulfate aggressive, most likely it also is chloride aggressive (96.4%), but it is not true vice versa.

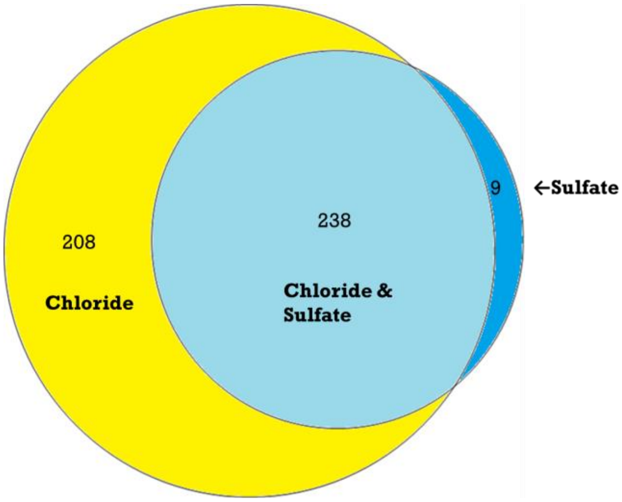


Figure 3. Extreme sulfate and chloride cases for water test results

Furthermore, the research team also investigated the cases that exceed the resistivity criteria. Figure 4 and Table 8 show further breakdown if add resistivity criteria into the consideration. It shows that 88.7% of the bridges with extremely aggressive environmental conditions fall into the resistivity category. There are a very limited number of cases that are aggressive in sulfate only (5 out of 627) or chloride only (14 out of 627). There are 235 cases (37.5%) categorized as extremely aggressive in chloride, sulfate, and resistivity.

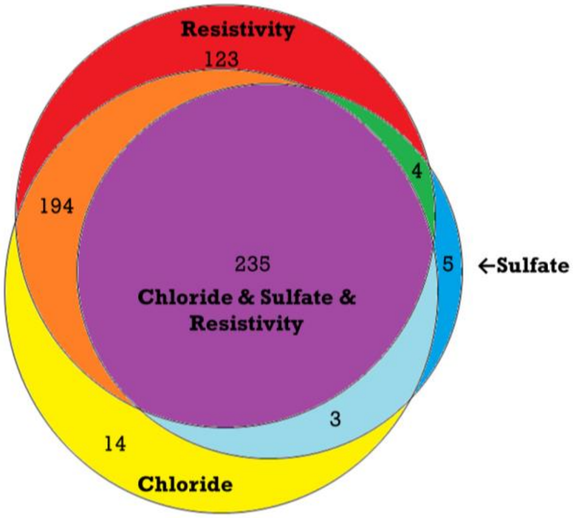
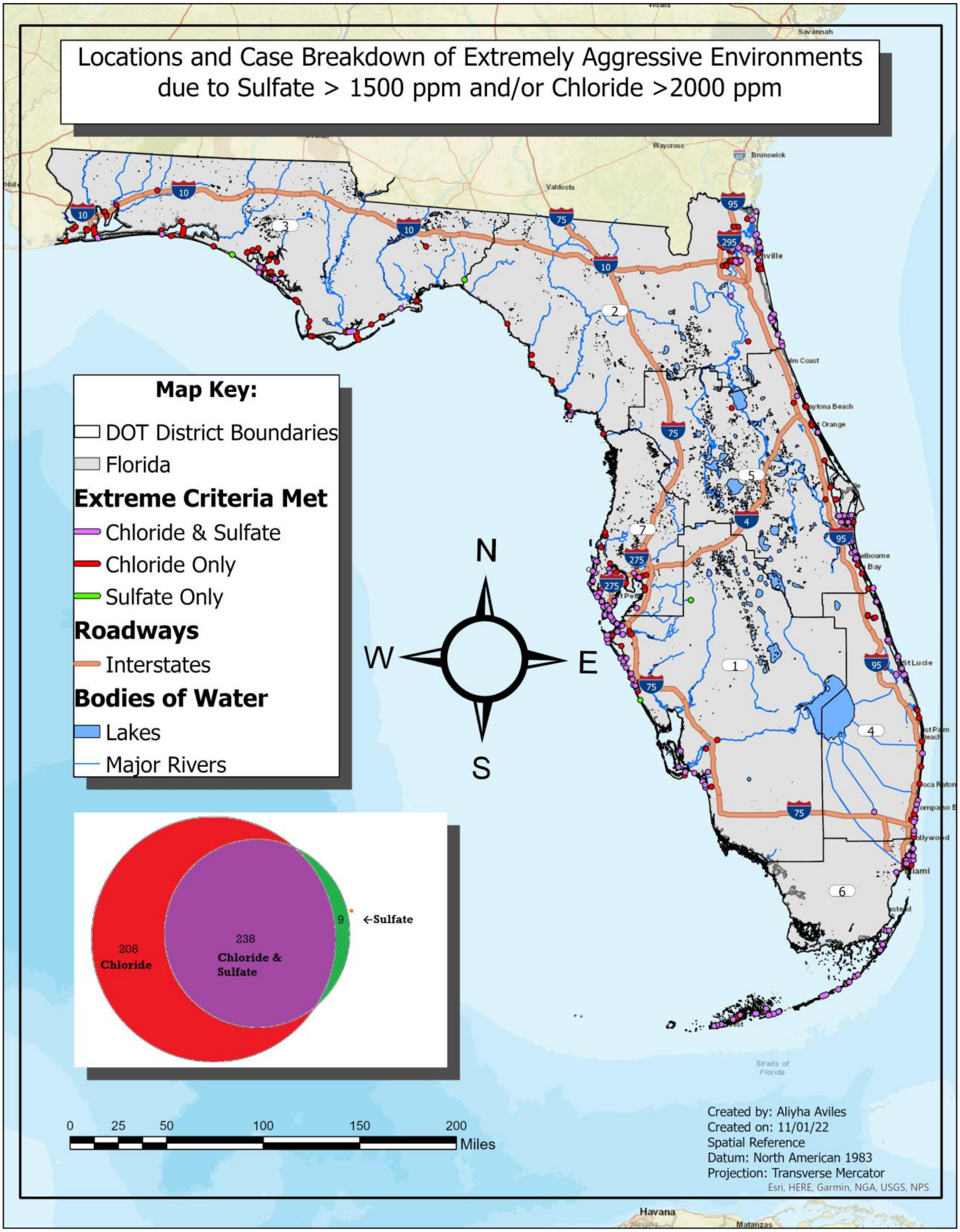


Figure 4. Extreme sulfate, chloride and resistivity cases for water test results

Table 6. Summarized count of criteria parameters met for extremely aggressive water samples

Case Criteria	**Count**	**Percentage of Extreme Cases**
All Sulfate Cases	247	39.4%
Sulfate Only	5	0.8%
All Chloride Cases	446	71.1%
Chloride Only	*14*	2.2%
All Chloride & Sulfate Cases	455	72.6%
Chloride & Sulfate Only	3	0.5%
All Resistivity Cases	556	88.7%
Resistivity Only	*123*	19.6%
All Sulfate & Resistivity Cases	239	38.1%
Sulfate and Resistivity only	4	0.6%
All Chloride & Resistivity Cases	429	68.4%
Chloride & Resistivity Only	*194*	30.9%
Sulfate & Chloride & Resistivity	*235*	37.5%
All pH cases	111	17.7%

Furthermore, January 2022 data was prepared for mapping following the procedures outlined in Appendix B. One of the resulting maps is Figure 5 which shows extremely aggressive bridge sites with respect chloride and sulfate water conditions. As can be seen, most of these sites are located along the coastal lines. More GIS maps can be found in Appendix C. Figure 6 shows an enhanced map of the FDOT management district 7 where it can be seen that most of the extremely aggressive sulfate and chloride environments are located in Tampa Bay and coastal areas.



Created by: Aliyha Aviles
Created on: 11/01/22
Spatial Reference
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS

Figure 5. Statewide map for bridges sites with extremely aggressive condition in chloride and sulfate

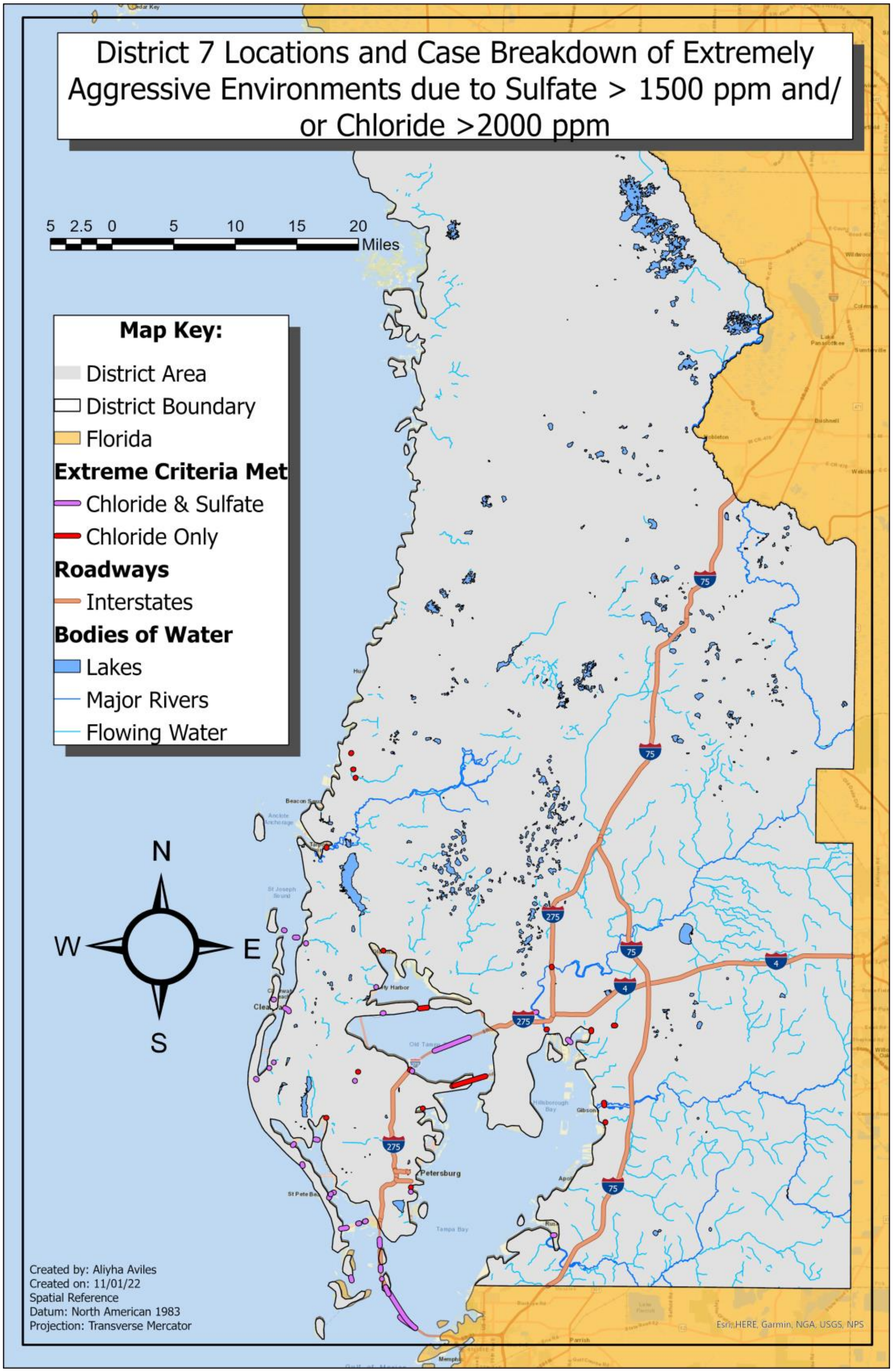


Figure 6 . District 7 Map for bridges with extremely aggressive conditions in sulfate and chloride

In order to estimate the possibility of meeting more than one criterion, the research team quantified the possibility using the conditional probability (dependent variable) equation $(B|A) = \frac{P(A \cap B)}{P(A)}$, the results are summarized in Table 7. If sulfate reached the extremely aggressive level, it has a 96.4% and 96.8% possibility of also meeting the criteria for extremely aggressive chloride and resistivity conditions, respectively. Also, if chloride reached the extremely aggressive level, it has a 96.2% possibility of meeting the extremely aggressive resistivity condition.

Table 7. Possibility of meeting multiple criteria for water samples

	P(B|A)
A = Sulfate	
B = Chloride	96.4%
B = Resistivity	96.8%
A = Chloride	
B = Sulfate	53.4%
B = Resistivity	96.2%
A = Resistivity	
B = Chloride	77.2%
B = Sulfate	43.0%
B = Chloride and Sulfate	42.3%

2.2.3 Soil Results

Similar to the water results, the soil results that were analyzed came from the preparation and screening procedure outlined in Appendix A. As shown in Table 8, there are total of 39 bridge sites with an extremely aggressive environmental condition based on soil test results. In comparison with Table 4, the total soil test results and the number of extremely aggressive sites are much less than the water test results.

Table 8. Summary of soil test results

Number of Soil test results	476
Entries with all four test results	428
Number of bridge structures with test results	88
% Of bridges tested (out of 12982)	0.68%
Bridges with extremely aggressive environmental condition	39

Table 9 and Figure 7 show that unlike the water results shown in section b.2, only one site is both chloride and sulfate aggressive based on soil test results. Therefore, it can be concluded there is no correlation between bridge sites classified as sulfate aggressive and chloride aggressive.

Table 9. Summary of extremely aggressive environmental conditions based on soil results

Case Criteria	Count	Percentage of Extreme Cases
Sulfate Aggressive	9	23.1%
Chloride Aggressive	7	17.9 %
Both Chloride & Sulfate Aggressive	1	2.56%
Only Sulfate Aggressive	8	20.5%
Only Chloride Aggressive	6	15.4 %

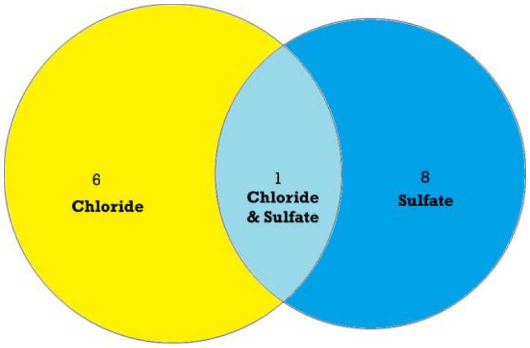


Figure 7. Extreme sulfate and chloride cases for soil test results

If the resistivity criteria were also considered, as shown in Figure 8 and Table 10, the correlation between resistivity, chloride, and sulfate is poor with only one site meeting extremely aggressive criteria for chloride, and sulfate. This poor correlation can also be seen in Table 11, as possibilities of sulfate cases also being chloride extreme 11.1% and 14.3% vice versa. With soil samples being far less in number compared to the number of water sample seen in Table 5.

Table 10. Summarized count of criteria parameters met for extremely aggressive soil samples

Case Criteria	**Count**	**Percentage of Extreme Cases**
All Sulfate Cases	9	23.1%
Sulfate Only	*6*	*15.4%*
All Chloride Cases	7	17.9%
Chloride Only	*1*	*2.6%*
All Chloride & Sulfate Cases	1	2.6%
Chloride & Sulfate Only	*1*	*2.6%*
All Resistivity Cases	11	28.2%
Resistivity Only	*3*	*7.7%*
All Sulfate & Resistivity Cases	2	5.1%
Sulfate and Resistivity only	*2*	*5.1%*
All Chloride & Resistivity Cases	5	12.8%
Chloride & Resistivity Only	*5*	*12.8%*
Sulfate & Chloride & Resistivity	*0*	*0%*

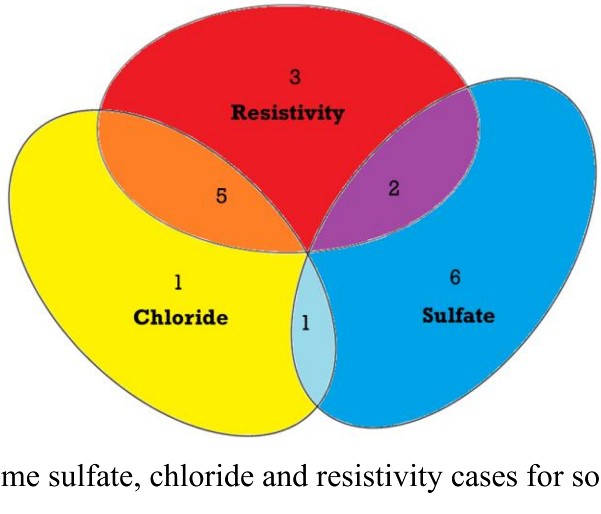


Figure 8. Extreme sulfate, chloride and resistivity cases for soil test results

Table 11. Possibility of meeting multiple criteria for soil samples

	P(B|A)
A = Sulfate	
B = Chloride	11.1%
B = Resistivity	22.2%
A = Chloride	
B = Sulfate	14.3%
B = Resistivity	71.4%
A = Resistivity	
B = Chloride	45.5%
B = Sulfate	18.2%
B = Chloride and Sulfate	0.0%

2.3 REVIEW AND COLLECT THE DATA IN THE LITERATURE THAT RELATED TO THE SR/BR THRESHOLDS AND SULFATE DURABILITY THRESHOLD

The research team conducted a comprehensive review and collect the available data in the literature that is related to the threshold for SR/BR and sulfate durability. First, the research team collected and reviewed specifications from various state DOTs. As shown in Table **12**, durability requirements vary significantly from state to state. Most of the states use AASHTO T 277, a Rapid Chloride Permeability Test (RCPT) to evaluate the permeability of chloride content. There are a couple of states (Minnesota and New Mexico) implemented ASTM C1202, a method similar to AASHTO T 277, for evaluation of chloride permeability. There are five states (Florida, Pennsylvania, Louisiana, Utah, and Vermont) utilize AASHTO T 358, a SR test method, to evaluate the durability of concrete mix. Nevertheless, the thresholds defined by these state agencies vary significantly and don’t associate with specific environmental conditions.

Table 12. Durability requirements from DOTs

Organization*	Type of Requirement	Performance Characteristic	Requirement	Test Method
Alaska Department of Transportation	Mix Design for Classes P and A-A	Chloride Ion Content	0.06%	ASTM C1218
	Mix Design for Classes A and DS	Chloride Ion Content	0.08%	
California Department of Transportation	Fast-Setting Concrete Requirements	Water soluble chlorides (max)	0.05% by weight	California Test 422
	Bonding materials	Soluble chlorides by weight (max)	0.05%	California Test 422
		Water soluble sulfates by weight (max)	0.25%	California Test 417
	Repairing existing structures: Alternative filler materials and bonding agents	Water soluble chlorides (max)	500 mg/kg	California Test 422
		Water soluble sulfates (max)	2500 mg/kg	California Test 417
	Rapid Strength Concrete Requirements	Soluble chloride (max)	0.05%	California Test 422
		Soluble sulfate (max)	0.30%	California Test 417
Delaware Department of Transportation	Concrete Mix Design	Chloride Permeability (max) Class A	1500	AASHTO T 277
		Chloride Permeability (max) Class B	3000	AASHTO T 277
		Chloride Permeability (max) Class B/SF	2500	AASHTO T 277
		Chloride Permeability (max) Class C	3500	AASHTO T 277
		Chloride Permeability (max) Class D	1500	AASHTO T 277
	Class D Portland Cement Concrete Requirements	Chloride by Weight (max)	0.1% by weight	AASHTO T 277
Florida Department of Transportation	Concrete Mix Proportions (Table 346-2)	A minimum concrete Surface Resistivity (SR) value if highly reactive pozzolans used in the mix design	29 KΩ-cm	AASHTO T 358
Illinois Department of Transportation	Requirements for Packaged, Dry, Rapid Hardening Mortar or Concrete	Chloride Ion Content	< 0.40 lb./cu yd.	ASTM C 1218
	Requirements for Concrete Admixtures	Chloride Content (max)	0.3% by weight	Illinois Modified AASHTO T 260, Procedure A, Method 1

Table 12. Durability Requirements from DOTs (Cont'd)

Organization	Type of Requirement	Performance Characteristic	Requirement	Test Method
Kansas Department of Transportation	Concrete Mix Design	Chloride Permeability (max)	3000 Coulombs	AASHTO T-277
	Structural Concrete (LPC)	Rapid Chloride Permeability (max)	1000 Coulombs	AASHTO T-277
	Structural Concrete (MPC)		2000 Coulombs	
	Structural Concrete (standard permeability)		3000 Coulombs	
	Silica Fume Modified Concrete	Rapid Chloride Permeability	1000 Coulombs	AASHTO T-277
	Air-Entrained Concrete for Shoulders or Pavement	Rapid Chloride Permeability, max	3000 Coulombs	AASHTO T-277
Louisiana Department of Transportation	Portland Cement Concrete Properties	Surface Resistivity	22 KΩ-cm	AASHTO T 358
Maryland Department of Transportation	Self-Consolidating Concrete Properties	Rapid Chloride Permeability (max)	2500 Coulombs	T 277
Minnesota Department of Transportation	Required Hardened Concrete Properties for Mixes 3YHPC-M & 3YHPC-S	Rapid Chloride Permeability	≤ 2500 coulombs at 28 calendar days, ≤ 1500 coulombs at 56 days	ASTM C1202
Missouri Department of Transportation	Early Strength Concrete Mixture	Chloride Permeability (28 days, max)	1000 coulombs	AASHTO T 277
New Jersey Department of Transportation	Acceptance Requirements for HPC	Chloride Permeability @ 56-days	2000 Coulombs	AASHTO T 277
New Mexico Department of Transportation	Concrete in Low-Risk Zones	Chloride Ion Permeability, max	3000 Coulombs	ASTM C1202
	Concrete in Medium-Risk Zones		2500 Coulombs	
	Concrete in High-Risk Zones		2000 Coulombs	

Table 12. Durability Requirements from DOTs (Cont'd)

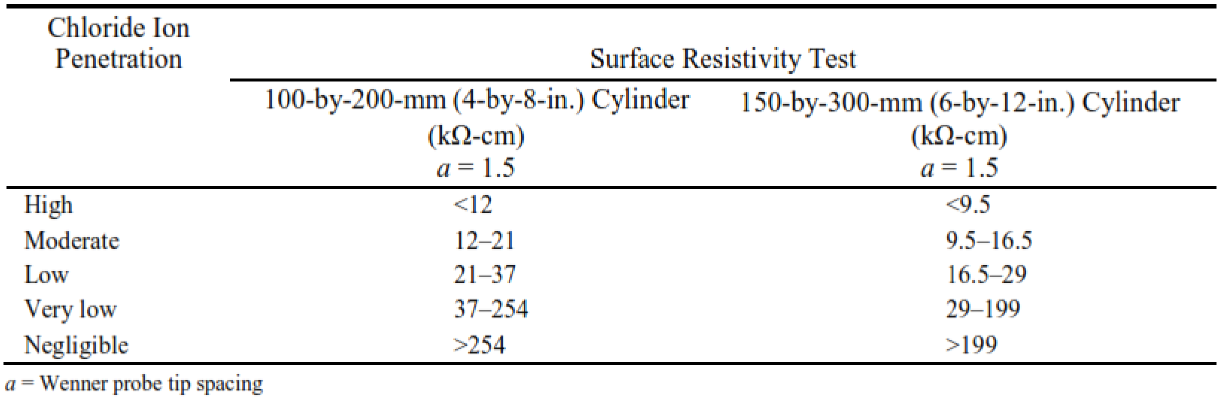
Organization	Type of Requirement	Performance Characteristic	Requirement	Test Method
New York State Department of Transportation	Concrete Repair Material	Total Chloride Content (max)	0.05%	Test Method NY 701-13P, C
		Total Sulfate Content (max)	5%	
	Penetrating Type Protective Sealers	Chloride Ion Penetration	< 15%	Not given
	Coating Type Protective Sealers for Portland Cement	Chloride Ion Penetration	< 25%	Not given
	Concrete Fabrication	Injurious Materials	< 0.05%	Not given
	Testing Requirements for HP Concrete	Chloride Penetration	p ≤ 0.025% @1 in.	AASHTO T 259
Ohio Department of Transportation	Shotcrete Mix Design	Chlorides (max)	10 ppm	ASTM D-512
		Sulfates (max)	10 ppm	APHA 427D (15th ED)
	Shotcrete Concrete Properties	Chloride Permeability (28 days, max)	750 coulombs	ASTM C 1202 / AASHTO T 277
Pennsylvania Department of Transportation	Requirements for Cement Concrete for Paving Applications	Chloride Ion Penetration Levels	Low, Very Low, or Negligible	AASHTO T 277 or AASHTO T 358
	Requirements for waving air content requirement	Rapid Chloride Permeability (max)	1500 Coulombs	AASHTO T 277
	Self-Consolidating Concrete Mixtures	Rapid Chloride Permeability (max)	2000 Coulombs	AASHTO T 277
Rhode Island Department of Transportation	Prequalification Criteria for HP Concrete	Chloride Permeability, 28-day std cure	2000 Coulombs	AASHTO T 277
		Chloride Permeability, 28-day accelerated cure	1000 Coulombs	
	Prequalification Criteria for MC Concrete	Chloride Permeability, 28-day std cure	3000 Coulombs	
		Chloride Permeability, 28-day accelerated cure	1500 Coulombs	

Table 12. Durability Requirements from DOTs (Cont'd)

Organization	Type of Requirement	Performance Characteristic	Requirement	Test Method
Utah Department of Transportation	Concrete Mix Requirements	Chloride Ion Penetration	"Low to Negligible"	AASHTO T 358
Vermont Department of Transportation	Concrete Mix Design	Chloride Ion Penetrability	"Low"	AASHTO T 358
Washington Department of Transportation	Mixed Concrete (prestressed)	Acid-Soluble Chloride Ions (percent by mass)	0.08	AASHTO T260
		Water-Soluble Chloride Ions	0.06	
	Mixed Concrete (reinforced)	Acid-Soluble Chloride Ions (percent by mass)	0.1	
		Water-Soluble Chloride Ions	0.08	
West Virginia Department of Transportation	Class H Concrete Requirements	Water Soluble Chloride Ion by Weight (max)	0.10%	
	Silica Fume Concrete Design Mix	Average Chloride Permeability (max)	750 coulombs	AASHTO T 277, ASTM C192
	Performance Requirements for Polymer Concrete Materials	Chloride Ion Penetration	Less than 750 C	AASHTO T 277, ASTM C192

Although no thresholds specified in T 358 and TP 119 for different environmental conditions, they specified different chloride ion penetration levels including “high”, “moderate”, “low”, “very low”, and “negligible”. These levels can be used as reference for selecting thresholds for different environmental conditions. However, as shown in Table 13 and Table 14, for “very low”, the range is very wide (37-254). Thus, these levels need to be evaluated carefully for different environmental conditions.

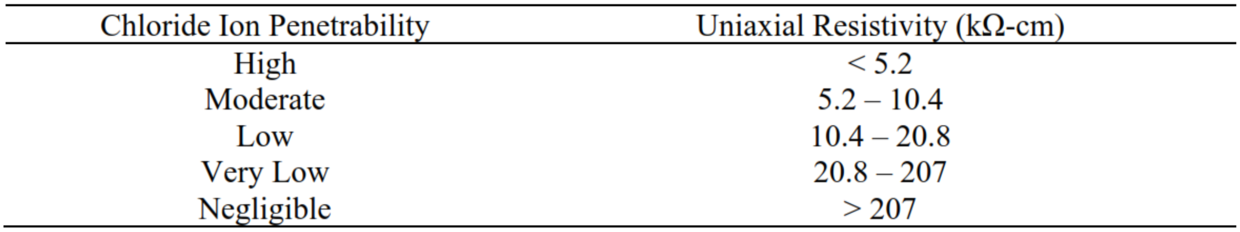
Table 13. AASHTO T 358 chloride ion penetrability classifications based on surface resistivity values for 4 in. x 8 in. and 6 in. x 12 in. cylinders (AASHTO, 2019a)



Chloride Ion Penetration	Surface Resistivity Test	
	100-by-200-mm (4-by-8-in.) Cylinder (kΩ-cm) $a = 1.5$	150-by-300-mm (6-by-12-in.) Cylinder (kΩ-cm) $a = 1.5$
High	<12	<9.5
Moderate	12–21	9.5–16.5
Low	21–37	16.5–29
Very low	37–254	29–199
Negligible	>254	>199

a = Wenner probe tip spacing

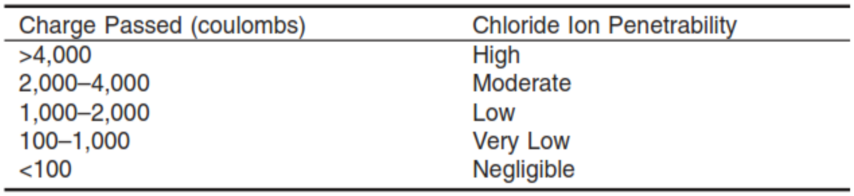
Table 14. AASHTO TP 119 chloride ion penetrability classifications based on uniaxial resistivity values (AASHTO, 2019b)



Chloride Ion Penetrability	Uniaxial Resistivity (kΩ-cm)
High	< 5.2
Moderate	5.2 – 10.4
Low	10.4 – 20.8
Very Low	20.8 – 207
Negligible	> 207

For rapid sulfate electrochemical test developed by Tumidajski and Turc (1995), they adapted it from ASTM C1202 by replacing one of the solutions with sodium sulfate. However, they didn’t establish the sulfate ion penetration levels based on charge passed. Table 15 shows the classification table for chloride ion penetrability based on charge passed developed by ASTM (2019).

Table 15. ASTM C1202 chloride ion penetrability based on charge passed (ASTM, 2019)



Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

Sirivivatnanon and Lucas (2011) conducted a similar study by testing samples from 19 concrete mixes including six sulfate-resisting cements. They concluded threshold of 2000 coulombs is adequate to resist both neutral and acidic sulfate conditions. There are other studies used rapid sulfate permeability testing method, but no classifications have been established (Ghafoori et. al, 2019 & 2020).

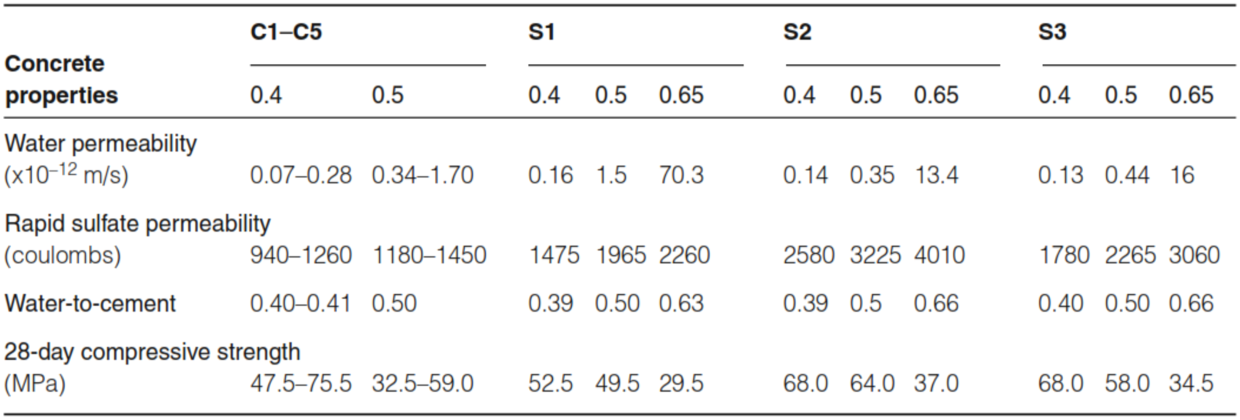
Cement Concrete & Aggregates (CCAA) Australia proposed the long-term performance and possible specifications (CCAA, 2011) as shown in Table 16. C1-C5 and S1 are mix designs with Type SR sulfate-resisting cements while S2 and S3 are mix designs with non-sulfate-resisting cements. In general, they proposed a semi-prescriptive and performance-based specifications for sulfate-resisting concrete as follows:

(1) Type SR cement and water-cement ratio ≤ 0.5, and

(2) Type SR cement and a water permeability coefficient ≤ 2x10^{-12}m/s or rapid sulfate permeability ≤ 2000 coulombs.

Since the recommendations from CCAA (2011) are developed based on Sirivivatnanon and Lucas (2011), their conclusions are similar.

Table 16. Summary of long-term performance and possible specifications (CCAA, 2011)



Concrete properties	**C1–C5**		**S1**			**S2**			**S3**		
	0.4	0.5	0.4	0.5	0.65	0.4	0.5	0.65	0.4	0.5	0.65
Water permeability (x10^{-12} m/s)	0.07–0.28	0.34–1.70	0.16	1.5	70.3	0.14	0.35	13.4	0.13	0.44	16
Rapid sulfate permeability (coulombs)	940–1260	1180–1450	1475	1965	2260	2580	3225	4010	1780	2265	3060
Water-to-cement	0.40–0.41	0.50	0.39	0.50	0.63	0.39	0.5	0.66	0.40	0.50	0.66
28-day compressive strength (MPa)	47.5–75.5	32.5–59.0	52.5	49.5	29.5	68.0	64.0	37.0	68.0	58.0	34.5

The research team has reviewed available methods to predict the service life of concrete structure based on chloride and sulfate resistivity and environmental conditions including Andrade (2011) and Andrade (2018). Andrade (2018) proposed a model to predict the service life of concrete mix with environmental factors, chloride reaction factors, and aging factors. The equation below shows the service life model:

$$t = \frac{x^2 \cdot \rho_{ef} \cdot \left(\frac{t}{t_0}\right)^q \cdot r_{Cl,CO2}}{F_{Cl,CO2}} \qquad \text{Eq. (1)}$$

where,

t = predicted service life, years

x = concrete cover, cm

ρ_{ef} = resistivity at 28 days

t_0 = age of the first measurement

q = aging factor

$r_{Cl,CO2}$ = reaction factor for chloride or CO2

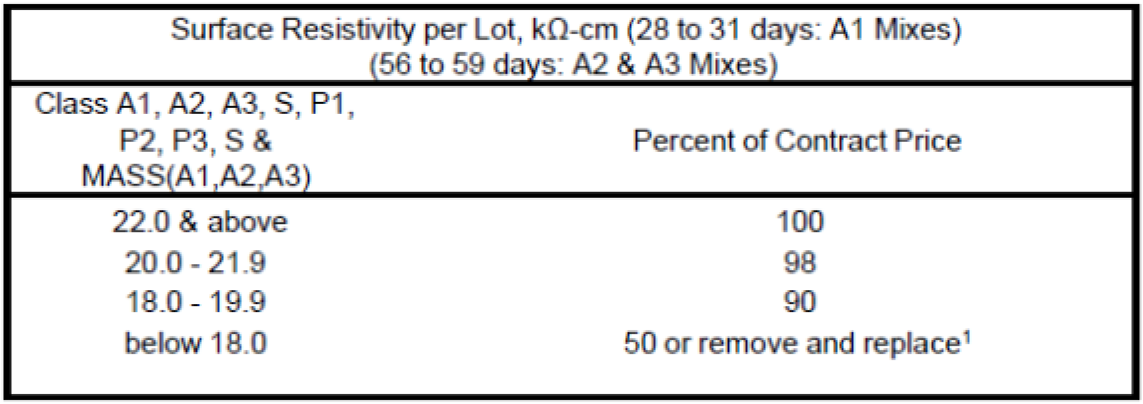
$F_{Cl,CO2}$ = environmental factor for chloride or CO2

This prediction method can be used to identify the resistivity thresholds at 28 days and 56 days. Using this prediction model, if set the service life to be 75- or 100-year, the corresponding resistivity at 28 days can be estimated.

2.4 REVIEW AND ANALYZE THE DATA FOR 4X8 INCH CYLINDERS AT 28 DAYS AND 56 DAYS OF CURING

One of the focuses of the literature review is to find the correlation between data from 28 days and 56 days of curing. Concrete containing SCMs will generally have delayed hydration and thus will need more time to develop resistance to permeation (Stanish et. al, 1997, ACI Committee 201, 2016, Ozyildirim, 1998). Because SCMs are widely used in high-performance concrete mixes, it is necessary to test the chloride and sulfate durability at 56 days of curing. Thus, it is crucial to identify the correlation between 28 days and 56 days' results. Saunders et. al (2022) investigated the feasibility and advantages of accepting concrete other than 28 days. They stated that earlier testing ages are possible with maturity but later testing ages are representative of durability. They concluded that evaluating concrete maturity and resistivity at testing ages other than 28 days could be more representative of performance. They also concluded that, in general, surface resistivity values at 28 days of age will be half of measured on the same specimens at ages of 56 and/or 90 days of age and moving surface resistivity testing to 56 days would ensure that the quality of concrete is meeting specifications. However, they didn’t provide the data that correlates 28 days results with 56 days results. Table 17 shows the acceptance and payment schedule

Table 17. Acceptance and payment schedules for cast-in-place structural concrete based on surface resistivity by LDOT (Saunders et. al, 2022)

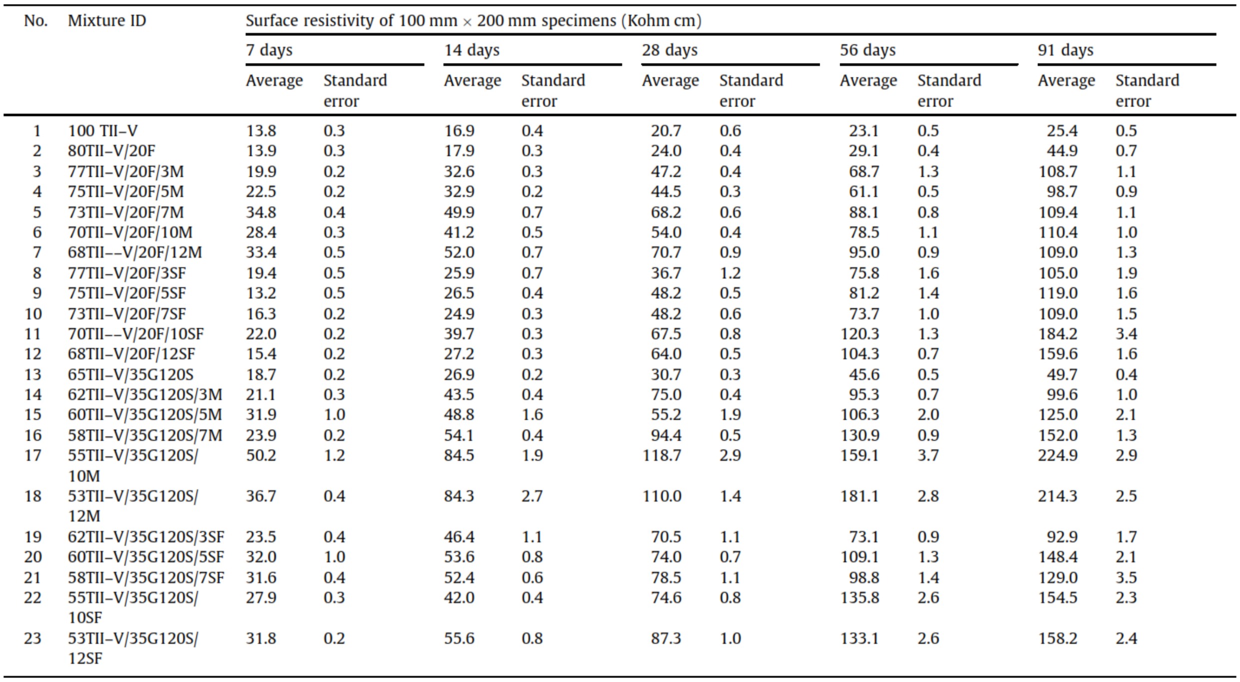


Surface Resistivity per Lot, kΩ-cm (28 to 31 days: A1 Mixes) (56 to 59 days: A2 & A3 Mixes)	
Class A1, A2, A3, S, P1, P2, P3, S & MASS(A1,A2,A3)	Percent of Contract Price
22.0 & above	100
20.0 - 21.9	98
18.0 - 19.9	90
below 18.0	50 or remove and replace[1]

Ghosh and Tran (2015) conducted a study on influence of parameters on surface resistivity of concrete. During their study, they tested the SR and BR for a series of specimens at 7 days, 14 days, 28 days, 56 days, and 91 days. As shown in Table 18, 56 days results demonstrate higher standard error with higher resistivity. Similar results were observed for 150 mm x 300 mm specimens as well (Table 19). As for bulk resistivity, as shown in Table 20, 56 days results also showed higher bulk resistivity for specimens with different mix designs. Based on the testing data from this study, the research team plotted 28 days vs. 56 days comparison and investigated the correlation between 28- and 56-day data for both SR and BR tests. As shown in Figure 9 through Figure 11, 28- and 56-day data showed a fair linear correlation with R-squared value ranging from

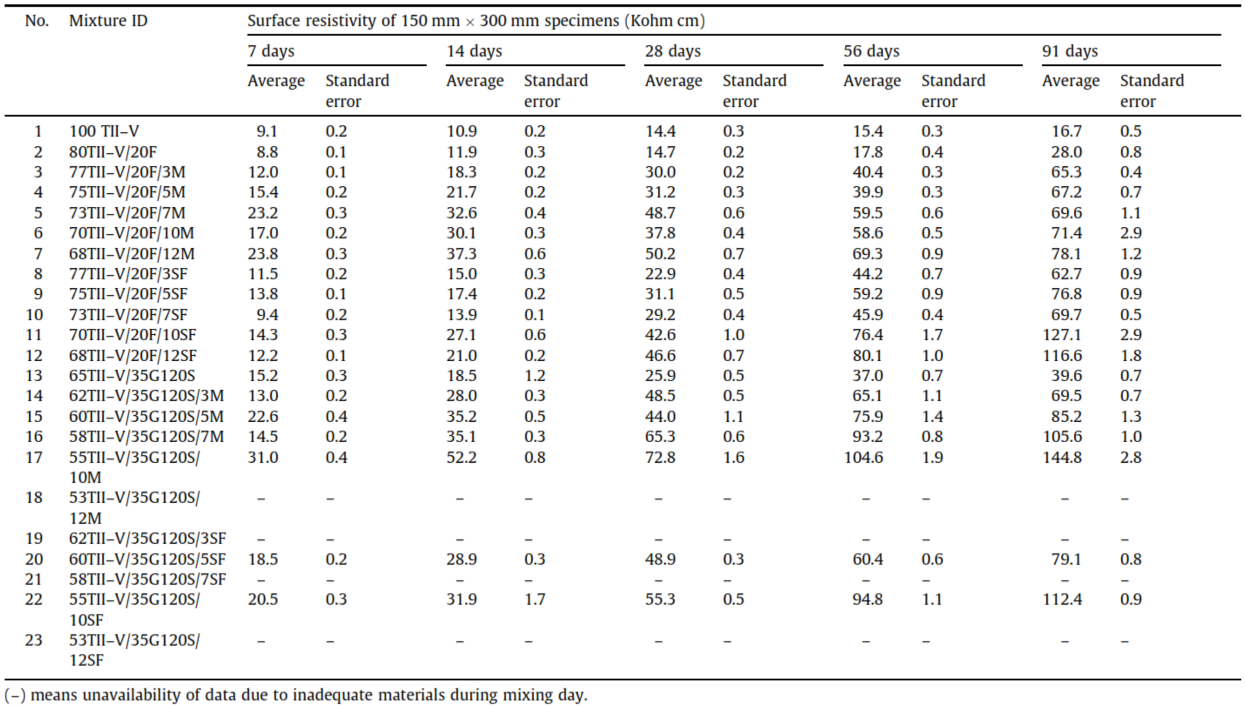
0.8506 to 0.9094. This correlation was also evaluated with the testing data obtained from this research project and the final recommendations were made.

Table 18. Surface resistivity of 100 mm x 200 mm concrete cylindrical specimens (Ghosh and Tran, 2015)



No.	Mixture ID	Surface resistivity of 100 mm × 200 mm specimens (Kohm cm)									
		7 days		14 days		28 days		56 days		91 days	
		Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error
1	100 TII–V	13.8	0.3	16.9	0.4	20.7	0.6	23.1	0.5	25.4	0.5
2	80TII–V/20F	13.9	0.3	17.9	0.3	24.0	0.4	29.1	0.4	44.9	0.7
3	77TII–V/20F/3M	19.9	0.2	32.6	0.3	47.2	0.4	68.7	1.3	108.7	1.1
4	75TII–V/20F/5M	22.5	0.2	32.9	0.2	44.5	0.3	61.1	0.5	98.7	0.9
5	73TII–V/20F/7M	34.8	0.4	49.9	0.7	68.2	0.6	88.1	0.8	109.4	1.1
6	70TII–V/20F/10M	28.4	0.3	41.2	0.5	54.0	0.4	78.5	1.1	110.4	1.0
7	68TII––V/20F/12M	33.4	0.5	52.0	0.7	70.7	0.9	95.0	0.9	109.0	1.3
8	77TII–V/20F/3SF	19.4	0.5	25.9	0.7	36.7	1.2	75.8	1.6	105.0	1.9
9	75TII–V/20F/5SF	13.2	0.5	26.5	0.4	48.2	0.5	81.2	1.4	119.0	1.6
10	73TII–V/20F/7SF	16.3	0.2	24.9	0.3	48.2	0.6	73.7	1.0	109.0	1.5
11	70TII––V/20F/10SF	22.0	0.2	39.7	0.3	67.5	0.8	120.3	1.3	184.2	3.4
12	68TII–V/20F/12SF	15.4	0.2	27.2	0.3	64.0	0.5	104.3	0.7	159.6	1.6
13	65TII–V/35G120S	18.7	0.2	26.9	0.2	30.7	0.3	45.6	0.5	49.7	0.4
14	62TII–V/35G120S/3M	21.1	0.3	43.5	0.4	75.0	0.4	95.3	0.7	99.6	1.0
15	60TII–V/35G120S/5M	31.9	1.0	48.8	1.6	55.2	1.9	106.3	2.0	125.0	2.1
16	58TII–V/35G120S/7M	23.9	0.2	54.1	0.4	94.4	0.5	130.9	0.9	152.0	1.3
17	55TII–V/35G120S/ 10M	50.2	1.2	84.5	1.9	118.7	2.9	159.1	3.7	224.9	2.9
18	53TII–V/35G120S/ 12M	36.7	0.4	84.3	2.7	110.0	1.4	181.1	2.8	214.3	2.5
19	62TII–V/35G120S/3SF	23.5	0.4	46.4	1.1	70.5	1.1	73.1	0.9	92.9	1.7
20	60TII–V/35G120S/5SF	32.0	1.0	53.6	0.8	74.0	0.7	109.1	1.3	148.4	2.1
21	58TII–V/35G120S/7SF	31.6	0.4	52.4	0.6	78.5	1.1	98.8	1.4	129.0	3.5
22	55TII–V/35G120S/ 10SF	27.9	0.3	42.0	0.4	74.6	0.8	135.8	2.6	154.5	2.3
23	53TII–V/35G120S/ 12SF	31.8	0.2	55.6	0.8	87.3	1.0	133.1	2.6	158.2	2.4

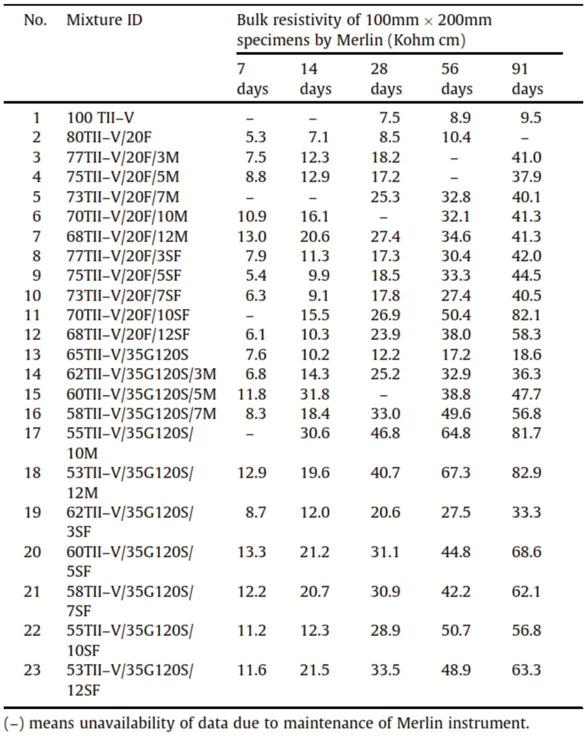
Table 19. Surface resistivity of 150 mm x 300 mm concrete cylindrical specimens (Ghosh and Tran, 2015)



No.	Mixture ID	Surface resistivity of 150 mm × 300 mm specimens (Kohm cm)									
		7 days		14 days		28 days		56 days		91 days	
		Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error	Average	Standard error
1	100 TII–V	9.1	0.2	10.9	0.2	14.4	0.3	15.4	0.3	16.7	0.5
2	80TII–V/20F	8.8	0.1	11.9	0.3	14.7	0.2	17.8	0.4	28.0	0.8
3	77TII–V/20F/3M	12.0	0.1	18.3	0.2	30.0	0.2	40.4	0.3	65.3	0.4
4	75TII–V/20F/5M	15.4	0.2	21.7	0.2	31.2	0.3	39.9	0.3	67.2	0.7
5	73TII–V/20F/7M	23.2	0.3	32.6	0.4	48.7	0.6	59.5	0.6	69.6	1.1
6	70TII–V/20F/10M	17.0	0.2	30.1	0.3	37.8	0.4	58.6	0.5	71.4	2.9
7	68TII–V/20F/12M	23.8	0.3	37.3	0.6	50.2	0.7	69.3	0.9	78.1	1.2
8	77TII–V/20F/3SF	11.5	0.2	15.0	0.3	22.9	0.4	44.2	0.7	62.7	0.9
9	75TII–V/20F/5SF	13.8	0.1	17.4	0.2	31.1	0.5	59.2	0.9	76.8	0.9
10	73TII–V/20F/7SF	9.4	0.2	13.9	0.1	29.2	0.4	45.9	0.4	69.7	0.5
11	70TII–V/20F/10SF	14.3	0.3	27.1	0.6	42.6	1.0	76.4	1.7	127.1	2.9
12	68TII–V/20F/12SF	12.2	0.1	21.0	0.2	46.6	0.7	80.1	1.0	116.6	1.8
13	65TII–V/35G120S	15.2	0.3	18.5	1.2	25.9	0.5	37.0	0.7	39.6	0.7
14	62TII–V/35G120S/3M	13.0	0.2	28.0	0.3	48.5	0.5	65.1	1.1	69.5	0.7
15	60TII–V/35G120S/5M	22.6	0.4	35.2	0.5	44.0	1.1	75.9	1.4	85.2	1.3
16	58TII–V/35G120S/7M	14.5	0.2	35.1	0.3	65.3	0.6	93.2	0.8	105.6	1.0
17	55TII–V/35G120S/10M	31.0	0.4	52.2	0.8	72.8	1.6	104.6	1.9	144.8	2.8
18	53TII–V/35G120S/12M	–	–	–	–	–	–	–	–	–	–
19	62TII–V/35G120S/3SF	–	–	–	–	–	–	–	–	–	–
20	60TII–V/35G120S/5SF	18.5	0.2	28.9	0.3	48.9	0.3	60.4	0.6	79.1	0.8
21	58TII–V/35G120S/7SF	–	–	–	–	–	–	–	–	–	–
22	55TII–V/35G120S/10SF	20.5	0.3	31.9	1.7	55.3	0.5	94.8	1.1	112.4	0.9
23	53TII–V/35G120S/12SF	–	–	–	–	–	–	–	–	–	–

(–) means unavailability of data due to inadequate materials during mixing day.

Table 20. Bulk resistivity of 100 mm x 200 mm concrete cylindrical specimens (Ghosh and Tran, 2015)



No.	Mixture ID	Bulk resistivity of 100mm × 200mm specimens by Merlin (Kohm cm)				
		7 days	14 days	28 days	56 days	91 days
1	100 TII–V	–	–	7.5	8.9	9.5
2	80TII–V/20F	5.3	7.1	8.5	10.4	–
3	77TII–V/20F/3M	7.5	12.3	18.2	–	41.0
4	75TII–V/20F/5M	8.8	12.9	17.2	–	37.9
5	73TII–V/20F/7M	–	–	25.3	32.8	40.1
6	70TII–V/20F/10M	10.9	16.1	–	32.1	41.3
7	68TII–V/20F/12M	13.0	20.6	27.4	34.6	41.3
8	77TII–V/20F/3SF	7.9	11.3	17.3	30.4	42.0
9	75TII–V/20F/5SF	5.4	9.9	18.5	33.3	44.5
10	73TII–V/20F/7SF	6.3	9.1	17.8	27.4	40.5
11	70TII–V/20F/10SF	–	15.5	26.9	50.4	82.1
12	68TII–V/20F/12SF	6.1	10.3	23.9	38.0	58.3
13	65TII–V/35G120S	7.6	10.2	12.2	17.2	18.6
14	62TII–V/35G120S/3M	6.8	14.3	25.2	32.9	36.3
15	60TII–V/35G120S/5M	11.8	31.8	–	38.8	47.7
16	58TII–V/35G120S/7M	8.3	18.4	33.0	49.6	56.8
17	55TII–V/35G120S/10M	–	30.6	46.8	64.8	81.7
18	53TII–V/35G120S/12M	12.9	19.6	40.7	67.3	82.9
19	62TII–V/35G120S/3SF	8.7	12.0	20.6	27.5	33.3
20	60TII–V/35G120S/5SF	13.3	21.2	31.1	44.8	68.6
21	58TII–V/35G120S/7SF	12.2	20.7	30.9	42.2	62.1
22	55TII–V/35G120S/10SF	11.2	12.3	28.9	50.7	56.8
23	53TII–V/35G120S/12SF	11.6	21.5	33.5	48.9	63.3

(–) means unavailability of data due to maintenance of Merlin instrument.

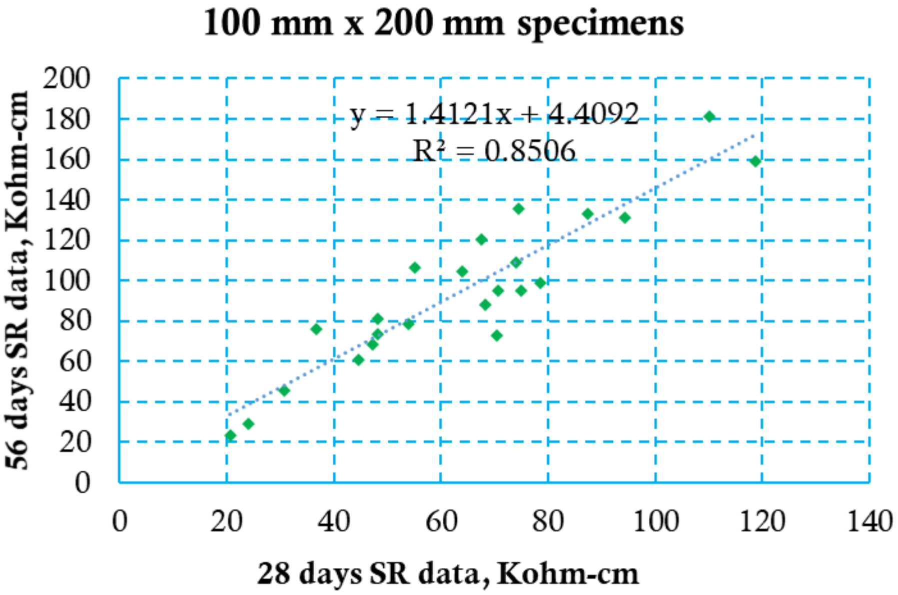


Figure 9. 28 days SR VS. 56 days SR for 100 mm x 200 mm specimens

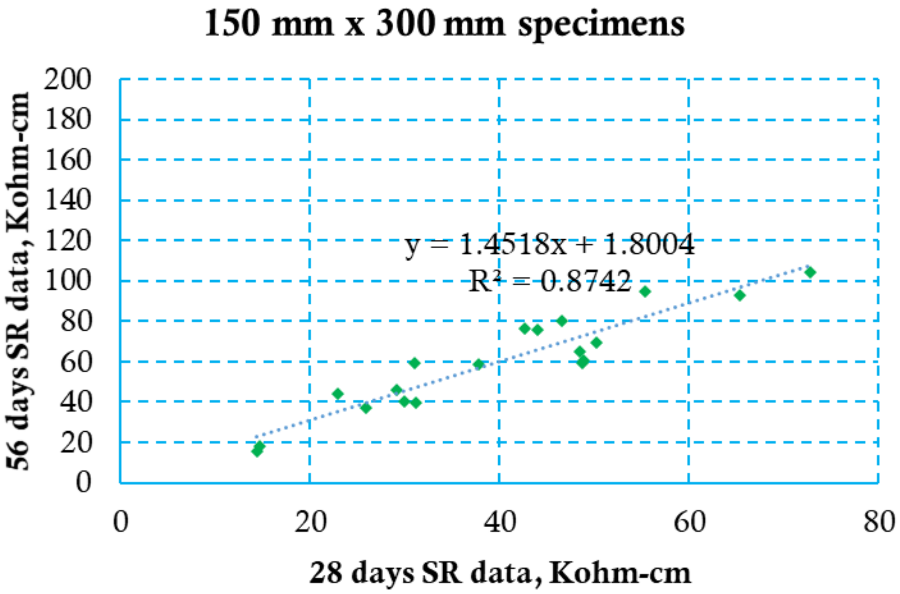


Figure 10. 28 days SR VS. 56 days SR for 150 mm x 300 mm specimens

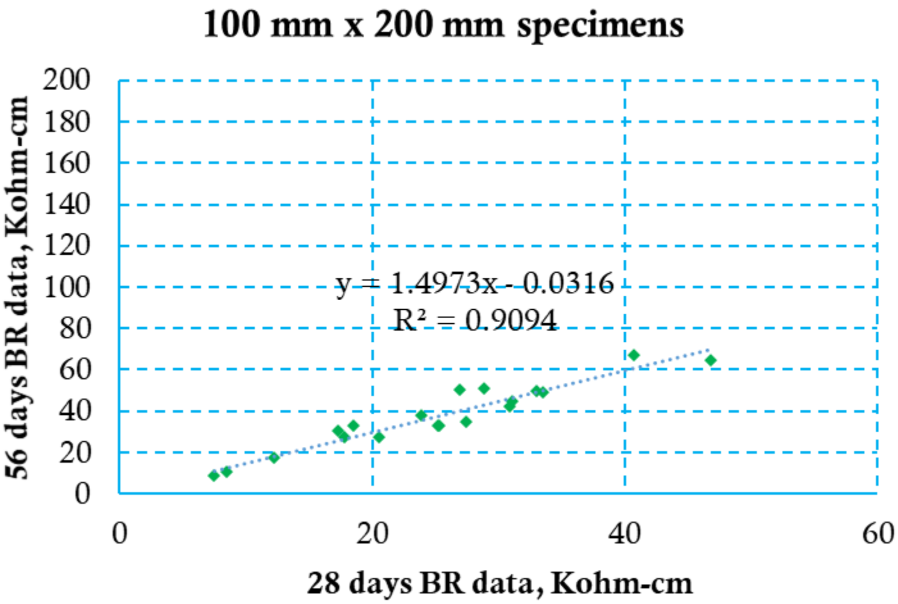


Figure 11. 28 days BR VS. 56 days BR for 100 mm x 200 mm specimens

Rupnow and Icenogle (2012) compared SR measurements with RCPT results for a series of mix designs. As shown in Figure 12, they established a regression equation to correlate SR measurements with RCPT results with a correlation coefficient of .87.

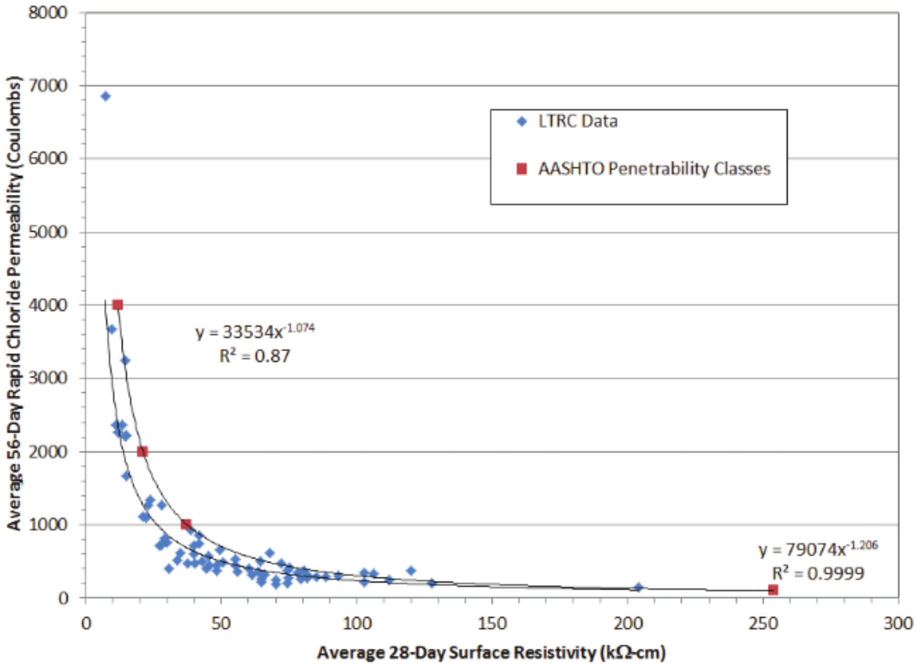
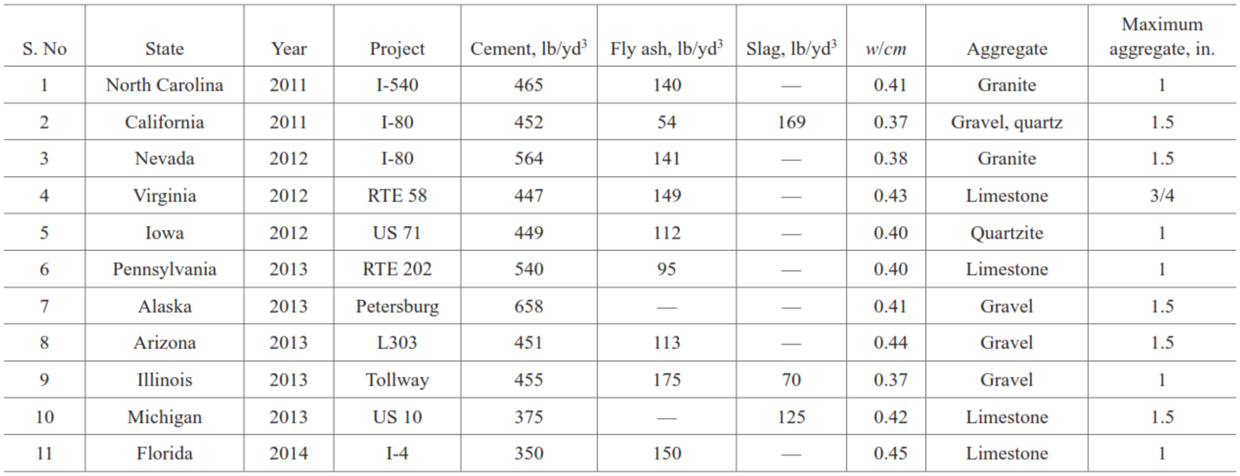


Figure 12. Relationship between average 28-day surface resistivity and average 56-day rapid chloride permeability results

Gudimettla and Crawford (2016) conducted a comprehensive study on SR, BR, and RCPT data collected from 11 concrete paving field projects from across the county. As shown in Table 21, these data were collected by the FHWA Mobile Concrete Laboratory (MCL) from 2011 to 2014 from 11 different states. Figure 13 (a) shows the relationship between SR at 28 days and 56 days. There is good linear correlation for some field projects ($R^2 > 0.80$ for Iowa, Illinois, and Virginia) but also in some cases there was no relationship between the two testing ages ($R^2 < 0.15$ for Michigan, North Carolina, and Nevada). They stated the correlation between SR at 28 days and 56 days appear to be mixture specific, which is contrary to the results from Grosh and Tran (2015). Grosh and Tran (2015) used various mixtures but showed good linear relationship.

Table 22 showed the coefficient of variation of various properties from field projects. The numbers next to the COV percentages in parentheses in each cell represent the number of data points used to arrive at the COV. It shows that the average COVs of the SR and BR are 13% and 12%, respectively. The COVs are very close for all the projects except Illinois and Nevada.

Table 21. Pavement projects and mixture designs (Gudimettla and Crawford, 2016)



S. No	State	Year	Project	Cement, lb/yd^3	Fly ash, lb/yd^3	Slag, lb/yd^3	*w/cm*	Aggregate	Maximum aggregate, in.
1	North Carolina	2011	I-540	465	140	—	0.41	Granite	1
2	California	2011	I-80	452	54	169	0.37	Gravel, quartz	1.5
3	Nevada	2012	I-80	564	141	—	0.38	Granite	1.5
4	Virginia	2012	RTE 58	447	149	—	0.43	Limestone	3/4
5	Iowa	2012	US 71	449	112	—	0.40	Quartzite	1
6	Pennsylvania	2013	RTE 202	540	95	—	0.40	Limestone	1
7	Alaska	2013	Petersburg	658	—	—	0.41	Gravel	1.5
8	Arizona	2013	L303	451	113	—	0.44	Gravel	1.5
9	Illinois	2013	Tollway	455	175	70	0.37	Gravel	1
10	Michigan	2013	US 10	375	—	125	0.42	Limestone	1.5
11	Florida	2014	I-4	350	150	—	0.45	Limestone	1

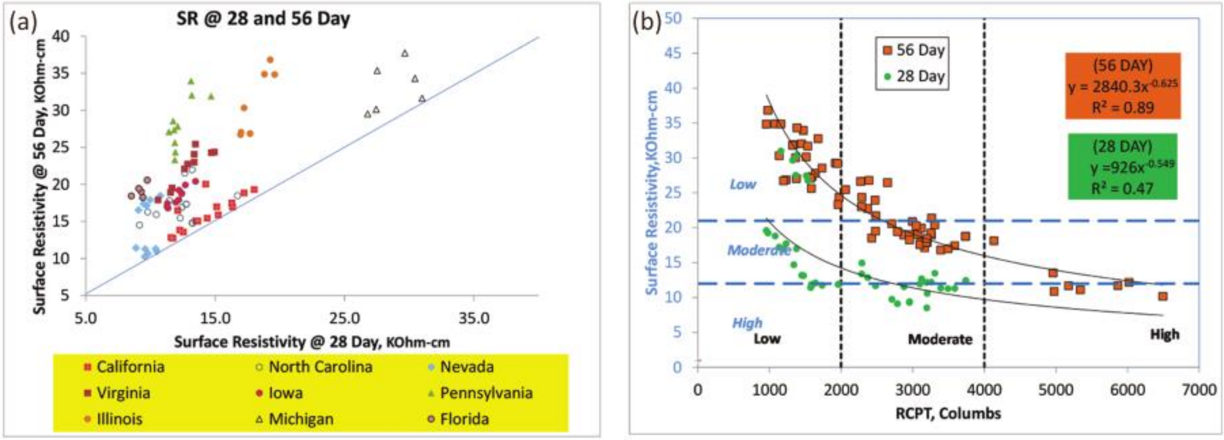


Figure 13. Relationship between SR at 28 days and 56 days (a) and between SR and RCPT data (b) (Gudimettla and Crawford, 2016)

Table 22. Coefficient of variation of various properties from field projects (Gudimettla and Crawford, 2016)

State	56 days			Slump	Air	Unit weight	Microwave water content	Compressive strength at 28 days
	RCPT	SR	BR					
NC	NA	14% (13)	NA	16% (13)	12% (13)	1% (13)	NA	8% (5)
CA	NA	14% (15)	NA	46% (15)	35% (15)	3% (15)	6% (9)	13% (5)
NV	31% (12)	25% (12)	24% (12)	16% (12)	12% (12)	1% (12)	NA	5% (4)
VA	14% (6)	11% (10)	9% (10)	25% (10)	16% (10)	1% (10)	NA	8% (3)
IA	7% (10)	7% (10)	7% (10)	16.5% (10)	5% (10)	0.2 (10)	NA	8% (8)
PA	13% (10)	12% (10)	7% (4)	19% (10)	9% (10)	1% (10)	2% (3)	6% (4)
AZ	23% (9)	14% (9)	14% (9)	41% (9)	15% (9)	1% (8)	NA	5% (3)
IL	13% (7)	14% (7)	19% (5)	NA	8% (7)	1% (7)	1% (3)	NA
MI	18% (9)	9% (9)	10% (9)	18% (9)	10% (9)	1% (9)	5% (7)	4% (4)
FL	6% (5)	5% (5)	5% (5)	20% (5)	15% (5)	1% (5)	3% (4)	8% (3)
Average COV, %	**16**	**13**	**12**	**24**	**14**	**1**	**3**	**7**
Extreme COV, %	**31**	**25**	**24**	**46**	**35**	**3**	**6**	**13**

Kevern et. al (2016) evaluated SR for concrete quality assurance in Missouri. The study was performed with three mixes for pavement, three mixes for bridge deck, and two mixes for structures. As shown in Figure 14 and Figure 15, good linear correlations can be seen for both bridge deck mixtures and structural mixtures.

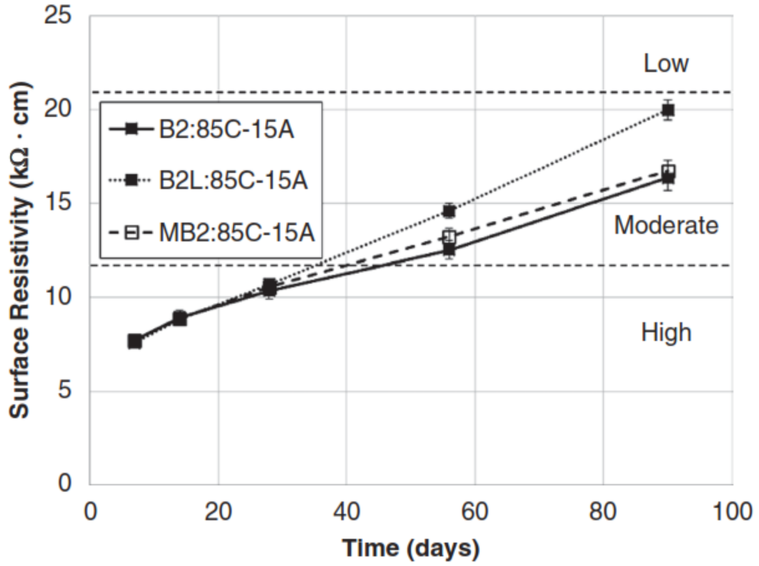


Figure 14. SR test results for bridge deck mixtures (Kevern et. al, 2016)

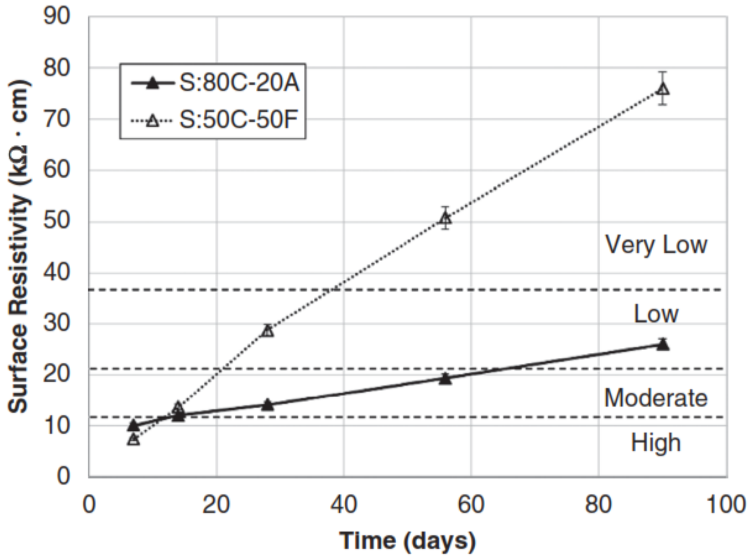


Figure 15. SR test results for structural mixtures (Kevern et. al, 2016)

2.5 REVIEW THE SR DATA AVAILABLE FROM THE DEPARTMENT'S MIX DESIGN DATABASE

The research team investigated the SR data available from the Department's mix design database. There are total 869 mix designs with various mix proportions and different materials. Table 23 shows the number of mix designs and percentage of mix designs with different concrete classes, aggregate types, and cement types. The type IV concrete class has the highest percentage among all concrete mix designs with 37.6%. For aggregate type, #57 stone was used the most as it was used in 66.6% of mix designs. 66.6% of the mix designs used Type II (MH) type of cement.

Table 23. Summary of FDOT mix designs with available SR data

Categories		# of Mix Designs	Percentage of Mix Designs
Concrete Class	Type I	60	6.9%
	Type I Pavement	13	1.5%
	Type II	118	13.6%
	Type II Bridge Deck	81	9.3%
	Type III	13	1.5%
	Type III Seal	14	1.6%
	Type IV	327	37.6%
	Type IV Drilled Shaft	39	4.5%
	Type V	91	10.5%
	Type V Special	35	4.0%
	Type VI	78	9.0%
Aggregate Type	#57 stone	579	66.6%
	#67 stone	107	12.3%
	#7 lightweight stone	2	0.2%
	#78 stone	2	0.2%
	#8 light weight stone	1	0.1%
	#8 stone	4	0.5%
	#89 stone	173	19.9%
	S1A stone	1	0.1%
Cement Type	Type II	4	0.5%
	Type II (MH)	579	66.6%
	Type IL (10)	106	12.2%
	Type IL (11)	5	0.6%
	Type IL (12)	61	7.0%
	Type IL (13)	66	7.6%
	Type IL (14)	40	4.6%

The FDOT SR data was analyzed based on the classifications presented in AASHTO T 358 (AASHTO, 2019a) as shown in Table 24. Figure 16 shows the histogram of the SR results of all mix designs. There are 67.2% of the mix designs showed a minimum 21 KΩ-cm SR result, which falls into low, very low, or negligible classification. If we use 29 KΩ-cm, which is the threshold FDOT used for mix designs with highly reactive pozzolans as a minimum requirement, there are 49.6% of the mix designs in this classification.

Table 24. AASHTO T 358 chloride ion penetrability classifications based on surface resistivity values for 4 in. x 8 in. and 6 in. x 12 in. cylinders (AASHTO, 2019a)

Chloride Ion Penetration	Surface Resistivity Test	
	100-by-200-mm (4-by-8-in.) Cylinder (kΩ-cm) *a* = 1.5	150-by-300-mm (6-by-12-in.) Cylinder (kΩ-cm) *a* = 1.5
High	<12	<9.5
Moderate	12–21	9.5–16.5
Low	21–37	16.5–29
Very low	37–254	29–199
Negligible	>254	>199

a = Wenner probe tip spacing

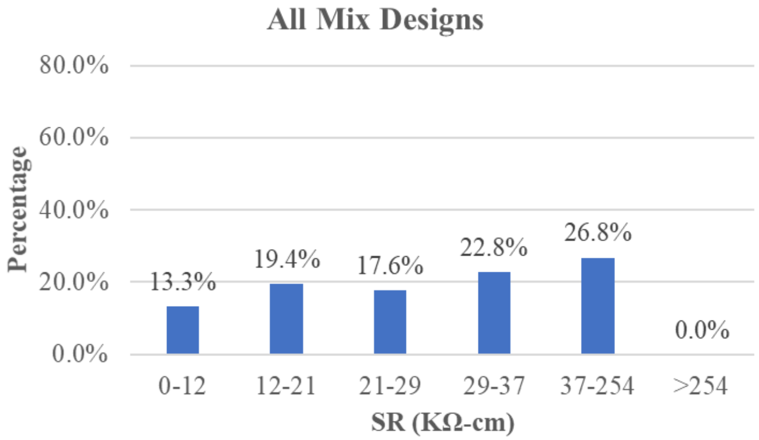
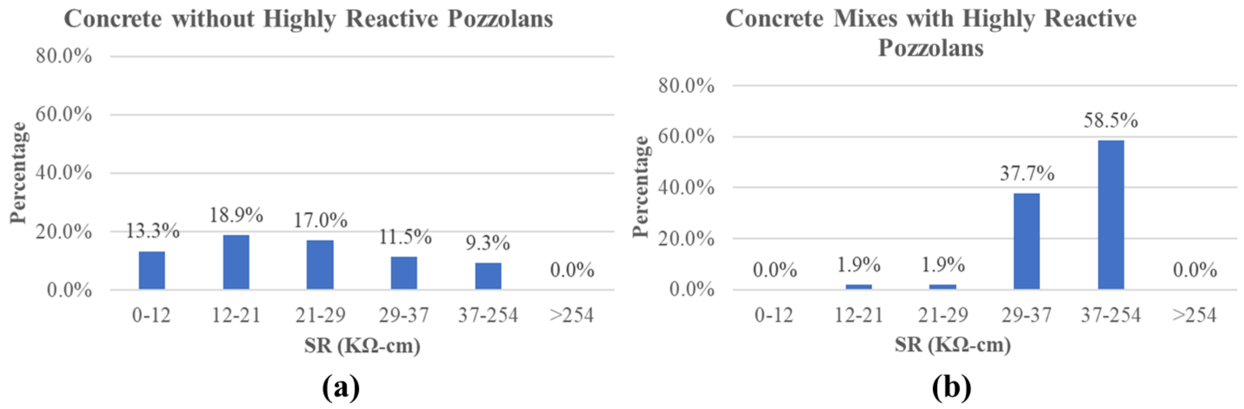


Figure 16. Histogram of SR test results from FDOT mix design database

Figure 17 shows the histogram of SR test results. For concrete mix designs without highly reactive pozzolans, there are only 37.9% and 20.8% of the mix designs above 21 KΩ-cm and 29 KΩ-cm, respectively. However, there are 98.1% and 96.2% of the mix designs above 21 KΩ-cm and 29 KΩ-cm, respectively, if the concrete mix designs used highly reactive pozzolans.

The research team also looked into the SR results of the type IV concrete. As shown in Figure 18 (a), 69.1% and 50% of the type IV concrete have a SR value above 21 KΩ-cm and 29 KΩ-cm, respectively. In addition, as shown in Figure 18 (b), (c), and (d), type of aggregate has very little effect on the SR results. The type IV concrete with #57 stone showed the highest percentage of mix designs above 21 KΩ-cm (71.2%) and 29 KΩ-cm (51.7%).



(a) **(b)**

Figure 17. Histogram of SR test results for concrete without highly reactive pozzolans (a) and with highly reactive pozzolans (b)

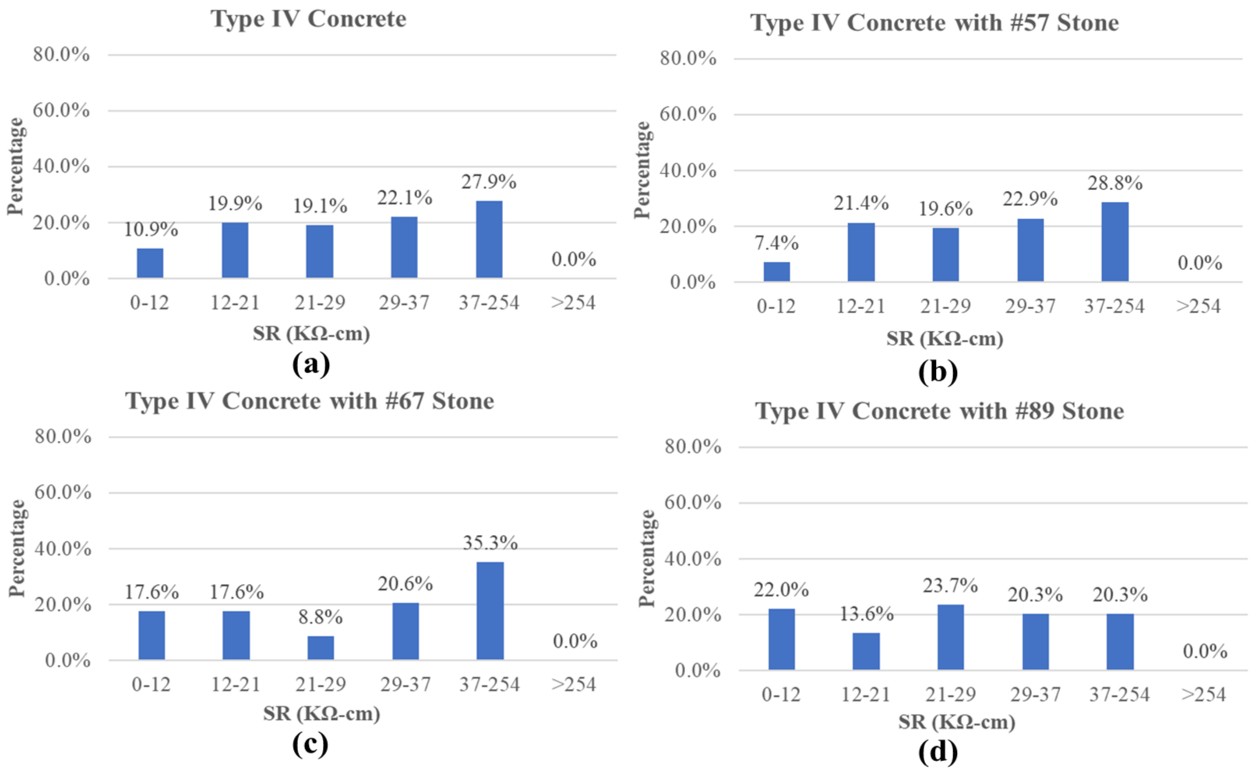


Figure 18. Histogram of SR test results for all type IV concrete (a), type IV concrete with #57 stone (b), type IV concrete with #67 stone (c), and type IV concrete with #89 stone (d)

The research team also studied the SR test results for type V and type VI concrete. As shown in Figure 19, in contrast to type IV concrete, type V and type VI concrete showed much higher SR results. There are 90.5% and 84.1% of type V concrete has SR higher than 21 KΩ-cm and 29 KΩ-cm, respectively. And there are 82.1% and 75.6% of type VI concrete has SR higher than 21 KΩ-cm and 29 KΩ-cm, respectively.

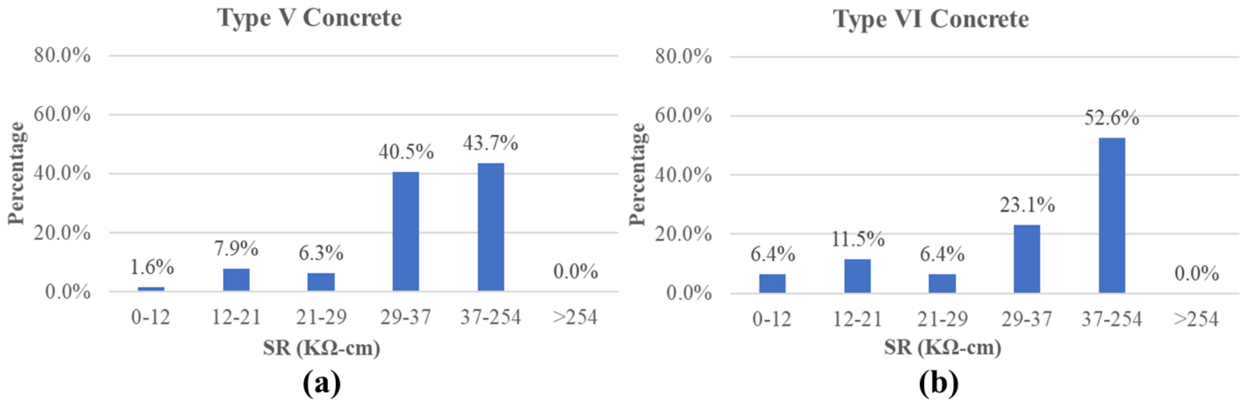


Figure 19. Histogram of SR test results for type V concrete (a) and type VI concrete (b)

2.6 KEY FINDINGS

Based on the literature review performed on five topics as presented in this report, the following key findings can be concluded:

(1) For chloride durability, Ferraro et. al (2021) recommended AASHTO T 358 and AASHTO TP 119 for further investigation. Since the department has elected to move forward with AASHTO T 358 and AASHTO TP 119, the research team will also use these two methods for chloride durability testing. For sulfate durability, Ferraro et. al (2021) investigated various testing methods including the United States Bureau of Reclamation (USBR) 4908, (Mulenga-Nobst-Stark) MNS Test (Mulenga et al., 1999), Soaking and Drying Test (de Almeida, 1991), Rapid Sulfate Electrochemical Test (Tumidajski and Turc, 1995), Partial Immersion, and Complete Immersion method. No recommendation made for sulfate durability testing method. However, for this research project, since the department has elected to move forward with RSPT described in section 4.3.4 of BDV31-977-136 for sulfate durability testing, the research team will use this method as well. In Ferraro et. al

(2021), 30 days was used as criteria to evaluate the testing method. However, 28 days is the target time for developing test thresholds in this research project.

(2) The research team has reviewed the SMO database including soil and water data for chlorides, sulfates, pH, and resistivity. The water data clearly showed that we can assume if a bridge site is sulfate aggressive, most likely it also is chloride aggressive (96.4%) and resistivity aggressive (96.8), but it is not true vice versa. The analysis results also suggested that if a bridge site is chloride aggressive, it has 96.2% possibility of reaching extremely aggressive level for resistivity too. Thus, for this research project, if we choose a site for collecting field samples, we may choose a site that is extremely aggressive in sulfate since most likely the site is also aggressive in chloride and resistivity also.

(3) The soil data from SMO database are limited to only 88 extremely aggressive records. There is no substantial correlation found between chloride aggressive and sulfate aggressive sites.

(4) The research team collected and reviewed specifications from various state DOTs. Durability requirements vary significantly from state to state. Most of the states use AASHTO T 277, a RCPT test to evaluate the permeability of chloride content. There are several states (Minnesota and New Mexico) implemented ASTM C1202, a method similar to AASHTO T 277, for evaluation of chloride permeability. There are five states (Florida, Pennsylvania, Louisiana, Utah, and Vermont) utilize AASHTO T 358, a surface resistivity test method, to evaluate the durability of concrete mix. Nevertheless, the thresholds defined by these state agencies vary significantly and don’t associate with specific environmental conditions. The research team will consider these thresholds as we are developing thresholds for various environmental conditions.

(5) Regarding threshold for the RSPT method, CCAA (2011) and Sirivivatnanon and Lucas (2011) concluded threshold of 2000 coulombs is adequate to resist both neutral and acidic sulfate conditions. Thus, the research team will use 2000 coulombs as the initial threshold for sulfate durability testing.

(6) The research team also investigated the correlation between SR/BR data from 28 days and 56 days of curing based on data from the literature. Some researchers stated, in general, surface resistivity values at 28 days of age will be half of measured on the same specimens at ages of 56 and/or 90 days of age (Saunders et. al, 2022). By analyzing available data

(Ghosh and Tran, 2015), 28- and 56-day data showed a fair linear correlation with R-squared value ranging from 0.8506 to 0.9094. Studies from Rupnow and Icenogle (2012) and Kevern et. al (2016) also showed linear correlation between 28- and 56-day SR results. Based on these previous research findings, the research team will test the correlation between 28- and 56-day SR and BR results.

(7) Table 25 shows a summary of thresholds that extracted from literature review. The research team will use these values as baseline as we are developing thresholds for various environmental conditions.

Table 25. Summary of thresholds that extracted from literature review

	Testing Methods		
Reference	SR (KΩ-cm)	BR (KΩ-cm)	RSPT (coulombs)
FDOT	29	-	-
PennDOT	21	-	-
La DOTD	22	-	-
UDOT	21	-	-
VDOT	21	-	-
CCAA (2011)	-	-	2000

(8) Based on the FDOT SR data, only 37.9% and 20.8% of the mix designs without highly reactive pozzolans has SR above 21 KΩ-cm and 29 KΩ-cm, respectively. However, if the concrete mix designs used highly reactive pozzolans, there are 98.1% and 96.2% of the mix designs above 21 KΩ-cm and 29 KΩ-cm, respectively. Also, 69.1% and 50% of the type IV concrete have a SR value above 21 KΩ-cm and 29 KΩ-cm, respectively. There are 90.5% and 84.1% of type V concrete has SR higher than 21 KΩ-cm and 29 KΩ-cm, respectively. And there are 82.1% and 75.6% of type VI concrete has SR higher than 21 KΩ-cm and 29 KΩ-cm, respectively. Thus, in this research project, 21 KΩ-cm and 29 KΩ-cm can be used as initial threshold for moderately aggressive and extremely aggressive environmental condition, respectively.

3 DEVELOPMENT OF TESTING PLAN

In the process of developing a testing plan, there are two main subtasks. One is to select mix designs that FDOT approved for extreme aggressive environment for lab sampling and testing. In order to evaluate the effects of various materials and parameters, three different groups of mix designs are proposed. One of them only uses limestone for coarse aggregate. The other two uses both limestone and granite for a number of mix designs with the same mix proportions. After in-depth discussion with PM and FDOT SMO, there are 31 mixes have been chosen for further investigation, as presented in section 3.1.4.

The research team also have developed a specific testing plan designed to provide the data to meet the objectives of this research project. The plan includes the minimum testing at 28- and 56-days of standard curing and consists of four tests: surface resistivity (SR) test (AASHTO T358), bulk resistivity (BR) test (AASHTO T119), rapid sulfate permeability test (RSPT) based on modified ASTM C1202, and length change test (ASTM C1012).

3.1 SELECTION OF MIXES

The chloride and sulfate durability highly depends on the mix design and mix proportions. Therefore, the research team worked with the FDOT project manager to select a minimum of 17 FDOT-approved design mixes from the mix designs proposed in this report. The reason for having a minimum of 17 mixes is to evaluate the effect of various parameters. In order to identify unbiased thresholds for SR/BR as well as sulfate rapid permeability test, the selected mix designs cover various parameters. To limit the number of parameters to be considered, it is proposed that all concrete made using Type II (MH) and No. 57 coarse aggregate as a baseline. FDOT standard specification section 346 and FDOT Structures Design Guidelines (SDG) were used as a general guideline for developing these mix designs.

The research team first investigated the concrete mix designs with SR data that provided by FDOT. In order to identify the mixes that suitable for this study, several filters were applied including:

(1) Only Class IV, Class IV (Drilled Shafts), Class V, Class V (Special), Class VI, and Class VII considered (based on Table 1.4.3-1 of FDOT SDG)

(2) Only Type II (MH) cement

(3) w/cm ratio ranging from 0.35 to 0.41

(4) SR larger or equal to 29 kΩ-cm

There are 43 mixes with highly reactive pozzolans (i.e. silica fume, metakaolin, and ultrafine fly ash) and 36 mixes without highly reactive pozzolans that satisfy these 4 criteria. Figure 20 and Figure 21 show the histogram of weight of different materials used in FDOT mix designs with and without highly reactive pozzolan, respectively. It shows that there is no clear distribution for cementitious material for mixes with or without highly reactive pozzolan. However, the weight of the coarse aggregate shows an approximate normal distribution. Per cubic yard, the average weight of coarse aggregate, fine aggregate, cementitious material, and water are 1672 lbs, 1143 lbs, 754 lbs, and 271 lbs for mixes with highly reactive pozzolans. On the other hand, the average weight of coarse aggregate, fine aggregate, cementitious material, and water are 1717 lbs, 1163 lbs, 708 lbs, and 272 lbs for mixes without highly reactive pozzolans. Thus, two baseline designs were selected and are summarized in Table 26.

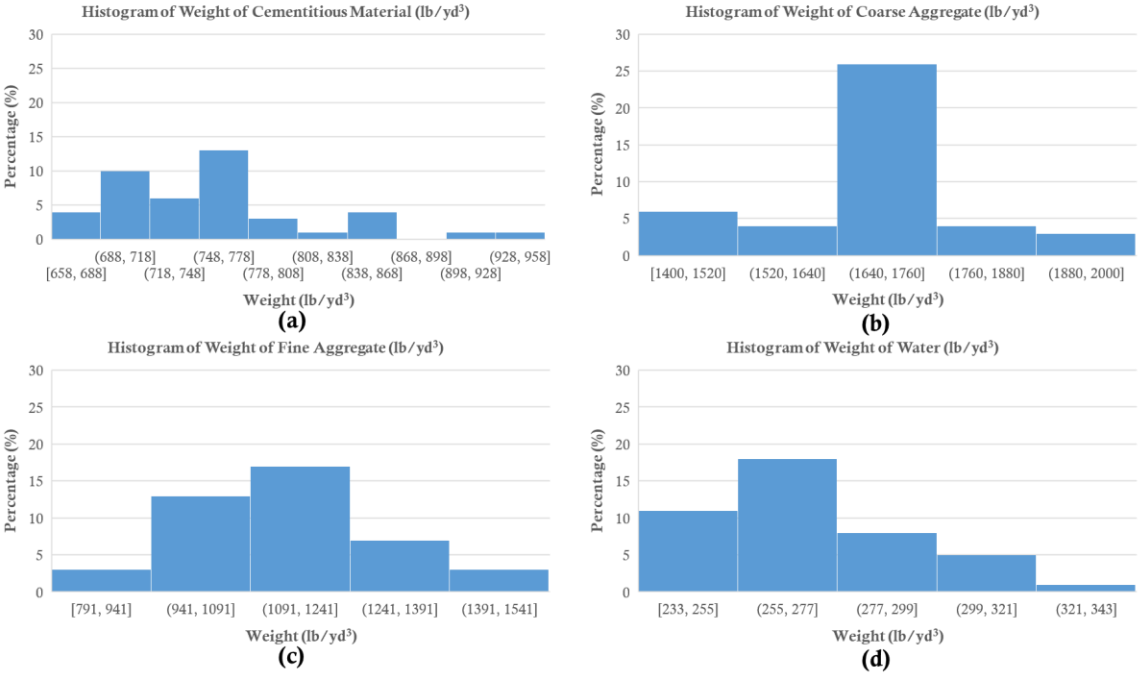


Figure 20. Histogram of weight of material from FDOT mix design database after filtering (with highly reactive pozzolan): (a) cementitious material, (b) coarse aggregate, (c) fine aggregate, and (d) water.

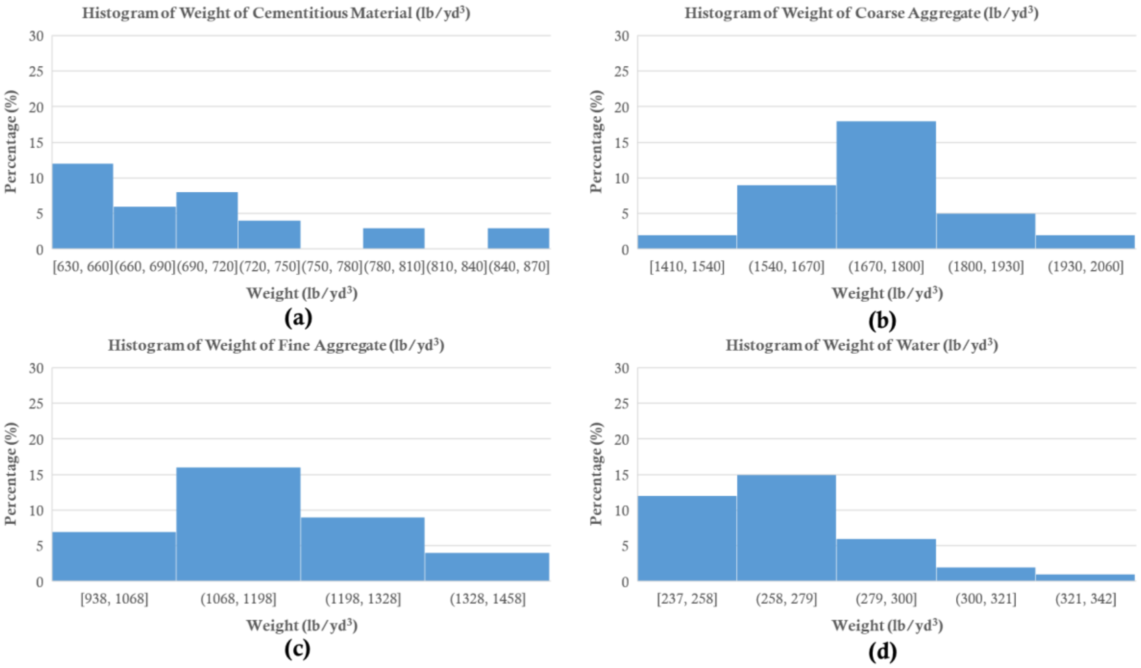


Figure 21. Histogram of weight of material from FDOT mix design database after filtering (without highly reactive pozzolan): (a) cementitious material, (b) coarse aggregate, (c) fine aggregate, and (d) water.

Table 26. Summary of the baseline mix designs

Use Highly Reactive Pozzolan	Coarse Aggregate (lbs/yd^3)	Fine Aggregate (lbs/yd^3)	Total Cementitious (lbs/yd^3)	Water (lbs/yd^3)	w/cm
No	1720	1160	710	270	0.38
Yes	1670	1140	770	270	0.35*

*Based on FDOT section 346 Table 346-3, the maximum w/cm will be 0.35 if silica fume or metakaolin is used. The maximum w/cm will be 0.3 if ultrafine fly ash is used.

The research team focused on concrete mix designs approved for an extremely aggressive environment. To this end, Table 27 provides a list of approved cement replacements specified by FDOT, and Figure 22 shows the parameters that were proposed to be considered when selecting mix designs. It is anticipated that all concrete made using Type II (MH) and No. 57 coarse aggregate as a baseline.

Although a minimum of 17 FDOT mixes was proposed, the actual number of mixes considered should be determined based on how many mixes are needed to cover the spectrum of various parameters.

Table 27. Comparison of cement replacement materials in an extremely aggressive environment

Cement Replacement Materials	FDOT Section 346	Literature
Fly Ash Class F - Drilled Shaft - Precast Concrete - Other Concrete	 33% to 37% >18% 18% to 30%	 <30% 70% for action on C-S-H
Slag Cement - Drilled Shaft - Precast Concrete - Other Concrete	 58% to 62% >50% 50% to 70%	>60% Not recommended for action on C-S-H
Fly Ash Class F and Slag	10% to 20% fly ash, 50% to 60% slag, 30% cement	>10% fly ash, >50% slag
Silica Fume	3% to 9%	>10%
Metakaolin	8% to 12%	~20%
Ultrafine Fly Ash	8% to 12%	

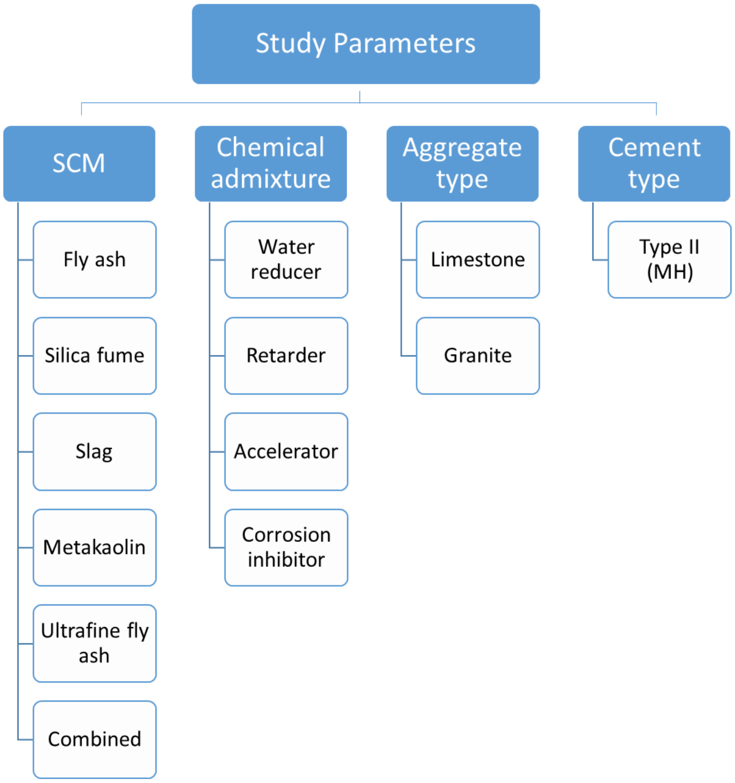


Figure 22. Parameters for Mix Design Selection

In light of aforementioned information, the research team developed three sets of mix designs.

3.1.1 Mix Design Set A

Mix design set A didn't include aggregate type as a variable and only considered limestone as a coarse aggregate. The following parameters will be evaluated:

- Seven different percentages of cement, i.e., 30%, 36%, 40%, 63%, 67%, 70%, and 100%.
- Six different percentages of fly ash, i.e., 10%, 18%, 20%, 22%, 33%, and 37%.
- Five different percentages of slag, i.e., 50%, 52%, 55%, 60%, 70%.
- Two different percentages of a ternary blend of fly ash and slag, i.e., 10%/60% and 20%/50% fly ash and slag combinations.
- Two silica fume percentages, i.e., 8% and 9%
- Three metakaolin percentages, i.e., 8%, 9%, and 12%
- Three ultrafine fly ash percentages, i.e., 8%, 9%, and 12%
- Three different w/cm ratios, i.e.., 0.30, 0.35, and 0.38
- Total of 19 mix designs. A18 and A19 are designed with w/cm of 0.38 for comparison purposes.

Table 28 shows a summary of mix design set A.

Table 28. Summary of mix design set A

Mix Design #	Coarse Aggregate	Fine Aggregate	Cement	Fly Ash	Slag	Metakaolin	Silica Fume	Ultra Fine Fly Ash	w/cm
	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	
A1	1720	1160	710						0.38
A2	1720	1160	213	142	355				0.38
A3	1720	1160	213	71	426				0.38
A4	1720	1160	475.7	234.3					0.38
A5	1720	1160	284		426				0.38
A6	1720	1160	447.3	262.7					0.38
A7	1720	1160	213		497				0.38
A8	1670	1140	539	169.4			61.6		0.35
A9	1670	1140	539	169.4		61.6			0.35
A10	1670	1140	539	169.4				61.6	0.30
A11	1670	1140	277.2		423.5		69.3		0.35
A12	1670	1140	277.2		423.5	69.3			0.35
A13	1670	1140	277.2		423.5			69.3	0.30
A14	1670	1140	539	138.6		92.4			0.35
A15	1670	1140	539	138.6				92.4	0.30
A16	1670	1140	277.2		400.4	92.4			0.35
A17	1670	1140	277.2		400.4			92.4	0.30
A18	1670	1140	539	169.4		61.6			0.38
A19	1670	1140	539	169.4				61.6	0.38

3.1.2 Mix Design Set B

Mix design set B include seven mix designs with granite aggregate. The following parameters will be evaluated:

- Six different percentages of cement, i.e., 30%, 36%, 40%, 67%, 70%, and 100%.
- Four different percentages of fly ash, i.e., 18%, 20%, 22%, and 33%.
- Three different percentages of slag, i.e., 50%, 52%, and 60%.
- One silica fume percentages, i.e., 8%
- Two metakaolin percentages, i.e., 8% and 12%
- Two ultrafine fly ash percentages, i.e., 8% and 12%
- Three different w/cm ratios, i.e.., 0.30, 0.35, and 0.38
- Total of 20 mix designs

Table 29 shows a summary of mix design set B.

Table 29. Summary of mix design set B

Mix Design #	Type of Coarse Aggregate	Coarse Aggr.	Fine Aggr.	Cement	Fly Ash	Slag	Metakaolin	Silica Fume	Ultra Fine Fly Ash	w/cm
		lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	
B1	Granite	1720	1160	710						0.38
B2	Limestone	1720	1160	710						0.38
B3	Granite	1720	1160	213	142	355				0.38
B4	Limestone	1720	1160	213	142	355				0.38
B5	Granite	1720	1160	475.7	234.3					0.38
B6	Limestone	1720	1160	475.7	234.3					0.38
B7	Granite	1720	1160	284		426				0.38
B8	Limestone	1720	1160	284		426				0.38
B9	Granite	1670	1140	539	169.4			61.6		0.35
B10	Granite	1670	1140	539	169.4		61.6			0.35
B11	Granite	1670	1140	539	169.4				61.6	0.30
B12	Limestone	1670	1140	539	169.4			61.6		0.35
B13	Limestone	1670	1140	539	169.4		61.6			0.35
B14	Limestone	1670	1140	539	169.4				61.6	0.30
B15	Limestone	1670	1140	539	138.6		92.4			0.35
B16	Limestone	1670	1140	539	138.6				92.4	0.30
B17	Limestone	1670	1140	277.2		400.4	92.4			0.35
B18	Limestone	1670	1140	277.2		400.4			92.4	0.30
B19	Limestone	1670	1140	539	169.4		61.6			0.38
B20	Limestone	1670	1140	539	169.4				61.6	0.38

3.1.3 Mix Design Set C

Mix design set C include three mix designs with granite aggregate. The following parameters will be evaluated:

- Seven different percentages of cement, i.e., 30%, 36%, 40%, 63%, 67%, 70%, and 100%.
- Six different percentages of fly ash, i.e., 10%, 18%, 20%, 22%, 33%, and 37%.
- Three different percentages of slag, i.e., 55%, 60%, and 70%.
- Two silica fume percentages, i.e., 8% and 9%
- Three metakaolin percentages, i.e., 8%. 9%, and 12%
- Three ultrafine fly ash percentages, i.e., 8%, 9%, and 12%

- Three different w/cm ratios, i.e.., 0.30, 0.35, and 0.38
- Total of 19 mix designs

Table 30 shows a summary of mix design set C.

Table 30. Summary of mix design set C

Mix Design #	Type of Coarse Aggregate	Coarse Aggr.	Fine Aggr.	Cement	Fly Ash	Slag	Metakaolin	Silica Fume	Ultra Fine Fly Ash	w/cm
		lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	
C1	Granite	1720	1160	710						0.38
C2	Limestone	1720	1160	710						0.38
C3	Granite	1720	1160	213	71	426				0.38
C4	Limestone	1720	1160	213	71	426				0.38
C5	Granite	1670	1140	539	169.4			61.6		0.35
C6	Limestone	1670	1140	539	169.4			61.6		0.35
C7	Limestone	1720	1160	475.7	234.3					0.38
C8	Limestone	1720	1160	284		426				0.38
C9	Limestone	1720	1160	447.3	262.7					0.38
C10	Limestone	1720	1160	213		497				0.38
C11	Limestone	1670	1140	539	169.4		61.6			0.35
C12	Limestone	1670	1140	539	169.4				61.6	0.30
C13	Limestone	1670	1140	277.2		423.5		69.3		0.35
C14	Limestone	1670	1140	277.2		423.5	69.3			0.35
C15	Limestone	1670	1140	277.2		423.5			69.3	0.30
C16	Limestone	1670	1140	539	138.6		92.4			0.35
C17	Limestone	1670	1140	539	138.6				92.4	0.30
C18	Limestone	1670	1140	539	169.4		61.6			0.38
C19	Limestone	1670	1140	539	169.4				61.6	0.38

3.1.4 Final Selected Mix Designs

The selected concrete mix designs are categorized into several groups based upon the type and proportion of cementitious materials used. Type IL cement was used in all mixes. There are a total of 10 groups with each being made up of three different mix designs, except for group 10 which includes four. Table 31 provides the mix proportions for each of the 31 concrete mix designs. Also, descriptions have been provided below about the proportion and water-cement ratios of the mix designs within each group.

1. Baseline Mixes (Group 1):

- Composed solely of cement.
- Consists of three mixes with a fixed w/c ratio of 0.44 but varying amounts of cement which results in different cement paste to aggregate ratios.

2. Fly Ash Mixes (Group 2):

- Composed of 20% fly ash and 80% cement.
- Consists of three mixes with varying w/c ratios of 0.30, 0.40, and 0.50.

3. Slag Mixes (Group 3):

- Composed of 70% slag and 30% cement.
- Consists of three mixes with varying w/c ratios of 0.30, 0.40, and 0.50.

4. Slag and Fly Ash Mixes (Group 4):

- Composed of 50% slag, 20% fly ash, and 30% cement.
- Consists of three mixes with varying w/c ratios of 0.25, 0.35, and 0.45.

5. Fly Ash and Silica Fume Mixes (Group 5):

- Composed of 20% fly ash, 8% silica fume, and 72% cement.
- Consists of three mixes with varying w/c ratios of 0.25, 0.34, and 0.44.

6. Slag and Silica Fume Mixes (Group 6):

- Composed of 55% slag, 6% silica fume, and 39% cement.
- Consists of three mixes with varying w/c ratios of 0.22, 0.34, and 0.46.

7. Fly Ash and Metakaolin Mixes (Group 7):

- Composed of 18% fly ash, 12% metakaolin, and 70% cement.
- Consists of three mixes with varying w/c ratios of 0.24, 0.30, and 0.36.

8. Slag and Metakaolin Mixes (Group 8):

- Composed of 55% slag, 8% metakaolin, and 37% cement.
- Consists of three mixes with varying w/c ratios of 0.22, 0.30, and 0.38.

9. South Florida Mixes (Group 9):

- Composed of 42% fly ash and 58% cement.
- Consists of three mixes with varying w/c ratios of 0.19, 0.23, and 0.27.

10. Alternative Slag Source Mixes (Group 10):

These mixes used slag from another source which has a different pozzolan content. The mix designs also included differing proportions of cementitious materials.

- Mix 28: 70% slag, 30% cement with a w/c ratio of 0.40.
- Mix 29: 50% slag, 20% fly ash, and 30% cement with a w/c ratio of 0.35.
- Mix 30: 55% slag, 6% silica fume, and 39% cement with a w/c ratio of 0.34.
- Mix 31: 55% slag, 8% metakaolin, and 37% cement with a w/c ratio of 0.30.

The first group of mix designs provides a baseline by keeping the water-cement ratio fixed and using cement as the only cementitious material in the mix. The mixes included in groups two through eight provide a large spectrum of proportions and water-cement ratios. The South Florida mixes were developed for mass concrete production and to explore regional variations in concrete performance. Last, the alternative slag source mix designs were introduced to assess the impact of different pozzolan contents on concrete durability. By providing such a significant sample size of concrete mix designs, the analysis and results of the testing methods to be discussed in the upcoming sections should adequately represent concrete mixes developed for extremely aggressive environments.

Table 31: Concrete mix design proportions

Batch #	Cement		Fly Ash		Slag1 <17%		Slag2 >17%		Silica Fume		Metakaolin		w/cm
	lb/yd^3	%	lb/yd^3	%	lb/yd^3	%			lb/yd^3	%	lb/yd^3	%	
1	450	100%	0	0%	0	0%	0	0%	0	0%	0	0%	0.44
2	750	100%	0	0%	0	0%	0	0%	0	0%	0	0%	0.44
3	600	100%	0	0%	0	0%	0	0%	0	0%	0	0%	0.44
4	520	80%	130	20%	0	0%	0	0%	0	0%	0	0%	0.30
5	520	80%	130	20%	0	0%	0	0%	0	0%	0	0%	0.40
6	520	80%	130	20%	0	0%	0	0%	0	0%	0	0%	0.50
7	195	30%	0	0%	455	70%	0	0%	0	0%	0	0%	0.30
8	195	30%	0	0%	455	70%	0	0%	0	0%	0	0%	0.40
9	195	30%	0	0%	455	70%	0	0%	0	0%	0	0%	0.50
10	210	30%	140	20%	350	50%	0	0%	0	0%	0	0%	0.25
11	210	30%	140	20%	350	50%	0	0%	0	0%	0	0%	0.35
12	210	30%	140	20%	350	50%	0	0%	0	0%	0	0%	0.45
13	576	72%	160	20%	0	0%	0	0%	64	8%	0	0%	0.25
14	576	72%	160	20%	0	0%	0	0%	64	8%	0	0%	0.34
15	576	72%	160	20%	0	0%	0	0%	64	8%	0	0%	0.44
16	312	39%	0	0%	440	55%	0	0%	48	6%	0	0%	0.22
17	312	39%	0	0%	440	55%	0	0%	48	6%	0	0%	0.34
18	312	39%	0	0%	440	55%	0	0%	48	6%	0	0%	0.46
19	665	70%	171	18%	0	0%	0	0%	0	0%	114	12%	0.24
20	665	70%	171	18%	0	0%	0	0%	0	0%	114	12%	0.30
21	665	70%	171	18%	0	0%	0	0%	0	0%	114	12%	0.36
22	277.5	37%	0	0%	412.5	55%	0	0%	0	0%	60	8%	0.30
23	277.5	37%	0	0%	412.5	55%	0	0%	0	0%	60	8%	0.22
24	277.5	37%	0	0%	412.5	55%	0	0%	0	0%	60	8%	0.38
SFM1	634.7	59%	450.3	42%	0	0%	0	0%	0	0%	0	0%	0.19
SFM2	634.7	59%	450.3	42%	0	0%	0	0%	0	0%	0	0%	0.23
SFM3	634.7	59%	450.3	42%	0	0%	0	0%	0	0%	0	0%	0.27
SLAG 2-1	195	30%	0	0%	0	0%	455	70%	0	0%	0	0%	0.40
SLAG 2-2	210	30%	140	20%	0	0%	350	50%	0	0%	0	0%	0.35
SLAG 2-3	312	39%	0	0%	0	0%	440	55%	48	6%	0	0%	0.34
SLAG 2-4	277.5	37%	0	0%	0	0%	412.5	55%	0	0%	60	8%	0.30

3.2 SAMPLING AND TESTING PLAN

Consulting with the FDOT project manager, 31 mixes were selected to perform lab trial batches to establish 28- and 56- day surface resistivity (SR) and bulk resistivity (BR) thresholds. In this section, detailed testing setup and testing plan are presented for chloride and sulfate durability testing.

3.2.1 Chloride Testing Setup

SR Test

The SR test was set up based on AASHTO T358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration.* For the SR test, a small alternating current (AC) is applied to the concrete specimen by means of a four-point Wenner probe array as shown in Figure 23. The current is applied through the outer pins and the resulting potential across the inner pins is measured instantaneously. Then the resistivity of concrete can be calculated based on the applied current, measured voltage, and dimensions of the cylinder. It is stated a minimum of three-cylinder specimens to be used for this testing. The cylinders should be marked into quadrants at 0°, 90°, 180°, and 270° following mold removal. Then the cylinders should immediately be placed into curing. The specimens should be moist cured for 28 days prior to testing unless specified otherwise. In this study, 56-days moist curing is also needed for 56-days testing.

In order to ensure proper sample conditioning, concrete cylinders must remain in a 100% relative humidity from the moment of mold removal to the moment of the test. The air temperature should maintain in the range of 20 to 25 °C (68 to 77°F). The average resistivity of each cylinder is calculated, and the percent relative standard deviation (%RSD) is checked to ensure it is less than 7.5%. Then the average resistivity is taken for the set of cylinders. Based on the average resistivity, the chloride ion penetrability resistance will be classified based on Table 32.

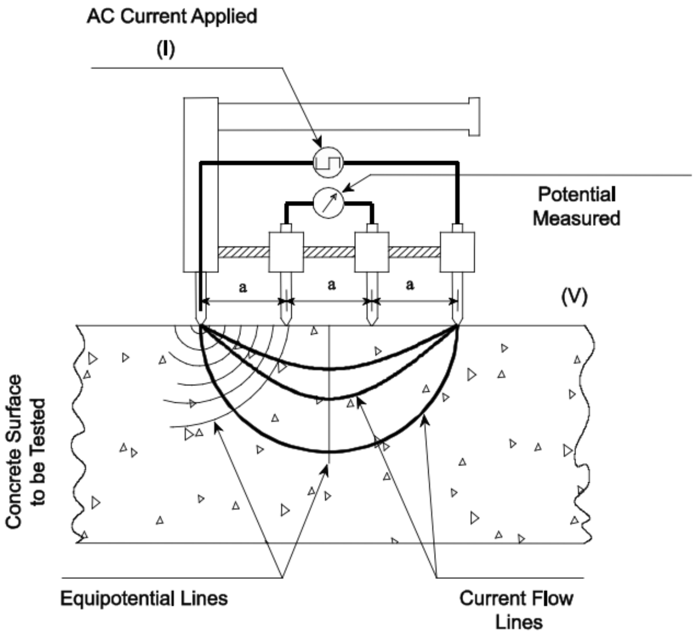


Figure 23. Four-Point Wenner Array Probe Test Setup (AASHTO, 2019a)

Table 32. AASHTO T 358 chloride ion penetrability classifications based on surface resistivity values for 4 in. x 8 in. and 6 in. x 12 in. cylinders (AASHTO, 2019a)

Chloride Ion Penetration	Surface Resistivity Test	
	100-by-200-mm (4-by-8-in.) Cylinder (kΩ-cm) *a* = 1.5	150-by-300-mm (6-by-12-in.) Cylinder (kΩ-cm) *a* = 1.5
High	<12	<9.5
Moderate	12–21	9.5–16.5
Low	21–37	16.5–29
Very low	37–254	29–199
Negligible	>254	>199

a = Wenner probe tip spacing

BR Test

The BR test was set up based on AASHTO TP 119, *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test.* Similar to the SR test, it measures the electrical resistance of concrete. However, it measures the electrical resistance of concrete across the ends of a concrete cylinder to measure a bulk resistivity instead of a surface resistivity. The testing is conducted by placing a concrete cylinder between two stainless steel plate electrodes for which current is passed through the specimen and the resistance across the specimen is measured as shown in Figure 24.

It is stated a minimum of three 4x8 inch cylindrical specimens will be used for testing, and the specimens will be moist-cured the entire time prior to testing unless specified otherwise. The conditioning procedure states to immerse the specimens in saturated limewater with the volume of solution being two to three times the volume of the specimens. The curing temperature should be maintained at 23 ± 2°C. However, the method does state that alternative curing regimes are allowed if approved by the sponsoring agency. During testing, the temperature should be maintained at 23°C ± 2°C, and the testing should be performed on a non-conductive surface (e.g., a rubber or plastic mat). A resistivity meter or surface resistivity apparatus (from AASHTO T 358) can be used to connect to the electrode plates. The combined resistance of the conductive media is subtracted from the measured resistance of each specimen, and corrections are made for the specimen geometry and probe tip spacing if a surface resistivity apparatus is used. After applying the correction factors, the average resistivity of the set is calculated, and the chloride ion penetrability resistance is determined from the ranges presented in Table 33.

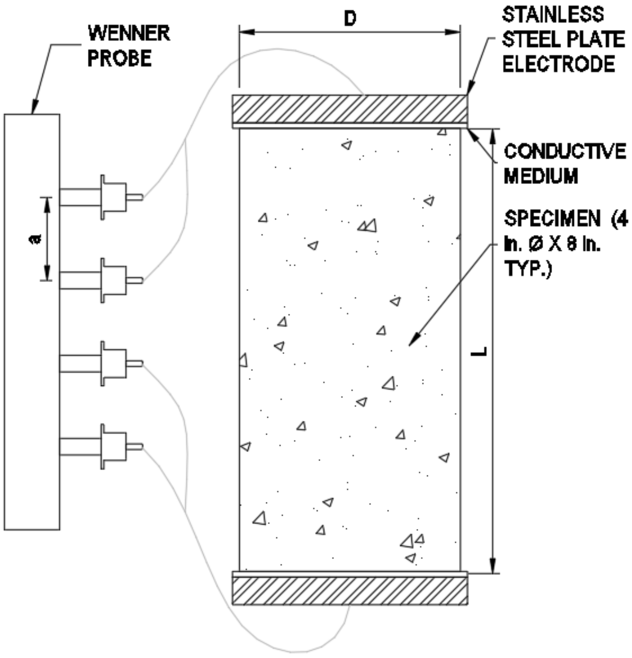


Figure 24. Diagram of bulk resistivity test setup (Ferraro, 2021)

Table 33. AASHTO TP119 chloride ion penetrability classifications based on uniaxial resistivity values (AASHTO, 2019b)

Chloride Ion Penetrability	Uniaxial Resistivity (kΩ-cm)
High	< 5.2
Moderate	5.2 – 10.4
Low	10.4 – 20.8
Very Low	20.8 – 207
Negligible	> 207

3.2.2 Sulfate Testing Setup

The test setup was based on ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.* However, to measure the sulfate ingress, one of the solutions needs to be replaced with sodium sulfate (Tumidajski and Turc, 1995). In a study by Tumidajski and Turc (1995), the results were correlated with sulfate penetration depth from two-year ponding experiments. As shown in Figure 25, the test specimens for ASTM C1202 are 2 in. thick slices taken from the middle of 4 in. x 8 in. cylinders. The specimens have been conditioned according to the procedure outlined in ASTM C1202 (ASTM, 2019). Once conditioned, the specimens have been assembled into the acrylic cells. The anolyte and catholyte solutions used for the cell chambers should be 88 g/L Na_2SO_4 and 12 g/L NaOH, respectively (Tumidajski and Turc, 1995). The solutions need to be replaced hourly, and the test will be conducted for six hours using 60 V. The resulting current has been measured and the total charge passed (coulombs) has been calculated the way similar to ASTM C1202.

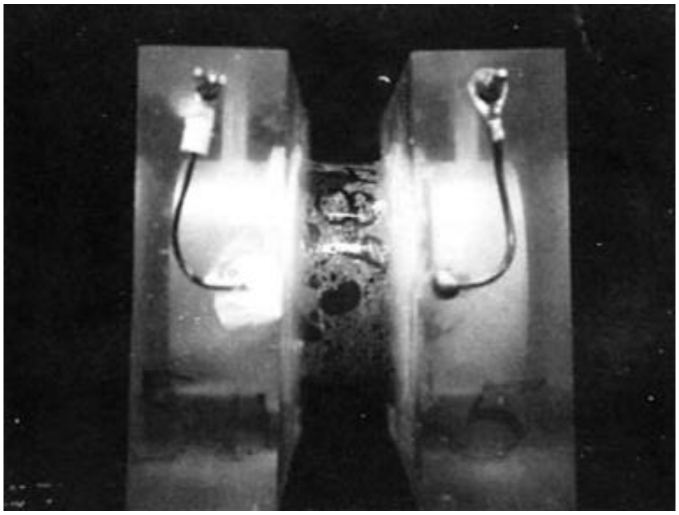


Figure 25. Specimen for ASTM C1202 (ASTM, 2018)

3.2.3 Sampling and Testing Plan

Since a large number of mixes have been investigated and a lot of tests needed to be conducted, a detailed lab testing schedule was needed. Table 34 shows the sampling and testing schedule for a typical mix. The testing schedule for each mix was imported to a calendar and shared with all team members so that close coordination and on time testing can be carried out.

Table 34. Sampling and testing schedule for a typical mix

Critical Dates	Action Item
Before mix	- Prepare and proportion materials - Prepare all the molds
Day 1	- Mix concrete - Record actual proportions and all the chemical and admixtures used - Cast samples
Day 2	- Demold all samples
1 week	- 1-week testing for ASTM C1012
2 weeks	- 2-week testing for ASTM C1012
3 weeks	- 3-week testing for ASTM C1012
Day 27	- Prepare and calibrate all equipment for testing
Day 28	- 4-week testing for ASTM C1012 - SR and BR tests - Conditioning for RSPT
Day 29	- RSPT test
Day 55	- Prepare and calibrate all equipment for testing
Day 56	- 8-week testing for ASTM C1012 - SR and BR tests - Conditioning for RSPT
Day 57	- RSPT test
Week 13	- 13-week testing for ASTM C1012
Week 15	- 15-week testing for ASTM C1012
4 Months	- 4-month testing for ASTM C1012
6 Months	- 6-month testing for ASTM C1012
9 Months	- 9-month testing for ASTM C1012
12 Months	- 12-month testing for ASTM C1012

4 TESTING RESUTLS AND ANALYSIS

In this project, four tests were conducted for the mix designs chosen in Task 2. These tests are surface resistivity (SR) test (AASHTO T358), bulk resistivity (BR) test (AASHTO T119), rapid sulfate permeability (RSPT) based on modified ASTM C1202, and length change test (ASTM C1012). SR test, BR test, and RSPT test were performed at both 28 days and 56 days while the length change test performed at various weeks according to ASTM C1012. In this report, testing results are presented and analyzed in sections 4.1 through 4.5.

4.1 SURFACE RESISTIVITY (SR) TEST

In this study, SR measurements were taken at 28 & 56 days of curing for a variety of concrete mixes with different combinations of supplementary cementitious materials (SCMs) such as fly ash, slag, silica fume, and metakaolin. The objective was to determine the proper thresholds for extreme aggressive environment conditions as well as to establish a correlation between results after 28 and 56 days of curing. The results were then classified into different chloride ion penetration categories ranging from high to very low based on the SR values obtained and the AASHTO T 358 chloride ion penetrability classifications.

By analyzing the SR values across the different mix designs, this section aims to provide a comprehensive understanding of how each type of mix performs in terms of chloride ion resistance. The findings will also serve as a foundation for establishing thresholds for SR that correlate with a desired service life, ensuring that the concrete mixes meet the durability requirements for long-term performance in aggressive environments.

Table 35 summarizes the SR measurements for each concrete mix, recorded after 28 and 56 days of curing, along with their corresponding chloride ion penetration classifications and mix details. The SR values ranged from 5.57 kΩ-cm to 144.31 kΩ-cm for 28-days testing, indicating a wide spectrum of chloride resistance among the tested mixes.

Table 35. SR results of concrete samples after 28 & 56 days of curing

Mix Number	***Apparent Surface Resistivity (kΩ-cm), 28 days***	***Chloride Ion Penetration Class, 28 days***	***Apparent Surface Resistivity (kΩ-cm), 56 days***	***Chloride Ion Penetration Class, 56 days***	***Type of mix***	***w/c ratio***
1	5.89	High	7.1	High	100 % Portland cement	0.44
2	5.57	High	6.09	High	100 % Portland cement	0.44
3	6.60	High	7.17	High	100 % Portland cement	0.44
4	13.13	Moderate	18.49	Moderate	20% fly ash	0.3
5	6.70	High	10.06	High	20% fly ash	0.4
6	8.38	High	10.41	High	20% fly ash	0.5
7	40.04	Very low	44.83	Very low	70% slag	0.3
8	40.25	Very low	46.41	Very low	70% slag	0.4
9	33.53	Low	34.58	Low	70% slag	0.5
10	35.94	Low	41.08	Very low	20% fly ash and 50% slag	0.25
11	37.58	Very low	46.04	Very low	20% fly ash and 50% slag	0.35
12	30.25	Low	39.08	Very low	20% fly ash and 50% slag	0.45
13	24.31	Low	46.40	Very low	20% fly ash and 8% silica fume	0.25
14	16.90	Moderate	30.36	Low	20% fly ash and 8% silica fume	0.34
15	11.18	High	19.68	Moderate	20% fly ash and 8% silica fume	0.44
16	57.95	Very low	80.51	Very low	55% slag & 6% silica fume	0.22
17	64.68	Very low	94.02	Very low	55% slag & 6% silica fume	0.34
18	49.85	Very low	65.23	Very low	55% slag & 6% silica fume	0.46
19	144.31	Very low	161.65	Very low	18% fly ash& 12% Metakaolin	0.24
20	42.31	Very low	47.50	Very low	18% fly ash& 12% Metakaolin	0.30
21	33.71	Low	38.68	Low	18% fly ash& 12% Metakaolin	0.36
22	77.86	Very low	92.50	Very low	55% slag & 8% Metakaolin	0.30
23	82.33	Very low	106.45	Very low	55% slag & 8% Metakaolin	0.22
24	77.56	Very low	98.78	Very low	55% slag & 8% Metakaolin	0.38
25 (SFM1)	27.68	Low	57.1	Very low	42% Fly Ash	0.19
26 (SFM2)	21.62	Low	36.06	Very low	42% Fly Ash	0.23
27 (SFM3)	17.80	Moderate	45	Very Low	42% Fly Ash	0.27
28 (SLAG2-1)	55.45	Very low	69.09	Very Low	70% slag2	0.4
29 (SLAG2-2)	59.65	Very low	77.68	Very Low	50% slag2, 20% Fly Ash	0.35
30 (SLAG2-3)	65.67	Very low	93.24	Very Low	55% slag2, 6% Silica Fume	0.34
31 (SLAG2-4)	101.68	Very low	134.75	Very Low	55% slag2, 8% Metakaolin	0.3

To further analyze the SR results of various concrete mixes over different water-to-cement (w/c) ratios, Figure 26 and Figure 27 illustrate the SR results measured at 28 and 56 days of curing for all tested mixes.

4.1.1 28-days curing results

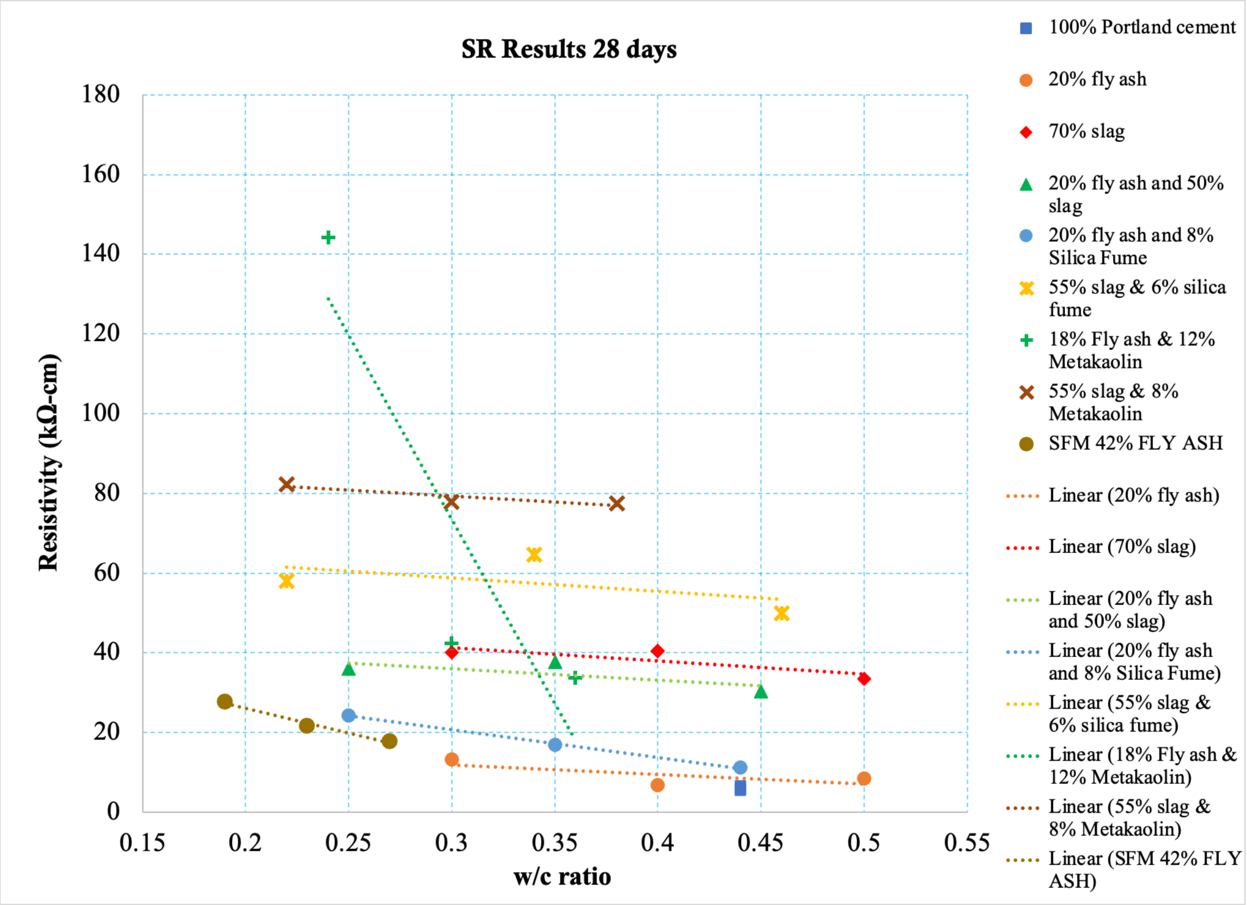


Figure 26. SR results of various concrete mixes over different water-to-cement (w/c) ratios after 28 days of curing

4.1.2 56 days curing results

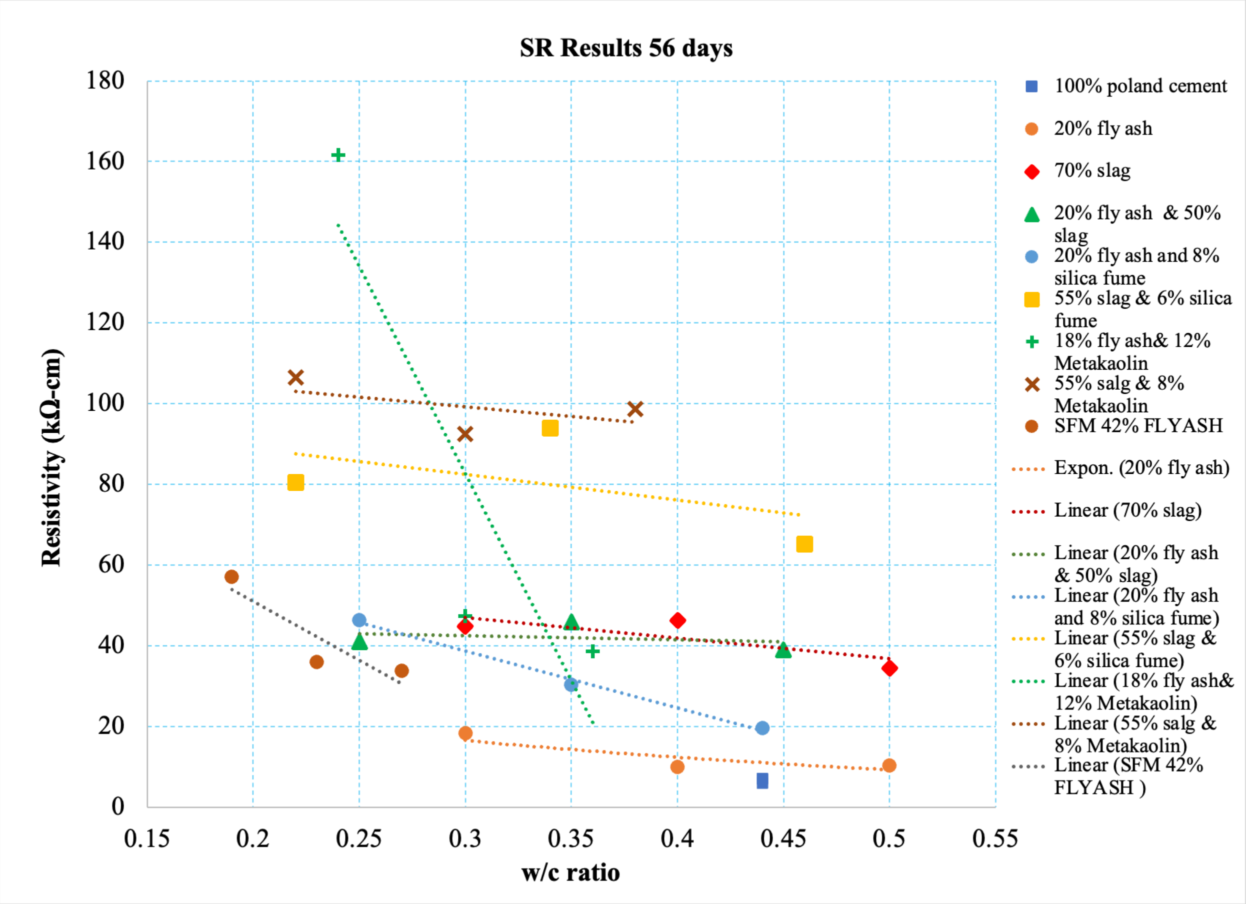


Figure 27. SR results of various concrete mixes over different water-to-cement (w/c) ratios after 56 days of curing

4.1.3 Comparative Analysis of SR Over 28 and 56 Days

To evaluate the impact of curing time on the SR across various concrete mix designs, Table 36 presents the SR results measured with both 28 and 56 days of curing. For baseline Portland cement mixes, the average percentage of increase is 12.78%. All other mixes with SCMs show greater increase except for 70% slag mixes, albeit the 70% slag mixes already show high SR. The other mixes show higher increase ranging from 13.01% to 86.57%, with 20% fly ash and 8% silica fume mixes and the South Florida Mixes show the best improvement from 28 days curing with 82.2% and 86.57%, respectively. It also shows that SR values increase substantially in mixes containing metakaolin and silica fume, indicating the ongoing pozzolanic reactions that contribute to a more refined pore structure.

Table 36. Comparison of SR results with 28 & 56 days of curing

Mix Number	Apparent Surface Resistivity for 28 days (kΩ-cm)	Apparent Surface Resistivity for 56 days (kΩ-cm)	% Difference in Resistivity between 28 and 56 days	Average % Difference
1	5.89	7.10	20.45%	12.78%
2	5.57	6.09	9.21%	
3	6.60	7.17	8.68%	
4	13.13	18.49	40.80%	38.41%
5	6.70	10.06	50.14%	
6	8.38	10.41	24.29%	
7	40.04	44.83	11.97%	10.14%
8	40.25	46.41	15.30%	
9	33.53	34.58	3.14%	
10	35.94	41.08	14.29%	22.00%
11	37.58	46.04	22.51%	
12	30.25	39.08	29.18%	
13	24.31	46.40	90.89%	82.20%
14	16.90	30.36	79.66%	
15	11.18	19.68	76.06%	
16	57.95	80.51	38.92%	38.38%
17	64.68	94.02	45.35%	
18	49.85	65.23	30.87%	
19	144.31	161.65	12.02%	13.01%
20	42.31	47.50	12.25%	
21	33.71	38.68	14.75%	
22	77.86	92.50	18.80%	25.15%
23	82.33	106.45	29.29%	
24	77.56	98.78	27.36%	
SFM1	27.68	57.11	106.33%	87.91%
SFM2	21.62	36.07	66.82%	
SFM3	17.80	33.93	90.58%	
SLAG2-1	55.45	69.10	24.61%	32.34%
SLAG2-2	59.65	77.68	30.24%	
SLAG2-3	65.67	93.24	41.99%	
SLAG2-4	101.68	134.75	32.52%	

4.1.4 Correlation Between 28-Day and 56-Day SR

To further analyze the development of SR over time, a correlation between the SR measurements at 28 and 56 days was investigated. Figure 28 displays a plot of the SR values at these two curing times, along with a fitted linear regression line.

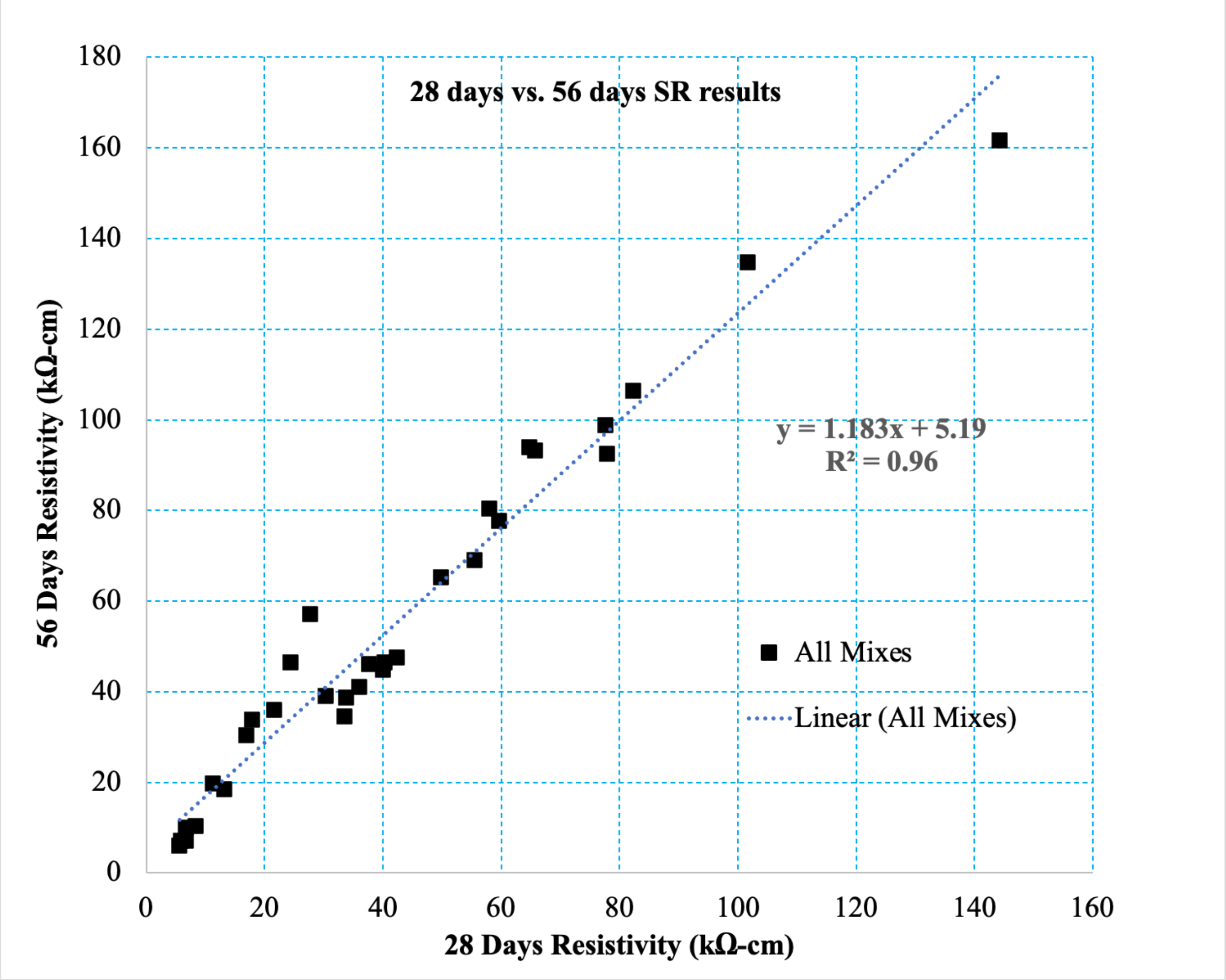


Figure 28. Correlation between 28-day and 56-day SR

The data indicates a strong linear correlation between the SR measurements at 28 days and those at 56 days. The linear regression line has a high R^2 value of 0.96, suggesting that approximately 97.9% of the variability in the 56-day SR can be explained by the 28-day SR values. This high correlation underscores the predictive capacity of early-age SR measurements for estimating longer-term resistivity performance.

The regression line is represented by the equation $y = 1.183x + 5.19$, where Y is the SR at 56 days, and X is the SR at 28 days. This equation can be used to estimate the SR at 56 days based on the SR values observed at 28 days, providing a useful tool for predicting the long-term performance of concrete mixes in terms of their chloride resistance.

The ability to predict 56-day SR values from 28-day measurements allows for early assessment and decision-making regarding the durability of concrete mixes. This can be particularly beneficial in optimizing the mix design and adjusting curing practices to meet durability requirements in aggressive environments, such as those exposed to chloride ingress.

- It's important to note that mixes with cement only are not applicable for using this graph as it has been found that the prediction accuracy for these mixes has a high percentage of error.

After verifying the graph with the results, it was observed that the prediction error is less than 13%.

4.2 BULK RESISTIVITY (BR) TEST

In this study, BR measurements were conducted at 28 and 56 days of curing for various concrete mixes, each containing different proportions of supplementary cementitious materials (SCMs) such as fly ash, slag, silica fume, and metakaolin. The primary goal was to evaluate how these SCMs influence the resistance of concrete to chloride ion penetration. The obtained BR values were categorized into different chloride ion penetration classes, ranging from high to very low, in accordance with AASHTO TP119 chloride ion penetrability classifications.

By examining the BR values across different mixes formulations, this section aims to provide insights into the effectiveness of various SCM combinations in enhancing concrete durability. The results will provide insights for selecting mix designs that meet specific durability requirements in chloride-rich environments. These findings will also help establish appropriate bulk BR thresholds aligned with the desired service life of infrastructure projects. Additionally, a key objective is to collect BR data at both 28 and 56 days to establish a correlation between these curing periods. This correlation will assist in predicting long-term concrete performance from early-age measurements.

Table 37 summarizes the BR measurements for each concrete mix, recorded at 28 days of curing, along with their respective chloride ion penetration classifications and mix composition details. The BR observed in this study ranged from 3.10 kΩ-cm to 42.73 kΩ-cm for 28 days and from 3.66 kΩ-cm to 52.92 kΩ-cm for 56 days, respectively.

Table 37 BR results of concrete samples after 28 & 56 days of curing

Mix Number	***Apparent Surface Resistivity (kΩ-cm), 28 days***	***Chloride Ion Penetration Class, 28 days***	***Apparent Surface Resistivity (kΩ-cm), 56 days***	***Chloride Ion Penetration Class, 56 days***	***Type of mix***	***w/c ratio***
1	3.1	High	3.66	High	100 % Portland cement	0.44
2	3.21	High	3.86	High	100 % Portland cement	0.44
3	3.63	High	4.31	High	100 % Portland cement	0.44
4	6.37	Moderate	9.85	Moderate	20% fly ash	0.3
5	3.40	High	5.59	Moderate	20% fly ash	0.4
6	3.98	High	5.82	Moderate	20% fly ash	0.5
7	19.52	Low	21.98	Very low	70% slag	0.3
8	16.62	Low	24.28	Very low	70% slag	0.4
9	11.42	Low	12.52	Low	70% slag	0.5
10	16.97	Low	21.16	Very low	20% fly ash and 50% slag	0.25
11	16.60	Low	18.92	Low	20% fly ash and 50% slag	0.35
12	12.01	Low	14.52	Low	20% fly ash and 50% slag	0.45
13	12.01	Low	21.54	Very low	20% fly ash and 8% silica fume	0.25
14	9.18	Moderate	14.58	Low	20% fly ash and 8% silica fume	0.34
15	5.79	Moderate	9.55	Moderate	20% fly ash and 8% silica fume	0.44
16	27.09	Very low	34.78	Very low	55% slag & 6% silica fume	0.22
17	26.43	Very low	31.76	Very low	55% slag & 6% silica fume	0.34
18	13.75	Low	15	Low	55% slag & 6% silica fume	0.46
19	42.73	Very low	52.92	Very low	18% fly ash& 12% Metakaolin	0.24
20	16.39	Low	21.75	Very low	18% fly ash& 12% Metakaolin	0.30
21	14.72	Low	16.84	Low	18% fly ash& 12% Metakaolin	0.36
22	26.13	Very low	32.46	Very low	55% slag & 8% Metakaolin	0.30
23	33.85	Very low	34.1	Very low	55% slag & 8% Metakaolin	0.22
24	26.38	Very low	36.24	Very low	55% slag & 8% Metakaolin	0.38
25 (SFM1)	9.83	Moderate	16.00	Low	42% Fly Ash	0.19
26 (SFM2)	8.64	Moderate	13.57	Low	42% Fly Ash	0.23
27 (SFM3)	8.30	Moderate	14.3	low	42% Fly Ash	0.27
28 (SLAG2-1)	11.88	Low	13.22	low	70% slag2	0.4
29 (SLAG2-2)	17.05	Low	17.55	low	50% slag2, 20% Fly Ash	0.35
30 (SLAG2-3)	17.77	Low	18.73	low	55% slag2, 6% Silica Fume	0.34
31 (SLAG2-4)	28.78	Low	30.96	very low	55% slag2, 8% Metakaolin	0.3

To further evaluate the performance of various concrete mixes in terms of BR, Figure 29 and Figure 30 illustrate the BR results measured at 28 and 56 days of curing for all tested mixes. These figures provide insights into how different combinations of SCMs and water-to-cement (w/c) ratios impact the concrete's ability to resist chloride ion penetration.

4.2.1 28-days curing results

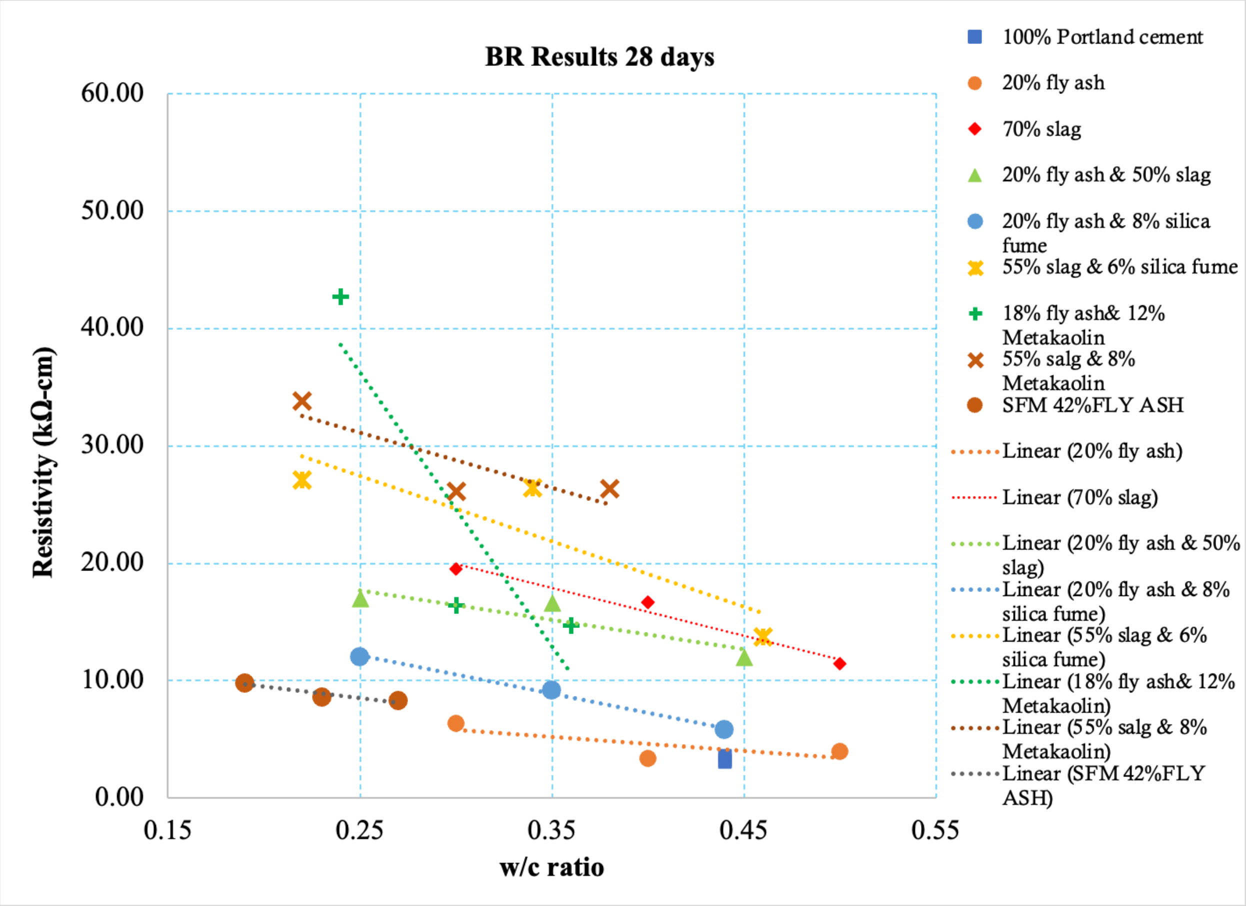


Figure 29. BR of various concrete mixes over different water-to-cement (w/c) ratios after 28 days of curing.

4.2.2 56 days curing results

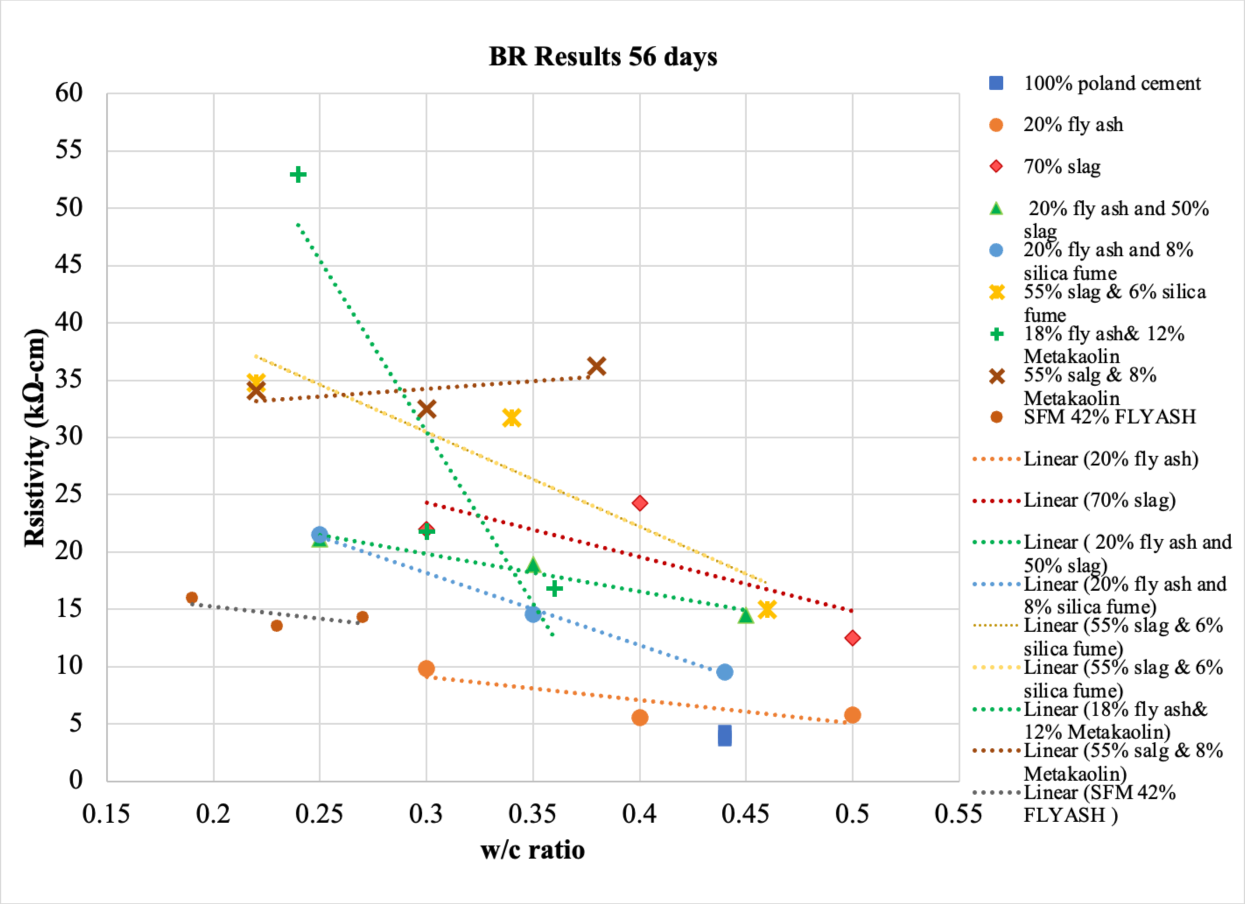


Figure 30. BR of various concrete mixes over different water-to-cement (w/c) ratios after 56 days of curing.

4.2.2.1 Impact of SCMs on BR

Mixes with a higher content of SCMs, such as those containing 55% slag and 8% metakaolin, consistently demonstrated the highest BR values across varying w/c ratios. These high-performing mixes showed resistivity values exceeding 50 kΩ-cm at both 28 and 56 days of curing, indicating excellent durability and low permeability. This performance highlights the effectiveness of metakaolin and slag in reducing chloride ion ingress and enhancing the long-term durability of concrete in aggressive environments.

In contrast, the 100% Portland cement mixes exhibited the lowest BR values, which further decreased as the w/c ratio increased. These mixes showed BR values below 5 kΩ-cm, suggesting high permeability and susceptibility to chloride ion penetration, which could lead to faster corrosion of reinforcing steel.

4.2.2.2 Effect of Water-Cement Ratio

As anticipated, the BR values generally declined with increasing w/c ratios for all mix types, emphasizing the critical role of water content in influencing concrete durability. Lower w/c ratios contribute to a denser microstructure, which effectively reduces the pathways for chloride ions to penetrate concrete. This trend was especially significant in mixes without SCMs or those with lower SCM content, where a higher w/c ratio led to a marked decrease in resistivity values.

Mixes that incorporated combinations of SCMs, such as slag with silica fume or metakaolin, managed to maintain relatively high BR values even at higher w/c ratios. For instance, the mix with 55% slag and 6% silica fume showed BR values ranging between 27 and 35 kΩ-cm at both 28 and 56 days of curing, indicating robust resistance to chloride ion penetration. These results highlight the effectiveness of using SCMs in improving concrete resistance to aggressive chloride environments.

4.2.2.3 Specific Observations for SCM Combinations

- The mix with 55% slag and 6% silica fume maintained BR values between 27 and 34 kΩ-cm across all w/c ratios tested, suggesting this combination significantly enhances the concrete's resistance to chloride ion ingress.
- Mixes containing 20% fly ash and 50% slag demonstrated improved BR compared to mixes with only Portland cement, especially at lower w/c ratios. With BR values ranging from approximately 16 to 22 kΩ-cm.
- The combination of 18% fly ash and 12% metakaolin achieved some of the highest BR readings, exceeding 50 kΩ-cm at lower w/c ratios and maintaining strong performance at higher ratios. These results suggest that metakaolin, even in moderate proportions, significantly improves the durability characteristics of concrete, providing excellent resistance against chloride penetration.

4.2.3 Comparative Analysis of BR Over 28 and 56 Days

To assess the effect of curing duration on the BR of various concrete mixes, Table 38 illustrates the BR results measured at both 28 and 56 days. This graph provides a comparative view of how different SCMs, and w/c ratios influence BR over time, offering insights into the durability performance of each mix design under chloride exposure. The baseline Portland cement mixes show an average percentage of increase of 19.09%, All other mixes with SCMs show greater increase except for 20% fly ash and 50% slag mixes and slag2 mixes. The other mixes show higher increase ranging from 19.22% to 67.56%, with 20% fly ash and 8% silica fume mixes and the South Florida mixes show the best improvement from 28 days curing with 67.56% and 64.11%, respectively.

Table 38. Comparison of BR results with 28 & 56 days of curing

Mix Number	Apparent Surface Resistivity for 28 days (kΩ-cm)	Apparent Surface Resistivity for 56 days (kΩ-cm)	% Difference in Resistivity between 28 and 56 days	Average % Difference
1	3.10	3.66	18.27%	19.09%
2	3.21	3.86	20.20%	
3	3.63	4.31	18.78%	
4	6.37	9.85	54.58%	55.19%
5	3.40	5.60	64.49%	
6	3.98	5.83	46.49%	
7	19.52	21.98	12.63%	27.81%
8	16.62	24.28	46.09%	
9	16.97	21.16	24.70%	
10	11.42	12.52	9.64%	14.85%
11	16.60	18.92	13.96%	
12	12.01	14.52	20.94%	
13	12.04	21.54	78.91%	67.56%
14	9.18	14.58	58.82%	
15	5.79	9.56	64.96%	
16	27.09	34.78	28.40%	19.22%
17	26.44	31.76	20.11%	
18	13.75	15.01	9.15%	
19	42.73	52.93	23.85%	23.64%
20	16.40	21.75	32.68%	
21	14.73	16.85	14.40%	
22	26.13	32.46	24.21%	20.78%
23	33.86	34.11	0.73%	
24	26.38	36.24	37.38%	
SFM1	9.83	16.01	62.88%	64.11%
SFM2	8.64	13.58	57.13%	
SFM3	8.30	14.30	72.28%	
SLAG2-1	11.88	13.22	11.27%	6.79%
SLAG2-2	17.05	17.55	2.94%	
SLAG2-3	17.78	18.73	5.36%	
SLAG2-4	28.78	30.96	7.57%	

4.2.4 Correlation Between 28-Day and 56-Day BR

To further understand the development of BR over time, a correlation between BR measurements at 28 and 56 days of curing was examined. Figure 31 presents a plot of the BR values at these two curing intervals, accompanied by a fitted linear regression line.

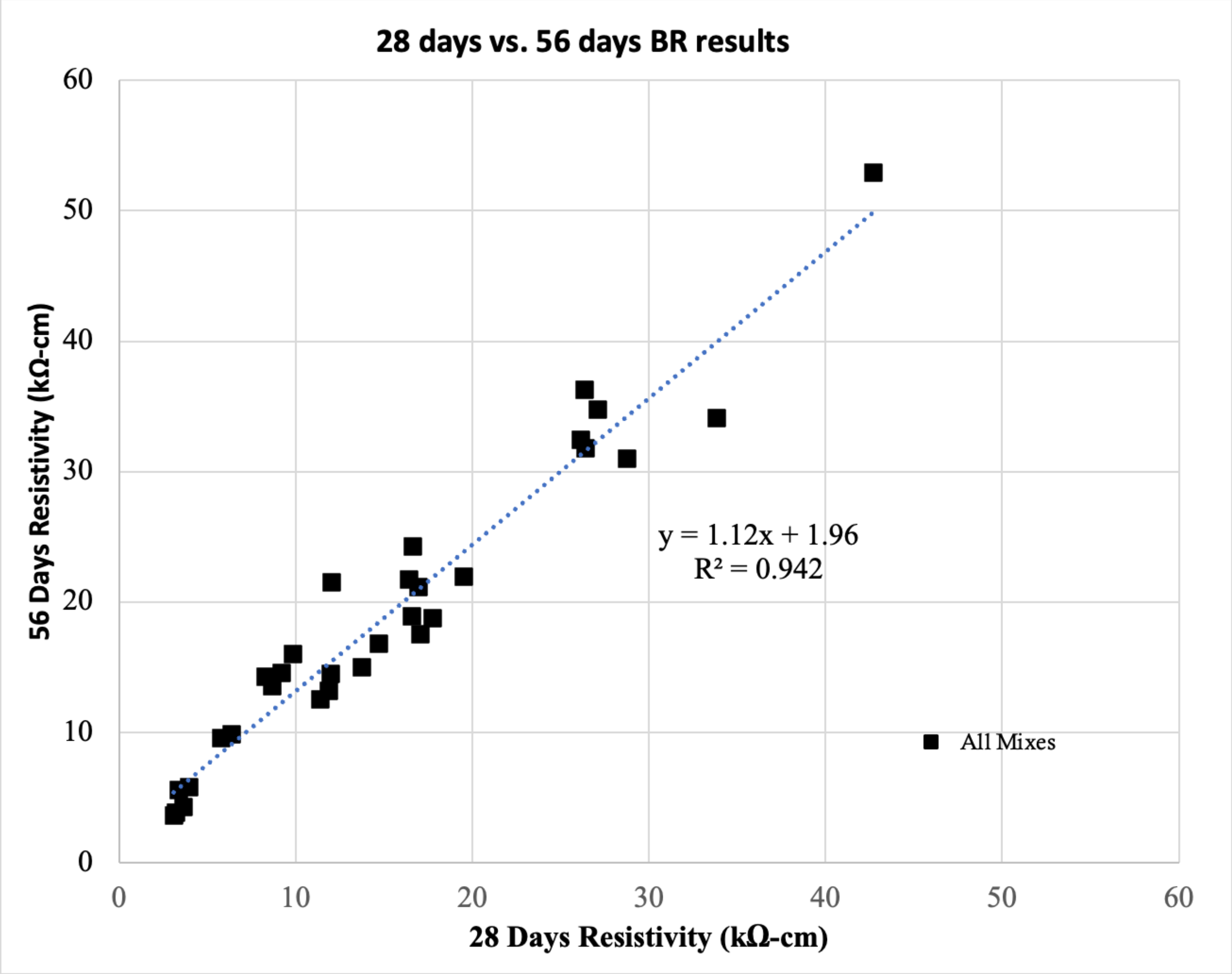


Figure 31. Correlation between 28-day and 56-day BR

The plot indicates a strong linear relationship between the BR measurements taken at 28 days and those taken at 56 days. The linear regression line shown in the figure has a high R^2 value of 0.94, implying that approximately 96.9% of the variability in the 56-day BR can be explained by the BR values measured at 28 days. This high correlation highlights the effectiveness of using early-age BR measurements to predict the longer-term resistivity performance of concrete mixes.

The regression equation is represented by $y = 1.12x + 1.96$, where Y is the BR at 56 days, and X is the BR at 28 days. This relationship can be used to estimate the BR at 56 days based on the BR values observed at 28 days. Such predictive capability is valuable for assessing the long-term durability of different concrete mixes, particularly in terms of their resistance to chloride ion penetration.

Using the 28-day BR measurements to forecast 56-day resistivity values enables early evaluation and decision-making regarding the durability performance of concrete mixes. This approach can significantly aid in optimizing mix designs and adjusting curing practices to meet specific durability requirements, particularly in environments subject to aggressive chloride exposure.

- It's important to note that mixes with cement only are not applicable for using this graph as it has been found that the prediction accuracy for these mixes has a high percentage of error.
- After verifying the graph with the results, it was observed that the prediction error is less than 13%.

4.3 COMPARISON OF SURFACE RESISTIVITY (SR) AND BULK RESISTIVITY (BR) RESULTS

To further investigate the relationship between SR and BR, a correlation analysis was performed using the measurements obtained at 28 days of curing. Figure 32 presents a plot illustrating the relationship between SR and BR for various concrete mixes, along with a fitted linear regression line.

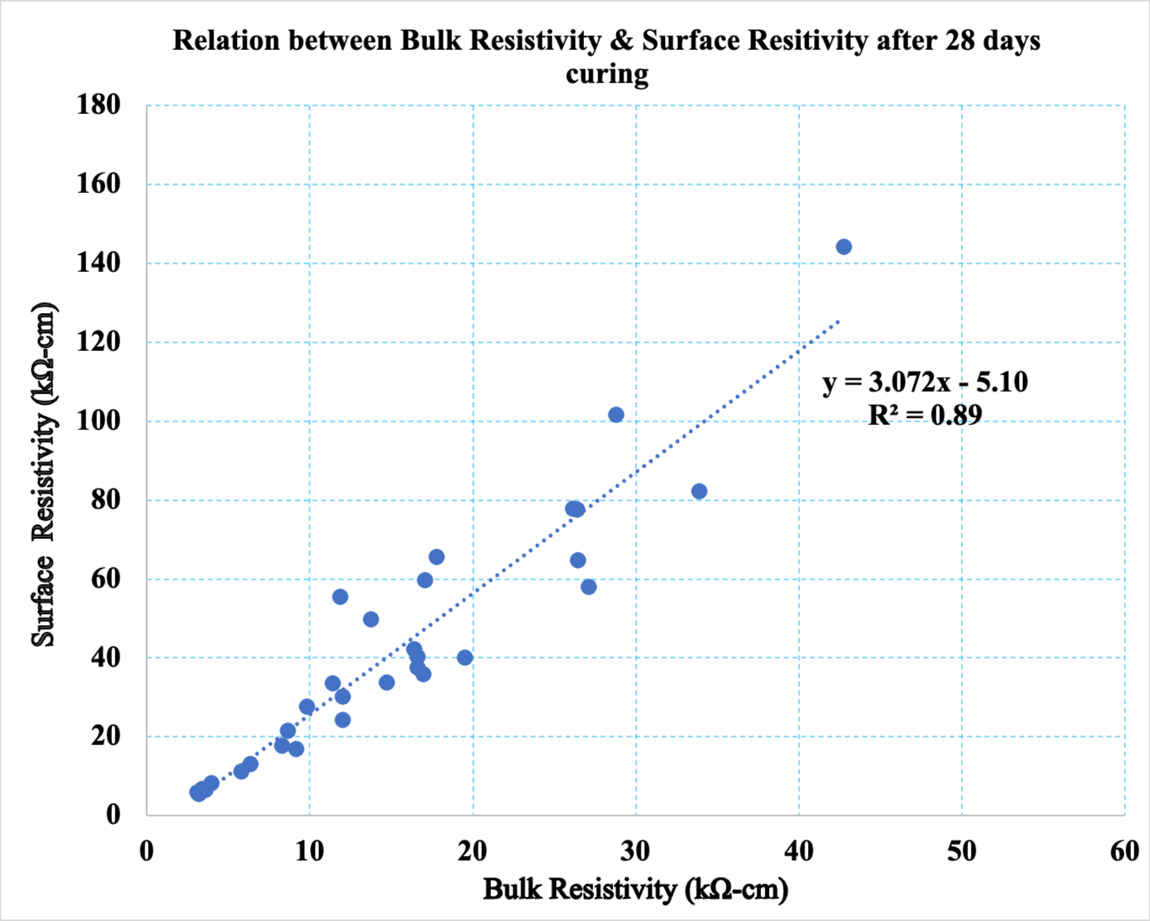


Figure 32. Correlation between BR and SR after 28 days of curing

The plot demonstrates a strong positive correlation between SR and BR values, as indicated by the linear regression line with an equation of y=3.072x−5.10. The R^2 value of 0.89 suggests that approximately 94.3% of the variability in SR can be explained by the BR measurements. This high degree of correlation confirms that BR measurements can reliably predict SR values, offering a valuable tool for assessing concrete durability against chloride ion penetration.

The relationship between SR and BR as represented by the regression line implies that as the BR of the concrete increases, the SR also increases. This trend is consistent across various mix designs.

By establishing this correlation, it can be utilized either SR or BR measurements to assess the chloride resistance of concrete. This flexibility allows us to select the most appropriate testing method based on available resources and specific project requirements. The ability to predict SR values from BR measurements, or vice versa, can aid in optimizing mix designs for enhanced durability in chloride-rich environments, ultimately contributing to the development of concrete infrastructure with prolonged service life.

4.4 RAPID SULFATE PERMEABILITY TEST (RSPT)

The 28 days RSPT results are presented in Table 39.

4.4.1 28 days results

Table 39. RSPT results of concrete samples after 28 days of curing

Mix Number	*Average Charge Passed (Adjusted) coulomb*	*Sulphate Penetration Class*	*Type of mix*	*w/c ratio*
1	3999.5	Moderate	100 % Portland cement	0.44
2	3343	Moderate	100 % Portland cement	0.44
3	2753	Moderate	100 % Portland cement	0.44
4	1257	Low	20% fly ash	0.3
5	2823	Moderate	20% fly ash	0.4
6	2359	Moderate	20% fly ash	0.5
7	533	Very Low	70% slag	0.3
8	572.5	Very Low	70% slag	0.4
9	806	Very Low	70% slag	0.5
10	459	Very Low	20% fly ash and 50% slag	0.25
11	661	Very Low	20% fly ash and 50% slag	0.35
12	698.5	Very Low	20% fly ash and 50% slag	0.45
13	729	Very Low	20% fly ash and 8% silica fume	0.25
14	1208	Low	20% fly ash and 8% silica fume	0.34
15	1991.5	Low	20% fly ash and 8% silica fume	0.44
16	439.61	Very Low	55% slag & 6% silica fume	0.22
17	421	Very Low	55% slag & 6% silica fume	0.34
18	667.5	Very Low	55% slag & 6% silica fume	0.46
19	132.2	Very Low	18% fly ash& 12% Metakaolin	0.24
20	462	Very Low	18% fly ash& 12% Metakaolin	0.30
21	288.05	Very Low	18% fly ash& 12% Metakaolin	0.36
22	618.5	Very Low	55% slag & 8% Metakaolin	0.30
23	255	Very Low	55% slag & 8% Metakaolin	0.22
24	297.5	Very Low	55% slag & 8% Metakaolin	0.38
25 (SFM1)	430.15	Very Low	42% Fly Ash	0.19
26 (SFM2)	900.4	Very Low	42% Fly Ash	0.23
27 (SFM3)	487.05	Very Low	42% Fly Ash	0.27
28 (SLAG2-1)	601.6	Very Low	70% slag2	0.4
29 (SLAG2-2)	391.8	Very Low	50% slag2, 20% Fly Ash	0.35
30 (SLAG2-3)	277.25	Very Low	55% slag2, 6% Silica Fume	0.34
31 (SLAG2-4)	168.85	Very Low	55% slag2, 8% Metakaolin	0.3

Figure 33 presents the RSPT results at 28 days, plotting the average charge passed (adjusted in coulombs) against the water-to-cement (w/c) ratio for various mix designs. For all mixes, there is a general trend that charge passed increases with w/c ratio increases. This indicates that higher w/c ratios lead to higher sulfate permeability, reflecting increased porosity and reduced durability. The figure clearly shows and explains the effects of SCMs on sulfate resistance. Mixes with high SCM content, especially combinations of SCMs, consistently show lower charge passed values and better performance. Lower w/c ratios are crucial for enhancing sulfate resistance. Even with effective SCMs, reducing the w/c ratio further improves the concrete's resistance to sulfate ingress, also combining of SCMs such as slag with silica fume or fly ash with metakaolin exhibit important effects, leading to superior sulfate resistance compared to mixes with single SCMs.

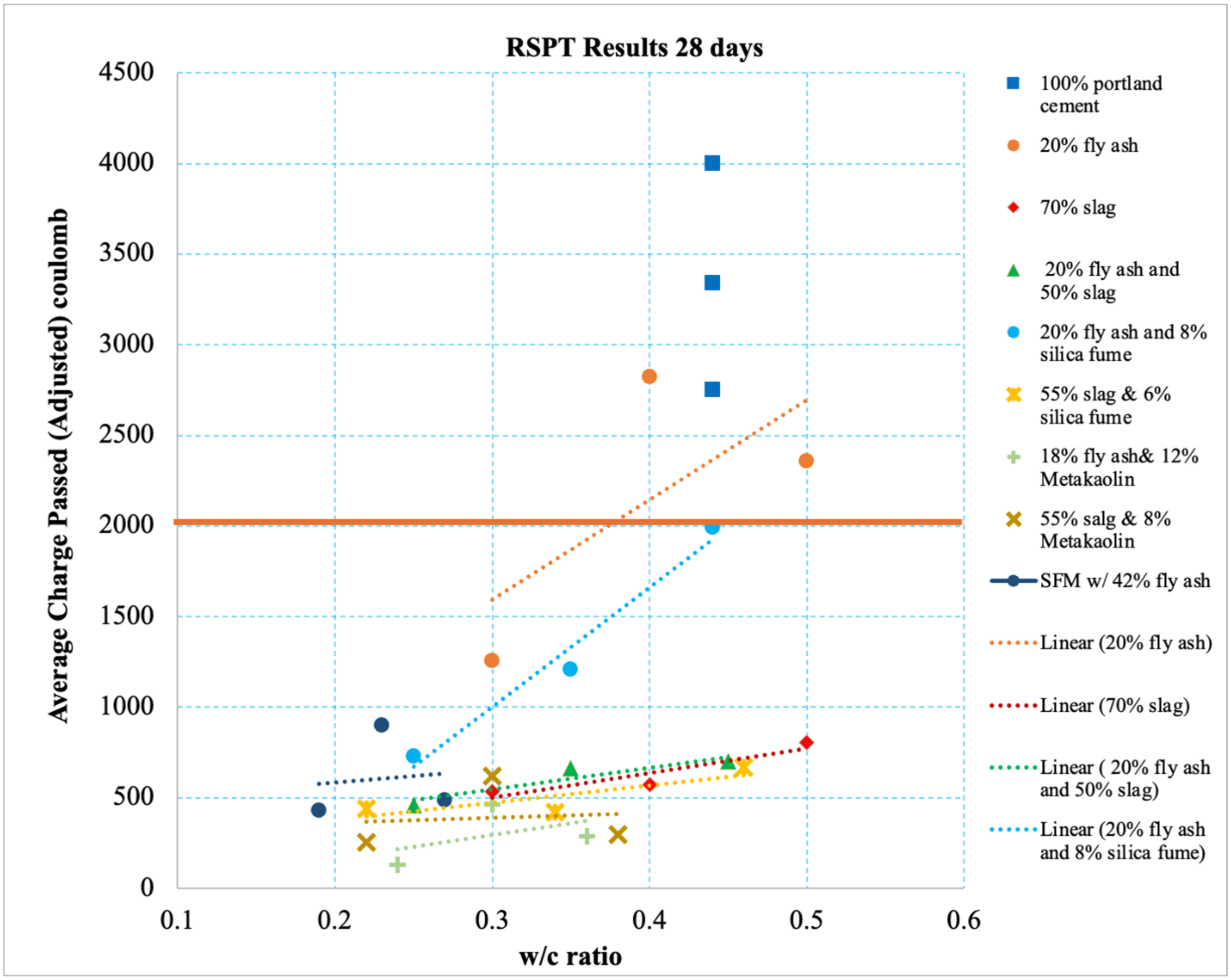


Figure 33. RSPT results at 28 days

4.4.2 56 days results

The RSPT results after 56 days of curing are shown in Table 40 and Figure 34. Comparing with 28 days results, there are significant decrease in average charge passed, indicating improvement in sulfate permeability.

Table 40. RSPT of concrete samples after 56 days of curing

Mix Number	*Average Charge Passed (Adjusted) coulomb*	*Sulphate Penetration Class*	*Type of mix*	*w/c ratio*
1	2194	Moderate	100 % Portland cement	0.44
2	3054	Moderate	100 % Portland cement	0.44
3	2946	Moderate	100 % Portland cement	0.44
4	796	Very Low	20% fly ash	0.3
5	1721	Low	20% fly ash	0.4
6	2041	Moderate	20% fly ash	0.5
7	566	Very Low	70% slag	0.3
8	660.5	Very Low	70% slag	0.4
9	741.5	Very Low	70% slag	0.5
10	440.13	Very Low	20% fly ash and 50% slag	0.25
11	595.5	Very Low	20% fly ash and 50% slag	0.35
12	694.5	Very Low	20% fly ash and 50% slag	0.45
13	551	Very Low	20% fly ash and 8% silica fume	0.25
14	826.5	Very Low	20% fly ash and 8% silica fume	0.34
15	818	Very Low	20% fly ash and 8% silica fume	0.44
16	287.4	Very Low	55% slag & 6% silica fume	0.22
17	404.5	Very Low	55% slag & 6% silica fume	0.34
18	764.5	Very Low	55% slag & 6% silica fume	0.46
19	84.25	Very Low	18% fly ash& 12% Metakaolin	0.24
20	267.7	Very Low	18% fly ash& 12% Metakaolin	0.30
21	181.48	Very Low	18% fly ash& 12% Metakaolin	0.36
22	166.29	Very Low	55% slag & 8% Metakaolin	0.30
23	153.29	Very Low	55% slag & 8% Metakaolin	0.22
24	281.55	Very Low	55% slag & 8% Metakaolin	0.38
25 (SFM1)	324.01	Very Low	42% Fly Ash	0.19
26 (SFM2)	430.32	Very Low	42% Fly Ash	0.23
27 (SFM3)	369.15	Very Low	42% Fly Ash	0.27
28 (SLAG2-1)	282.15	Very Low	70% slag2	0.4
29 (SLAG2-2)	210.73	Very Low	50% slag2, 20% Fly Ash	0.35
30 (SLAG2-3)	194.25	Very Low	55% slag2, 6% Silica Fume	0.34
31 (SLAG2-4)	139.83	Very Low	55% slag2, 8% Metakaolin	0.3

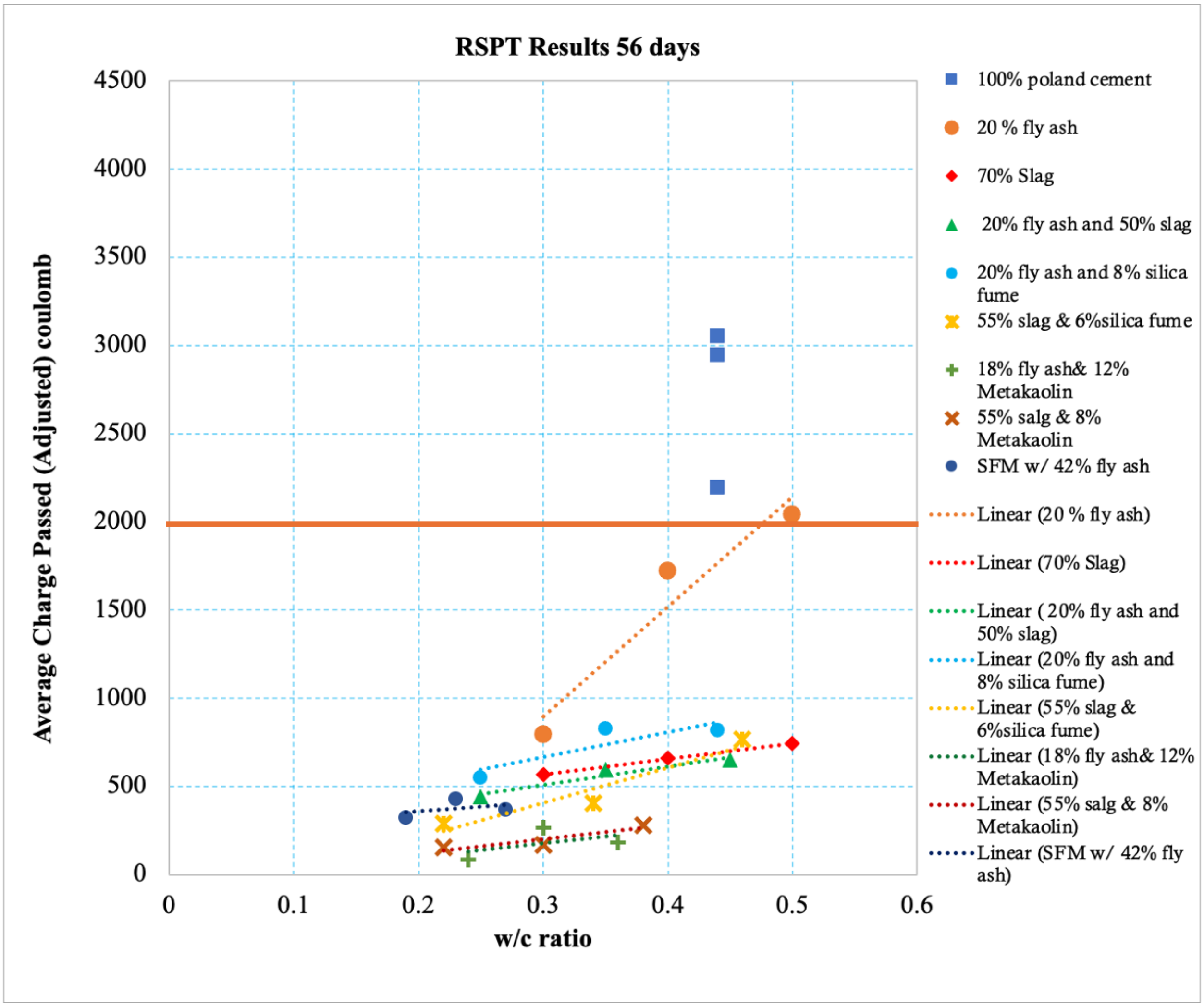


Figure 34. RSPT results after 56 days curing

4.4.3 28 Days vs. 56 Days RSPT Results

Figure 35 shows the relationship between the average charge passed during the RSPT test after 28 days and 56 days of curing for various concrete mixes. A strong correlation can be observed, as represented by the linear regression line. The regression equation is given as: $y=0.7243x+21.514$ with an R^2 value of 0.8505. This high R value indicates that approximately 92.2% of the variability in the 56-day charge passed can be explained by the 28-day charge passed. The linear trend suggests that the results at 28 days can serve as a reasonably reliable predictor for long-term behavior (56 days), although further investigation is recommended to refine this relationship for mixes with higher variability.

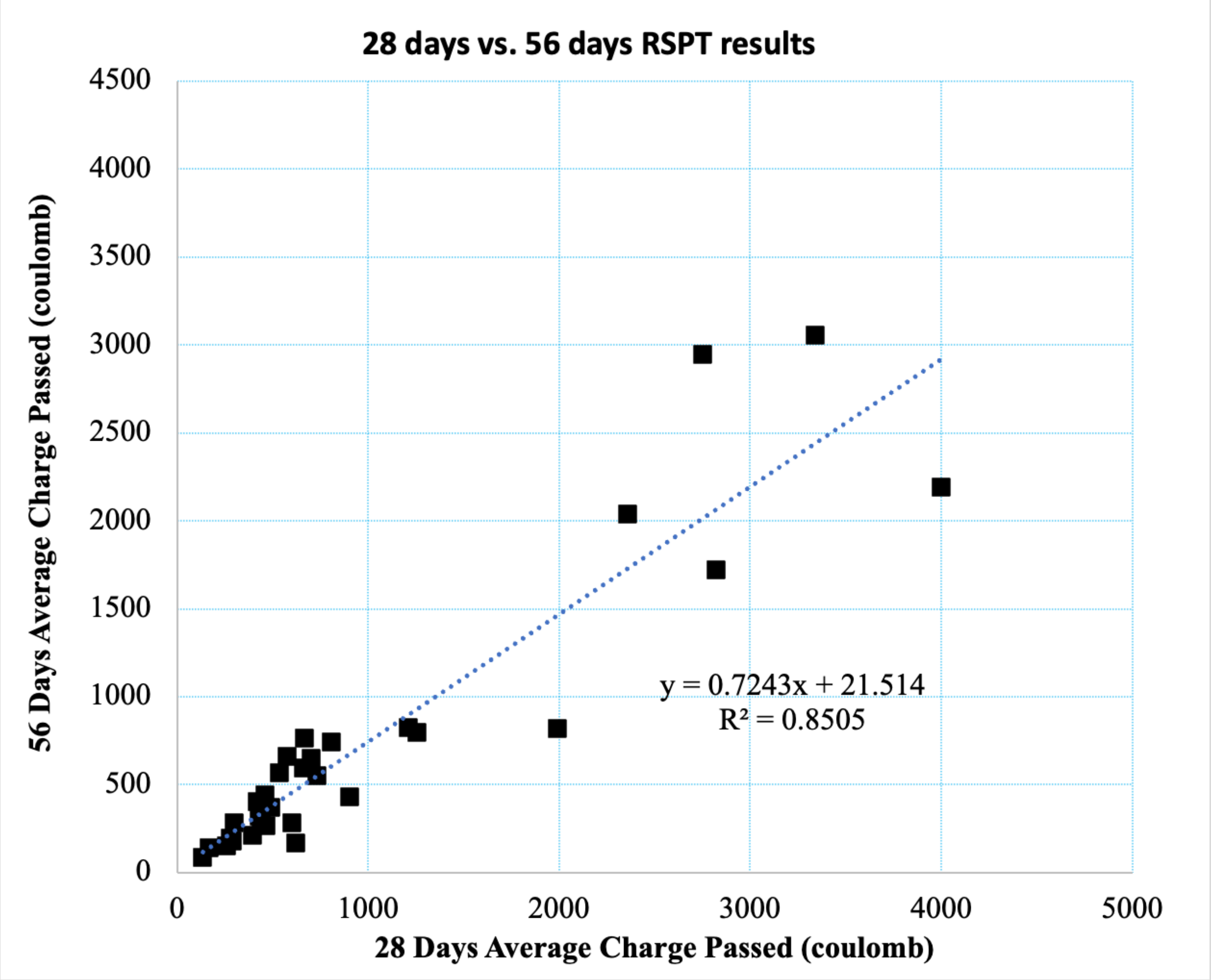


Figure 35. RSPT results with 28 days vs. 56 days curing

4.5 LENGTH CHANGE TEST RESULTS

The length change tests were conducted according to *ASTM C1012 Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*. This is a companion test to RSPT aims at evaluating the sulfate resistance of cementitious mortars by measuring the expansion or contraction of mortar bars when immersed in a sulfate solution over an extended period. This test simulates conditions that concrete structure may experience in environments exposed to sulfates, such as soil or groundwater, to assess its durability and long-term stability. At predetermined intervals (1 week, 2 weeks, 3 weeks, 4 weeks, 8 weeks, etc.), the bars are removed from the solution, and their length is measured using a comparator. The change in length is calculated as a percentage relative to the initial length of the bars. This process is repeated until the end of the test period, which can extend up to 72 weeks in some cases.

The percentage of length change provides an indication of the mortar's resistance to sulfate attack. Higher expansions indicate a higher susceptibility to sulfate-induced deterioration, while minimal length change reflects good sulfate resistance and dimensional stability. Mix designs with supplementary cementitious materials (SCMs), such as slag or fly ash, tend to show reduced expansion compared to those with ordinary Portland cement (OPC), as SCMs enhance the microstructure, reducing porosity and improving sulfate resistance.

As shown in Table 41 through Table 43, length change tests track the length change (%) for different concrete mixes over various time intervals (from 1 week to 72 weeks).

Table 41. Length change test results (Part 1)

Testing Age	100 % Portland cement			20% fly ash			70% slag		
Weeks	Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	Mix #6	Mix #7	Mix #8	Mix #9
1	0.023	0.018	-0.014	0.006	-0.002	0.014	-0.0008	-0.0022	-0.0030
2	0.014	0.018	-0.014	0.006	0.003	0.008	-0.0002	-0.0025	-0.0042
3	0.016	0.011	-0.012	0.001	0.003	0.011	-0.0015	-0.0028	-0.0043
4	0.016	0.002	-0.012	0.000	-0.025	0.002	-0.0020	-0.0038	-0.0055
8	0.000	0.000	-0.010	0.001	-0.036	0.040	-0.0013	-0.0028	-0.0062
13	0.000	0.000	0.008	0.021	0.011	0.039	0.0003	-0.0023	-0.0078
15	0.039	0.000	0.005	-	-0.006	-	-0.0015	-0.0037	-0.0097
16	0.020	0.015	0.008	0.013	-0.014	0.040	-0.0013	-0.0035	-0.0065
24	0.035	0.024	0.013	0.017	-0.020	0.048	-0.0002	-0.0027	-0.0040
36	0.034	0.024	0.017	0.017	0.001	0.062			
48	0.042	0.029	0.031	0.013	-0.002	0.082			
72	0.077	0.038			-0.003				

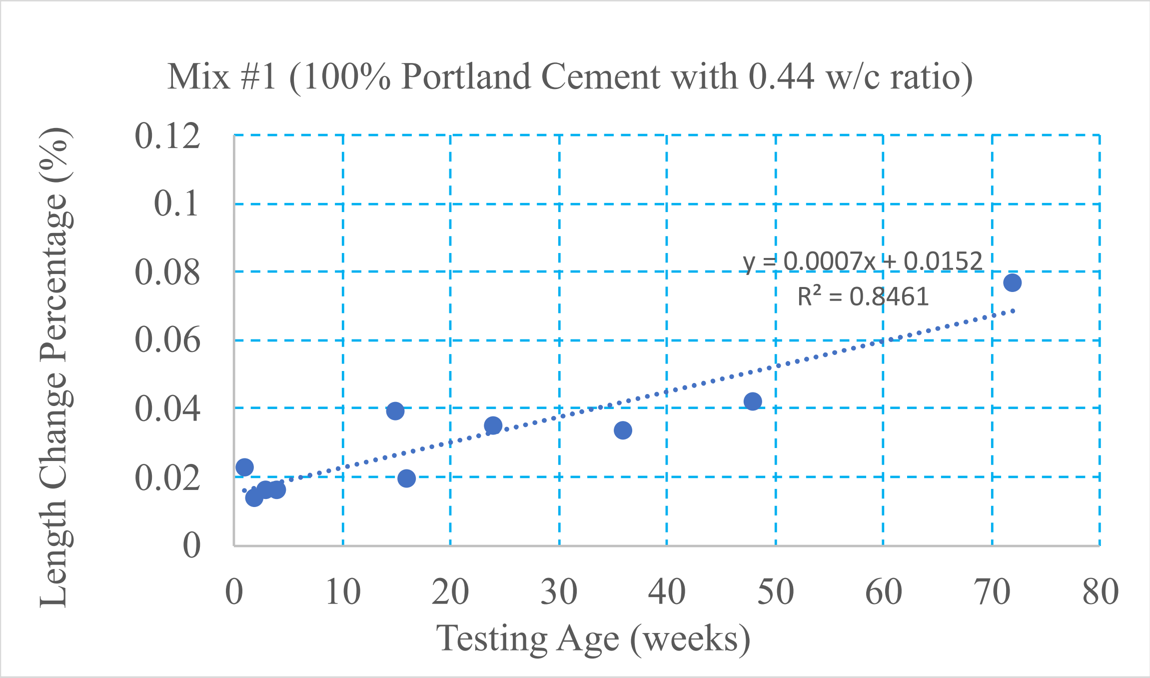


Figure 36. Length change test results for Mix #1

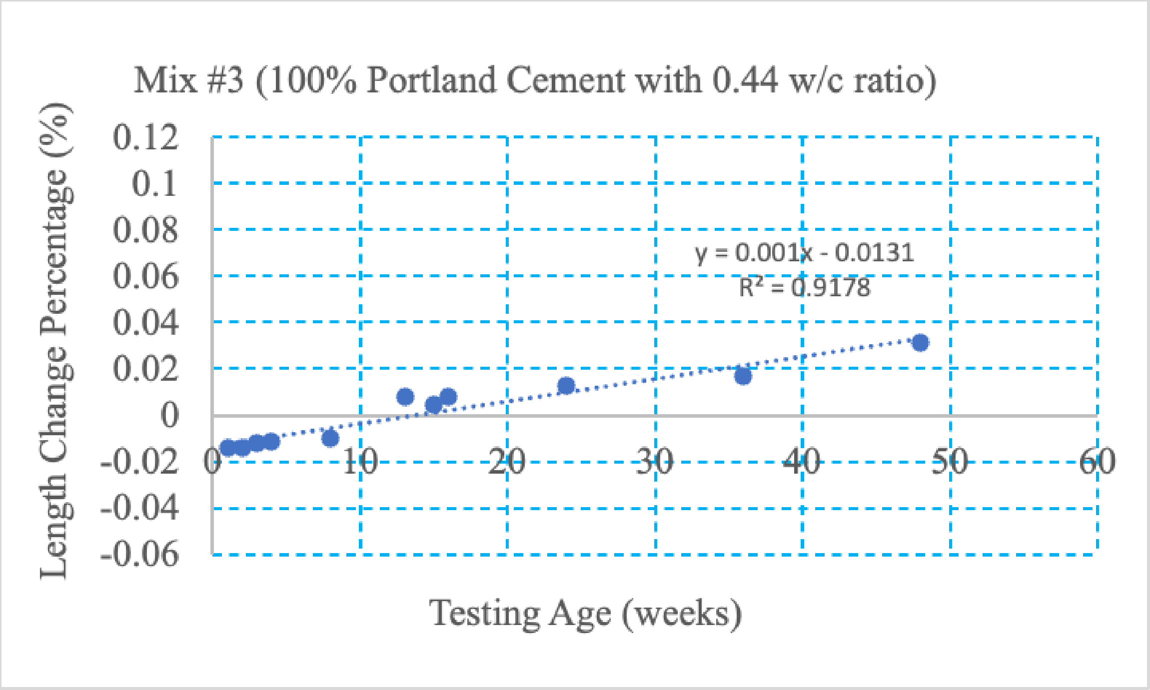


Figure 37. Length change test results for Mix #3

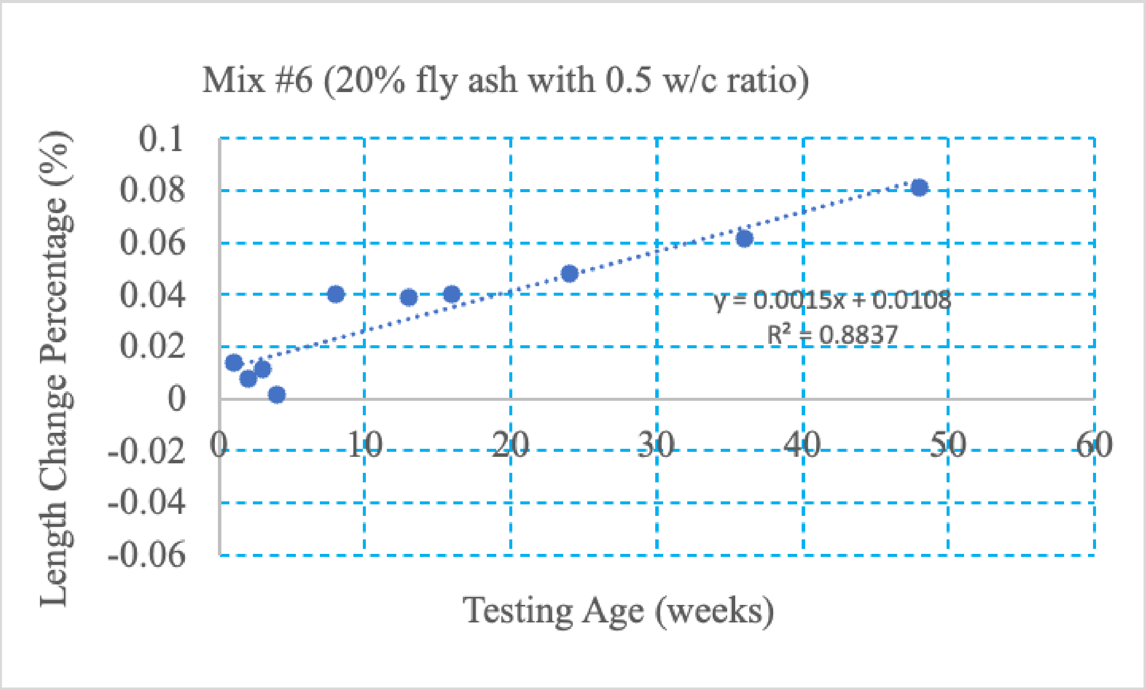


Figure 38. Length change test results for Mix #6

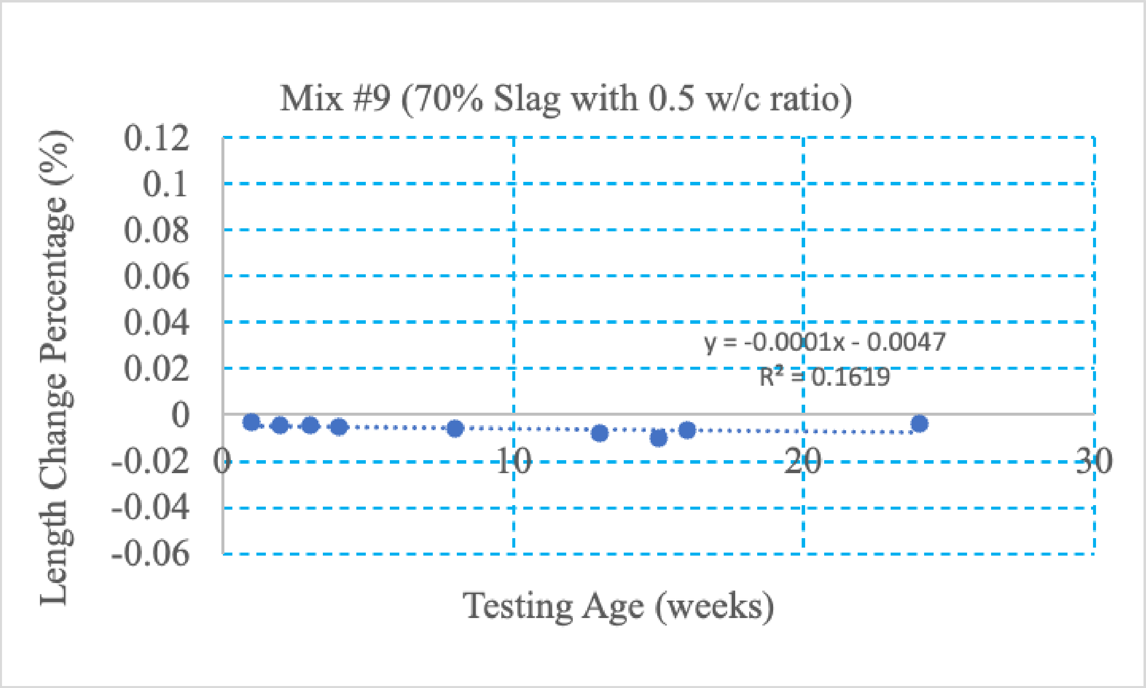


Figure 39. Length change test results for Mix #9

Table 42. Length change test results (Part 2)

Testing Age	20% fly ash and 50% slag			20% fly ash and 8% silica fume			55% slag & 6% silica fume		
Weeks	Mix #10	Mix #11	Mix #12	Mix #13	Mix #14	Mix #15	Mix #16	Mix #17	Mix #18
1	0.001	-0.001	-0.001	-0.0010	-0.003	-0.029	-0.002	-0.001	0.002
2	0.004	0.000	0.006	-0.0040	0.019	-0.033	-0.005	-0.004	0.005
3	-0.017	0.001	0.002	-0.0032	0.015	-0.029	-0.003	-0.003	-0.002
4	-0.013	0.000	-0.003	-0.0045	-0.011	-0.032	-0.004	-0.005	0.002
8	0.032	0.005	0.010	-0.0048	0.001	-0.019	-0.005	-0.005	-0.002
13	0.017	0.007	0.004	-0.0045	0.004	-0.024	-0.003	-0.003	-0.006
15	0.017	0.008	0.010	-0.0067	0.013	-0.015	-0.005	-0.005	-
16	0.018	0.006	-0.003	-0.0063	0.000	-0.026	-0.006	-0.007	0.006
24	0.004	0.008	0.008	-0.0055	0.012	-0.018	-0.004	-0.004	0.005
36	0.017		0.005		0.015	-0.019			0.005
48	0.021		0.010		0.021	-0.015			
72	0.021								

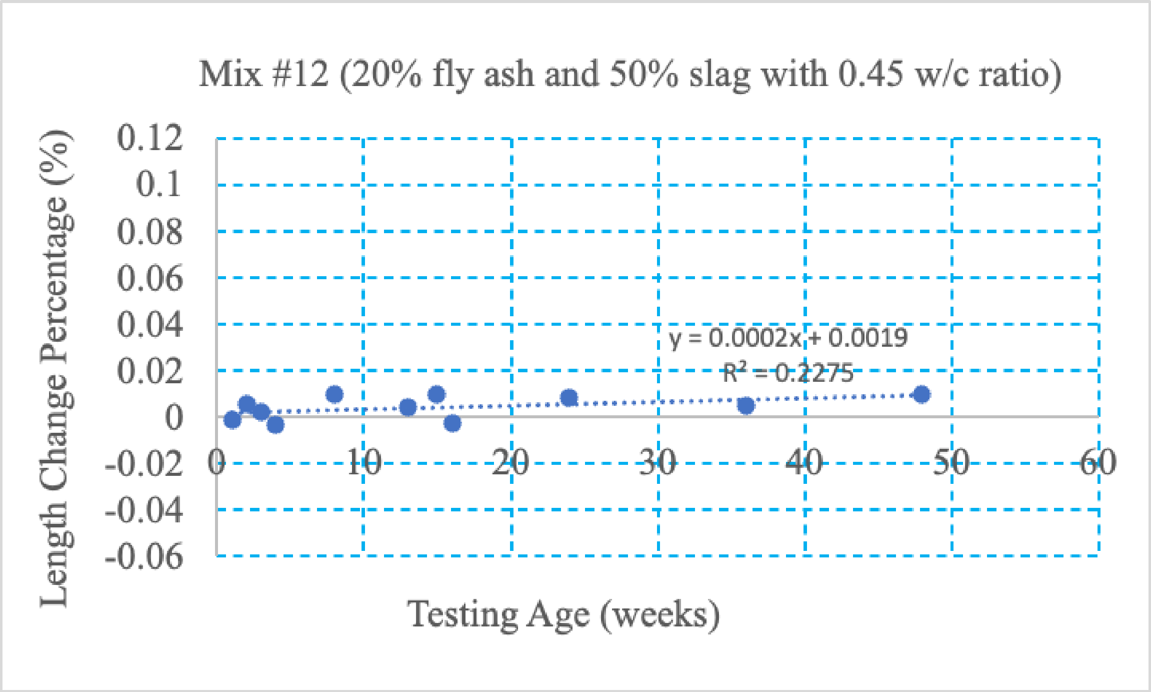


Figure 40. Length change test results for Mix #12

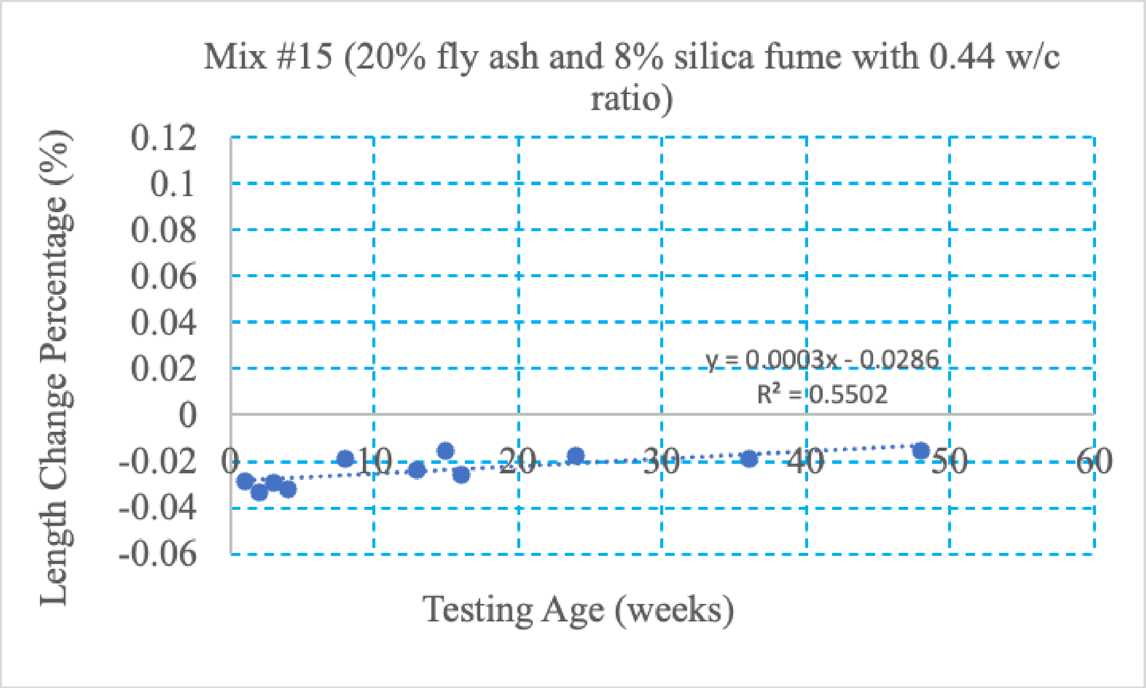


Figure 41. Length change test results for Mix #15

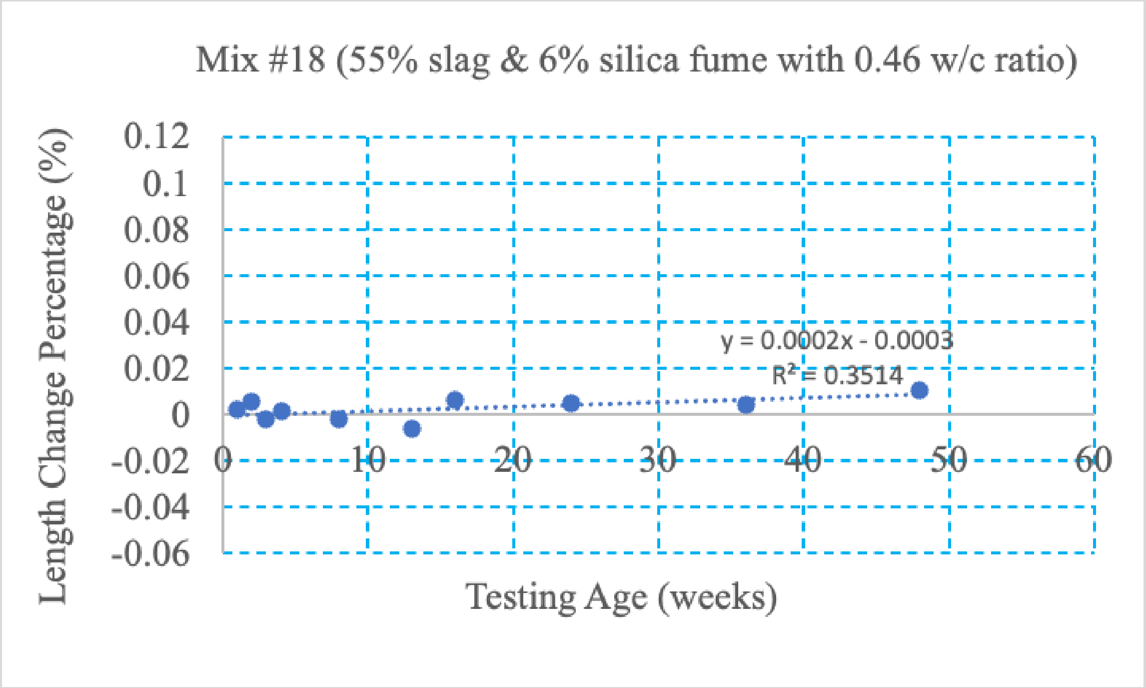


Figure 42. Length change test results for Mix #18

Table 43. Length change test results (Part 3)

Testing Age	18% fly ash& 12% Metakaolin			55% slag & 8% Metakaolin		
Weeks	Mix #19	Mix #20	Mix #21	Mix #22	Mix #23	Mix #24
1	-	-	-0.009	0.004	-0.001	-0.006
2	0.010	-0.002	0.004	-0.006	-0.015	-0.011
3	-	-	-	-	-	-
4	0.016	-0.004	0.002	0.017	0.007	0.007
8	0.021	-0.005	0.001	0.020	0.006	0.002
13	0.026	-0.005	0.000	0.027	0.005	0.007
15	0.027	-0.005	-0.002	0.028	0.006	0.005
16	0.027	-0.006	-0.001	0.031	0.005	0.007
24	0.030	-0.006	0.000	0.036	0.005	0.007
36	0.036	-0.005				
48						
72						

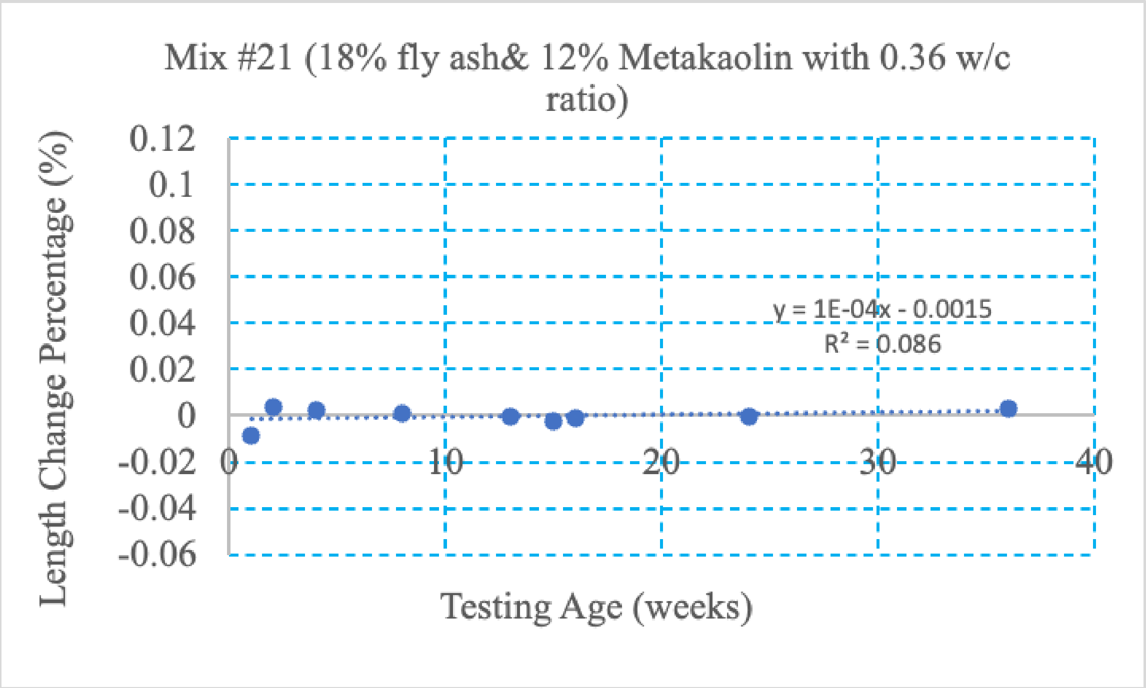


Figure 43. Length change test results for Mix #21

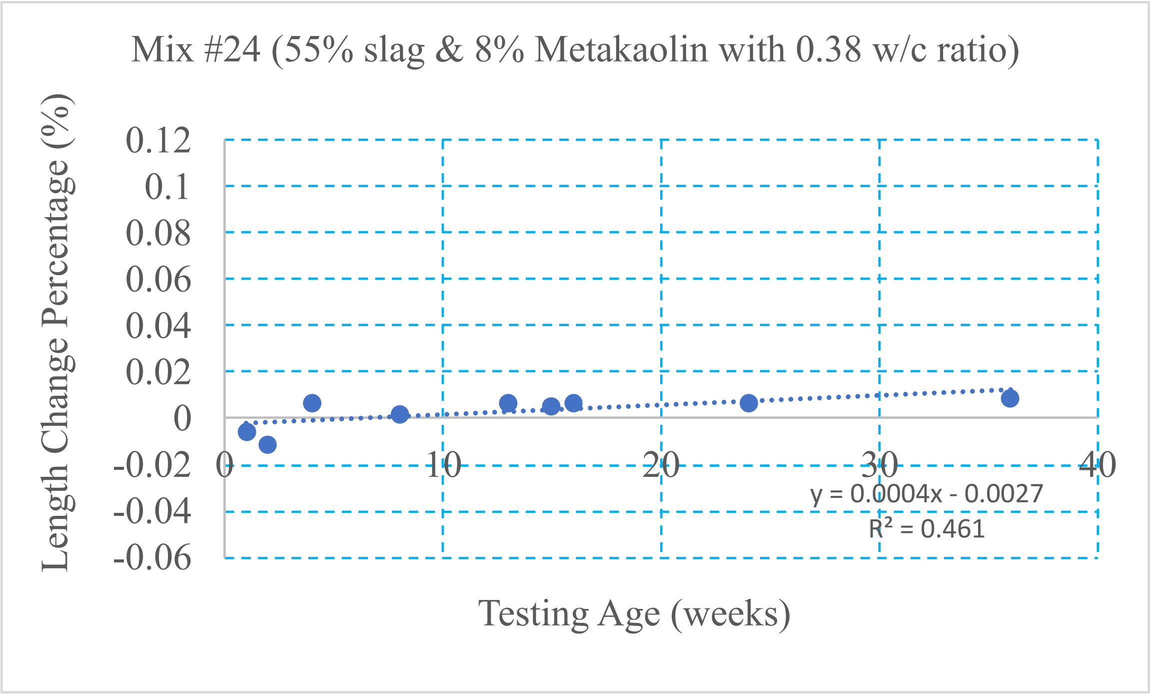


Figure 44. Length change test results for Mix #24

Table 44. Length change test results (Part 4)

Testing Age	42% Fly Ash			Slag2			
Weeks	SFM #1	SFM #2	SFM #3	Slag2 #1	Slag2 #2	Slag2 #3	Slag2 #4
1	-0.0045	-0.0032	-0.0038	-0.0033	-0.0027	-0.0060	-0.0018
2	-0.0053	-0.0032	-0.0038	-0.0058	-0.0053	-0.0075	-0.0037
3	-0.0058	-0.0057	-0.0050	-0.0058	-0.0052	-0.0068	-0.0043
4	-0.0055	-0.0045	-0.0060	-0.0048	-0.0045	-0.0063	-0.0043
8	-0.0038	-0.0030	-0.0043	-0.0052	-0.0045	-0.0060	-0.0052
13	-0.0060	-0.0038	-0.0037	-0.0063	-0.0053	-0.0072	-0.0078
15	-	-	-	-0.0090	-0.0087	-0.0100	-0.0097
16	-0.0062	-0.0038	-0.0055	-0.0090	-0.0082	-0.0097	-0.0063
24	-0.0053	-0.0025	-0.0023	-0.0033	-0.0025	-0.0033	-0.0045
36							
48							
72							

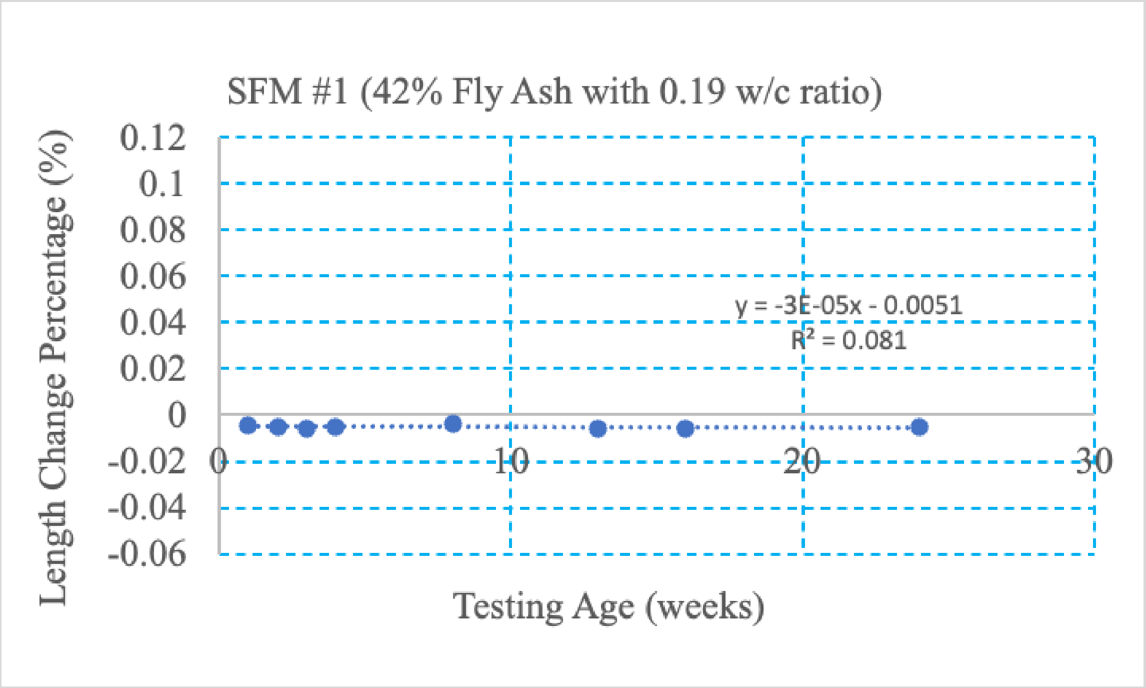


Figure 45. Length change test results for SFM #1

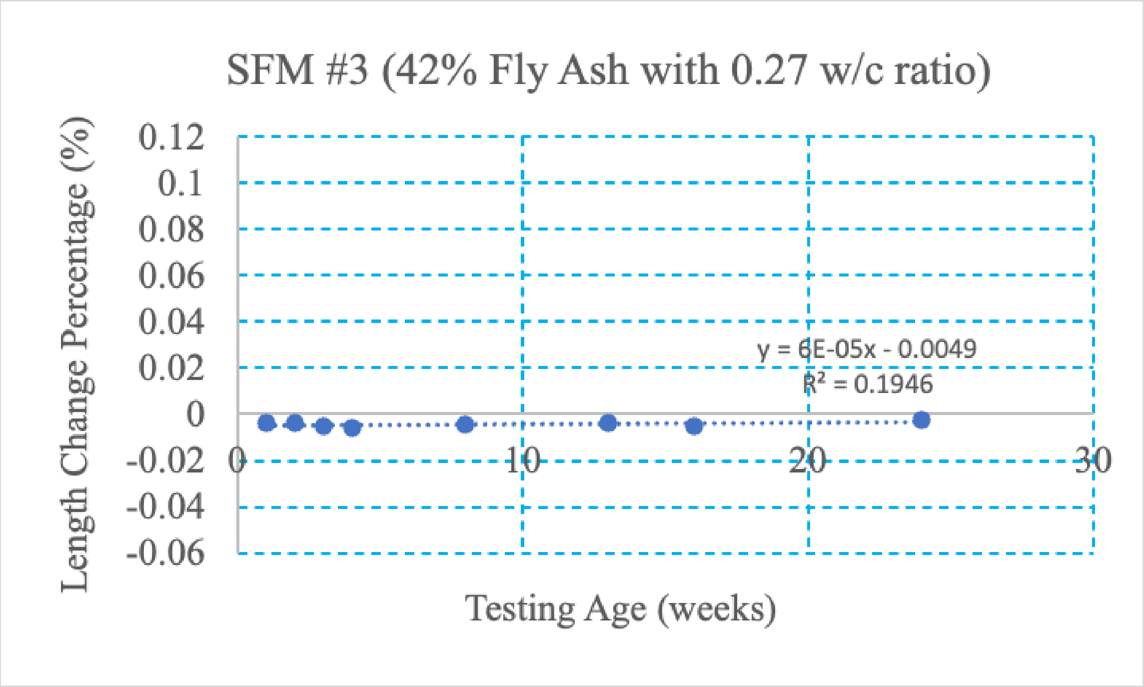


Figure 46. Length change test results for SFM #3

5 CONCLUSIONS AND RECOMMENDATIONS

The main goals of this project are:

1. Investigate and recommend the appropriate thresholds to use for bulk resistivity (SR) (TP 119) and surface resistivity (SR) (T 358) resistivity for a concrete mix designed for an extremely aggressive chloride environment.
2. Investigate and recommend the appropriate thresholds to use for a rapid sulfate permeability (RSPT) test for a concrete mix designed for an extremely aggressive sulfate environment.

In order to achieve these two objectives, the research team conducted a series of tests for selected 31 mix designs for both 28-days and 56-days curing conditions and the following conclusions and recommendations are drawn. It is worth noting that to choose the appropriate thresholds for chloride resistivity, experimental results from a companion project BED32: Chloride Diffusion were used to correlate between resistivity and concrete service life.

5.1 THRESHOLDS FOR SR AND BR TESTS

Although one of the main goals of this project is to choose thresholds for SR and BR tests, it is important to investigate the correlation between concrete resistivity and chloride diffusion coefficient because the chloride diffusion coefficient is the parameter that directly affects the service life of the reinforced concrete structure. Aiming at selecting appropriate thresholds for SR and BR tests for an extremely aggressive environment, the research team developed the following program that correlates service life, chloride diffusion coefficient and concrete resistivity. Based on these correlations, as shown in Figure 47, a comprehensive approach was developed, and the appropriate thresholds are proposed.

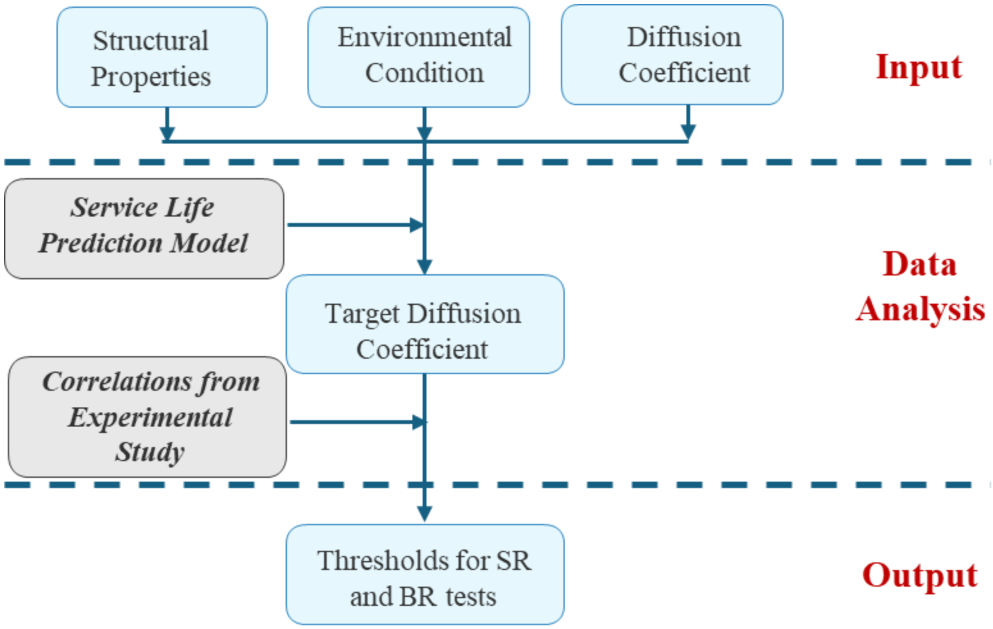


Figure 47. Comprehensive Approach for Thresholds Selection

5.1.1 Target Diffusion Coefficient

Fick’s Second Law is widely used in Diffusion-based service life models including ACI 365.1R-17, fib Model Code 2010 and ISO 16204:2012. A general Fick’s Second Law model can be expressed as:

$$C_{(x,t)} = C_0(1 - erf\frac{x}{2\sqrt{D_c t}}) \qquad \text{Eq. (1)}$$

Where:

$C_{(x,t)}$ = chloride concentration at depth and time,

C_0 = surface chloride concentration,

D_c = apparent diffusion coefficient,

t = time for diffusion,

x = depth

erf = statistical error function.

There are several key parameters in this model including the critical concentration at depth and time, surface chloride concentration, depth, time for diffusion, and apparent diffusion coefficient. For this study, the extremely aggressive environment condition is considered, and the surface chloride concentration is assumed to be 2000 ppm as specified in FDOT SDG. The service life of a reinforced concrete structural element can be divided into two periods: initiation period and propagation period (Life 365, 2020). The propagation period is the period starting from initiation of steel corrosion to the time to repair. It depends on the rebar type and the moisture condition. Life 365 (2020) assumes 20 years for epoxy-coated steel and 6 years for any other types of rebars (i.e. Black steel and stainless steel). ACI 365.1R-17 (2017) uses 20 years for a diaphragm wall exposed to saline ground water. In this study, it is assumed that the propagation period of 20 years for epoxy-coated steel and 6 years for all other types of rebars. Then the required initiation period to reach 75 years of service life will be 55 years for epoxy-coated steel and 69 years for all other types of rebars. Chloride concentration necessary to initiate corrosion is another important parameter. The research team is using the assumptions that Life 365 (2020) uses, which is black steel = 0.05 % wt. concrete, epoxy-coated = 0.05 %, and stainless steel = 0.5 %. The depth t depends on the type of structure and its respective concrete cover. The minimum cover specified in the FDOT 2025 Structures Manual will be used in this study (Table 46). A summary of input parameters is presented in Table 45.

Table 45. Input parameters for service life model

Parameters	Recommended Values
C_0, ppm	2000
t_i, years	55 for epoxy-coated steel
	69 for all other types of rebars
x, inches	Table 46
$C_{critical}$	black steel = 0.05 % wt. concrete
	epoxy-coated = 0.05 %
	stainless steel = 0.5 %

Table 46. Concrete cover (FDOT 2025 Structures Manual, 2025)

Component (Precast and Cast-in-Place)	Concrete Cover (inches)	
	S or M[1]	E[1]
Superstructure		
All internal and external surfaces (except riding surfaces) of segmental concrete boxes, and external surfaces of prestressed beams (except the top surface)	2	
Top surface of beam top flange	¾ (min.)	
Top deck surfaces: Short Bridges[2]	2	
Top deck surfaces: Long Bridge[2]	2½[3]	
All components and surfaces not included above (including wall copings and traffic and pedestrian railings which are not allowed to be constructed using the slip forming method)	2	
Front and back surfaces of pedestrian railings and traffic railings, other than single-slope traffic railings, which may be constructed using the slip forming method	3	
Front and back surfaces of single-slope traffic railings which may be constructed using the slip forming method	2½	
Noise Wall Posts and Panels	2	
Precast Concrete Perimeter Wall Posts and Panels	1¾	
Substructure		
External surfaces cast against earth and surfaces in contact with water (excluding Drilled Shafts)	4	4½
Exterior formed surfaces, columns, and tops of footings not in contact with water and all components or surfaces not included elsewhere	3	4
Internal surfaces	3	
Beam/Girder Pedestals, Cheekwalls & MSE Wall Interface Lugs	2	
Prestressed Piling	3	
Spun Cast Cylinder Piling[4]	2	
Drilled Shafts	6	
Auger Cast Piles	4	
Micropiles	2	3
Retaining Walls (Excluding MSE walls[5] and external surfaces cast against earth)	2	3
Box and Three-sided Culverts (including wingwalls and wingwall footings)	2	3
Bulkheads	4	

Using the Fick's Second Law service life model, the target diffusion apparent diffusion coefficients were derived based on a design service life of 75 years. The target diffusion coefficients are presented in Table 47 for different structural components. Please note that only black steel is considered because FDOT does not allow the use of epoxy coasted rebar, and the corrosion mechanism of stainless steel is beyond the scope of this project.

Table 47. Target apparent diffusion coefficients (Extremely aggressive environment)

Structural Component	Cover, inches (mm)	Target apparent diffusion coefficients, $x10^{-12}$ (m^2/s)
End bent	4" (101.6 mm)	1.79
Piers in contact with water	4.5" (114.3 mm)	2.27
Piers not in contact with water	4" (101.6 mm)	1.79
Retaining walls	3" (76.2 mm)	1.01
Pier cap and intermediate bent	4" (101.6 mm)	1.79

5.1.2 Correlations between diffusion and resistivity

The Rapid Migration Test (RMT) was conducted to determine the non-steady state migration coefficient (Dnssm) for various concrete mixes after 28 days of curing. This coefficient is an essential parameter in assessing the chloride ion diffusion rate within concrete, which directly impacts its durability and service life in chloride-rich environments.

Table 48 summarizes the RMT results, presenting the average penetration depth and the calculated non-steady state migration coefficient (D_{nssm}) for each mix. The test results show a wide range of diffusion coefficients, reflecting the influence of different supplementary cementitious materials (SCMs) and water-to-cement (w/c) ratios on the permeability characteristics of concrete.

Table 48. RMT results after 28 days of curing

Mix Number	**Average Penetration depth (mm)**	**Non steady migration coefficient. Dnssm x10^{-12} (m^2/s)**	**Type of mix**	**w/c ratio**
1	NA	NA	100 % Portland cement w/ 0.44 w/c	0.44
2	18.94	17.61	100 % Portland cement w/ 0.44 w/c	0.44
3	24.69	24.60	100 % Portland cement w/ 0.44 w/c	0.44
4	22.04	11.88	20% fly ash with 0.3 w/c	0.3
5	28.79	19.80	20% fly ash with 0.4 w/c	0.4
6	28.99	19.89	20% fly ash with 0.5 w/c	0.5
7	9.97	2.65	70% slag with 0.3 w/c	0.3
8	7.23	2.35	70% slag with 0.4 w/c	0.4
9	9.70	2.78	70% slag 0.5w/c	0.5
10	14.38	3.96	20% fly ash and 50% slag	0.25
11	14.84	4.05	20% fly ash and 50% slag	0.35
12	11.16	3.62	20% fly ash and 50% slag	0.45
13	20.35	6.79	20% fly ash and 8% silica fume	0.25
14	20.05	8.18	20% fly ash and 8% silica fume	0.34
15	37.97	17.70	20% fly ash and 8% silica fume	0.44
16	7.94	1.77	55% slag & 6% silica fume with 0.22 w/c	0.22
17	5.29	1.12	55% slag & 6% silica fume with 0.34 w/c	0.34
18	8.37	2.17	55% slag & 6% silica fume with 0.46 w/c	0.46
19	NA	NA	18% fly ash& 12% Metakaolin	0.24
20	8.87	2.92	18% fly ash& 12% Metakaolin	0.3
21	14.28	4.65	18% fly ash& 12% Metakaolin	0.36
22	5.12	1.51	55% slag & 8% Metakaolin	0.3
23	5.85	1.20	55% slag & 8% Metakaolin	0.22
24	NA	NA	55% slag & 8% Metakaolin	0.38
SFM1	8.93	3.18	42% Fly Ash	0.19
SFM2	15.96	6.51	42% Fly Ash	0.23
SFM3	10.35	3.54	42% Fly Ash	0.27
SLAG2-1	8.75	1.97	70% SLAG 2	0.4
SLAG2-2	7.41	1.65	50% SLAG 2, 20% FLY ASH	0.35
SLAG2-3	6.50	1.40	55% SLAG 2, 6% SILICA FUME	0.34
SLAG2-4	NA	NA	55% SLAG 2, 8% Metakaolin	0.3

The relationship between the chloride migration coefficients derived from the RMT and the SR results after 28 days of curing shows valuable insights into the permeability and durability characteristics of various concrete mix designs. Figure 48 illustrates the correlation between the

SR measurements at 28 days and the non-steady state migration coefficient (D_{nssm}), emphasizing the connection between resistivity and chloride ion diffusion in concrete.

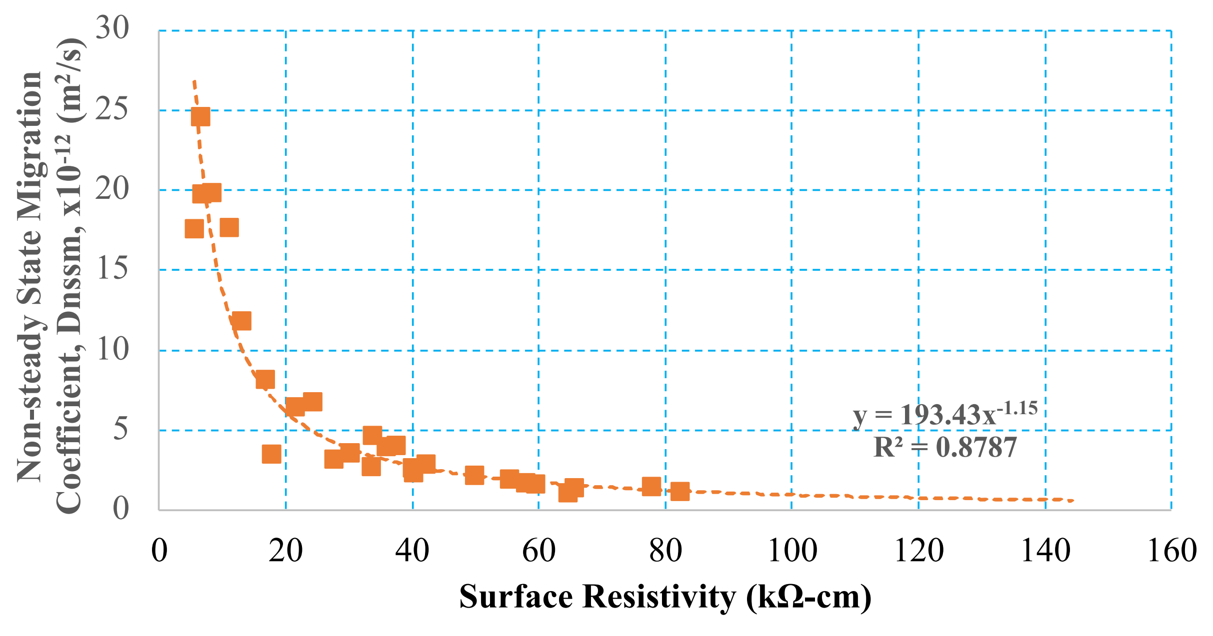


Figure 48. Correlation between SR and non-steady state migration coefficient (D_{nssm})

In the figure, the plot demonstrates an inverse relationship between SR and the migration coefficient. As the resistivity values increase, indicating reduced permeability, the corresponding migration coefficients decrease, reflecting lower chloride ion diffusivity. This trend is consistent with the understanding that higher resistivity in concrete typically corresponds to a denser microstructure and, consequently, a greater resistance to chloride ingress.

The fitted power-law regression curve, represented by the equation $y=193.43x^{-1.15}$, with an R^2 value of 0.8787, indicates a strong inverse correlation between SR and D_{nssm}. The high coefficient of determination (R) suggests that approximately 93.7% of the variability in the migration coefficient can be explained by the variations in SR. This strong correlation supports the use of SR as a predictive measure for estimating the chloride diffusion rates in concrete, which is essential for assessing the long-term durability and service life of concrete structures exposed to chloride environments.

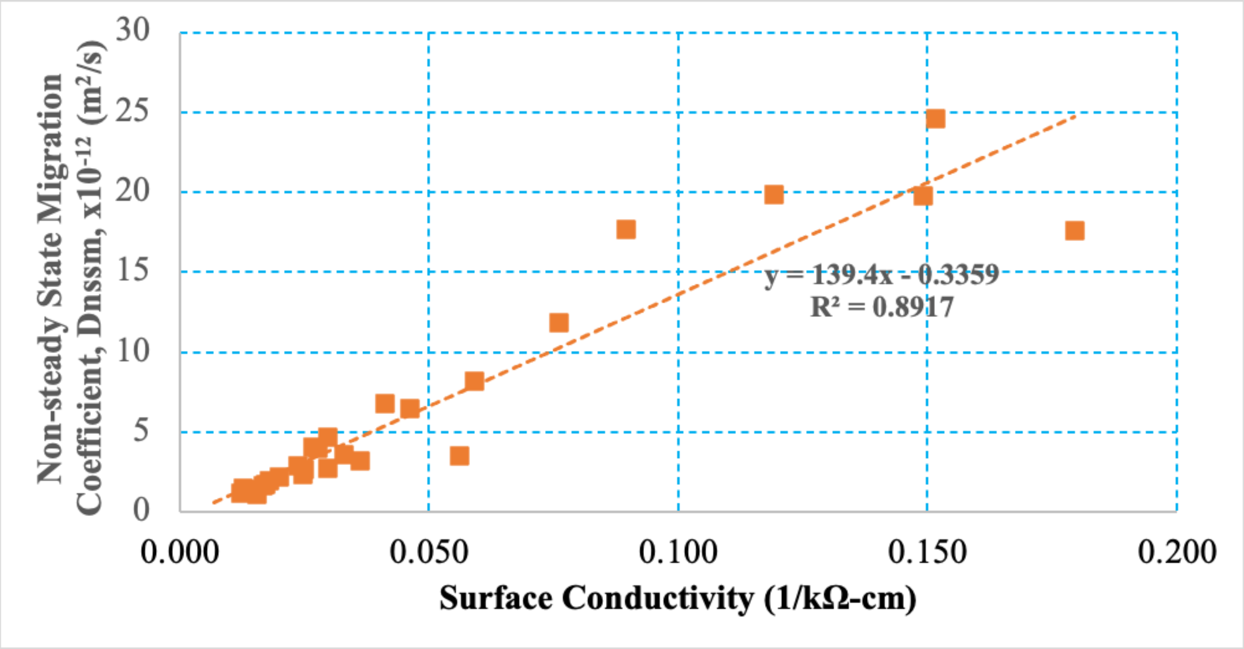


Figure 49. Correlation between SR and non-steady state migration Coefficient (D_{nssm})

Figure 49 further explores this relationship by plotting the surface conductivity, the inverse of SR, against the migration coefficient. The positive correlation observed, represented by the linear regression equation y=139.4x-0.3359, with an R^2value of 0.8917, reinforces the findings from Figure 48. Higher surface conductivity (lower resistivity) is associated with higher chloride migration coefficients, indicating greater permeability and reduced durability. The strong linear relationship, with approximately 94.7% of variability in migration coefficients explained by surface conductivity, highlights the effectiveness of resistivity measurements in evaluating chloride transport properties.

The relationship between the chloride migration coefficients derived from the RMT and the BR results is critical for understanding the chloride ion penetration resistance of various concrete mixes. This section explores the correlations observed between BR and RMT, emphasizing their importance in predicting the long-term durability of concrete structures exposed to chloride environments.

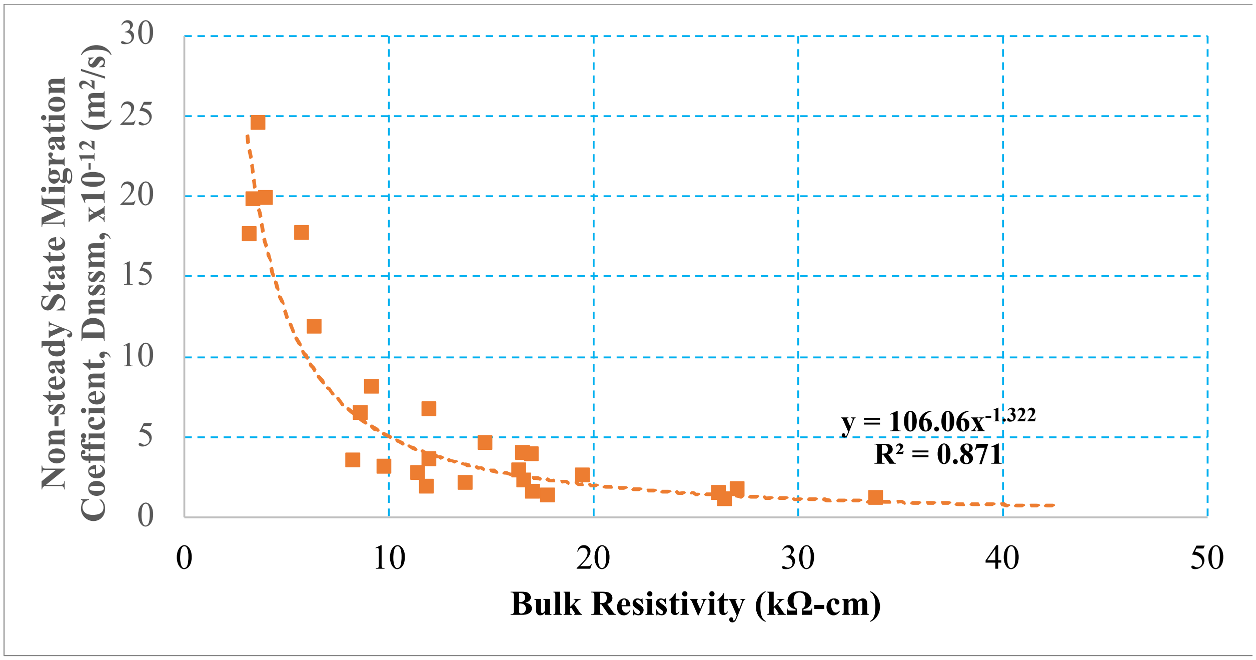


Figure 50. Correlation between BR and non-steady state migration coefficient (D_{nssm})

Figure 50 presents a plot demonstrating the inverse relationship between BR measured at 28 days and the non-steady state migration coefficient (D_{nssm}). Similar to the findings observed with SR, as BR values increase, indicating lower permeability, the migration coefficients decrease, reflecting reduced chloride ion diffusivity.

The fitted power-law regression line is represented by the equation $y=109.06x^{-1.322}$ with an R^2 value of 0.87. This high coefficient of determination suggests that approximately 94.2% of the variability in the migration coefficient can be attributed to changes in BR. The strong inverse correlation between BR and D_{nssm} shows the potential of using resistivity measurements to estimate chloride diffusion rates and assess the permeability of concrete mixes.

Figure 51 illustrates the linear relationship between bulk conductivity values measured at 28 days and the non-steady state migration coefficient (D_{nssm}). The positive linear trend is represented by the regression equation $y=79.638x-2.0165$, with an R^2 value of 0.8812. This indicates that about 93.8% of the variation in the migration coefficient can be explained by bulk conductivity. The strong correlation shows that as bulk conductivity increases, signifying higher ionic mobility, the migration coefficient also increases, reflecting greater chloride diffusivity.

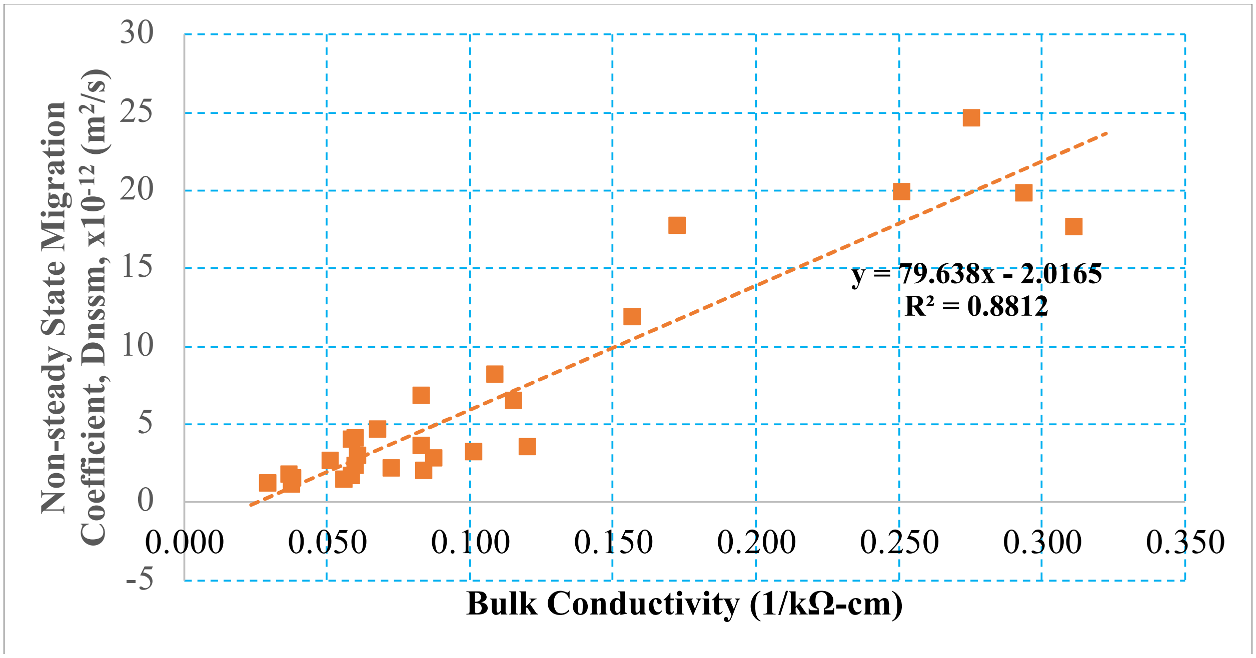


Figure 51. Correlation between bulk conductivity and non-steady state migration coefficient (D_{nssm})

RMT results showed a good correlation with the SR and BR results and indicate that correlation can be established between chloride diffusion and concrete resistivity. However, the non-steady state migration coefficient D_{nssm} obtained from the RMT tests is a rapid migration test that doesn't reflect the characteristics of natural chloride diffusion. Thus, the Bulk Diffusion (BD) test results from Project BED32 "NextGEN Concrete-Chloride Diffusion" were also studied and were used for this project.

As shown in Table 49, apparent diffusion coefficients were obtained from twenty-four mixes with various w/c ratio and SCM proportions. The samples from South Floride Mixes (SFM) and Slag2 mixes are still in the exposure tank thus the BD results from these mixes are not available for this study.

Table 49. BD test results after 28 days of curing and six months of exposure

Mix Number	**Apparent diffusion coefficient. Da x10-12 (m2/s)**	**Type of mix**	**w/c ratio**
1	21.2	100 % Portland cement w/ 0.44 w/c	0.44
2	11.8	100 % Portland cement w/ 0.44 w/c	0.44
3	12.9	100 % Portland cement w/ 0.44 w/c	0.44
4	8.88	20% fly ash with 0.3 w/c	0.3
5	13.1	20% fly ash with 0.4 w/c	0.4
6	8.54	20% fly ash with 0.5 w/c	0.5
7	1.47	70% slag with 0.3 w/c	0.3
8	1.81	70% slag with 0.4 w/c	0.4
9	3.83	70% slag 0.5w/c	0.5
10	1.85	20% fly ash and 50% slag	0.25
11	1.61	20% fly ash and 50% slag	0.35
12	2.17	20% fly ash and 50% slag	0.45
13	3.28	20% fly ash and 8% silica fume	0.25
14	4.59	20% fly ash and 8% silica fume	0.34
15	9.7	20% fly ash and 8% silica fume	0.44
16	0.978	55% slag & 6% silica fume with 0.22 w/c	0.22
17	2.56	55% slag & 6% silica fume with 0.34 w/c	0.34
18	1.78	55% slag & 6% silica fume with 0.46 w/c	0.46
19	1.27	18% fly ash& 12% Metakaolin	0.24
20	2.29	18% fly ash& 12% Metakaolin	0.3
21	3.22	18% fly ash& 12% Metakaolin	0.36
22	2.85	55% slag & 8% Metakaolin	0.3
23	1.5	55% slag & 8% Metakaolin	0.22
24	0.944	55% slag & 8% Metakaolin	0.38
SFM1		42% Fly Ash	0.19
SFM2		42% Fly Ash	0.23
SFM3		42% Fly Ash	0.27
SLAG2-1		70% SLAG 2	0.4
SLAG2-2		50% SLAG 2, 20% FLY ASH	0.35
SLAG2-3		55% SLAG 2, 6% SILICA FUME	0.34
SLAG2-4		55% SLAG 2, 8% Metakaolin	0.3

Similar to the RMT results, the correlation between apparent diffusion coefficients from BD tests and resistivity results from SR and BR tests were investigated. Figure 52 shows the correlation between SR and apparent diffusion coefficient while Figure 53 shows the correlation between BR and apparent diffusion coefficient. Good correlations were observed between diffusion coefficients and SR/BR results. The coefficients of determination (R2) are 0.8785 and 0.8894 for SR vs. D_a and BR vs. D_a, respectively, imply correlation coefficients of 93.7% and 94.3% which indicate good correlations between them.

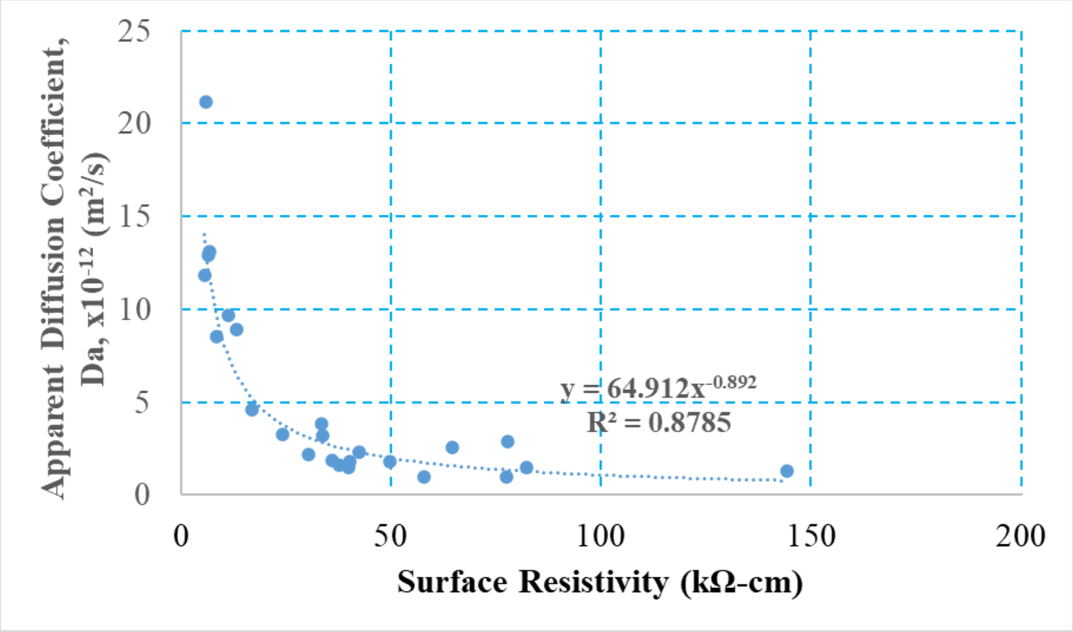


Figure 52. Correlation between SR and apparent diffusion coefficient (D_a)

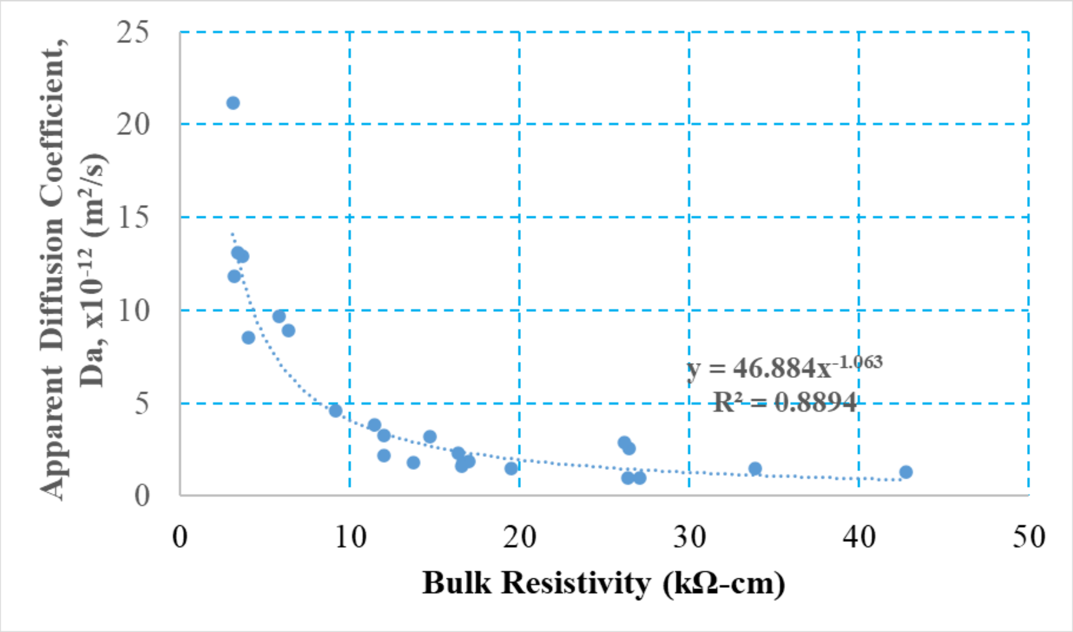


Figure 53. Correlation between BR and apparent diffusion coefficient (D_a)

In order to depict the correlations in a more intuitive way, the inverse of resistivity, conductivity was plotted with apparent diffusion coefficients. As shown in Figure 54 and Figure 55, good correlations are observed between surface conductivity vs. apparent diffusion coefficient as well as bulk conductivity vs. apparent diffusion coefficient. It also observed that the correlation is stronger if the conductivity and diffusion coefficient are low but weaker when conductivity and diffusion coefficient are high. In this study, the correlation equations from Figure 52 through Figure 55 will be used to correlate the diffusion coefficient and concrete resistivity.

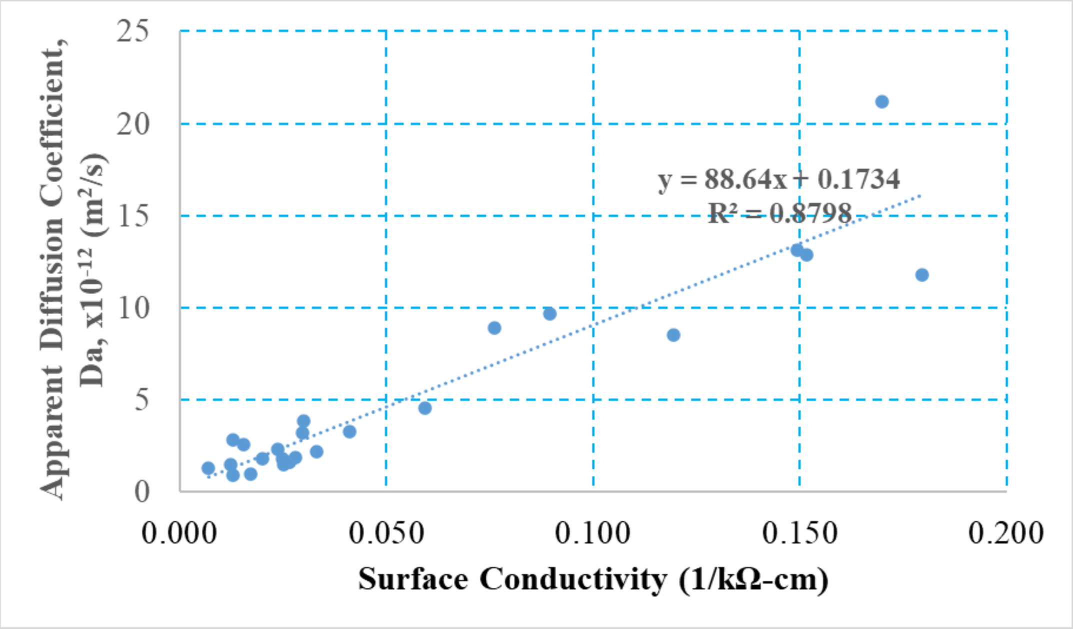


Figure 54. Correlation Between Surface Conductivity and Apparent Diffusion Coefficient (D_a)

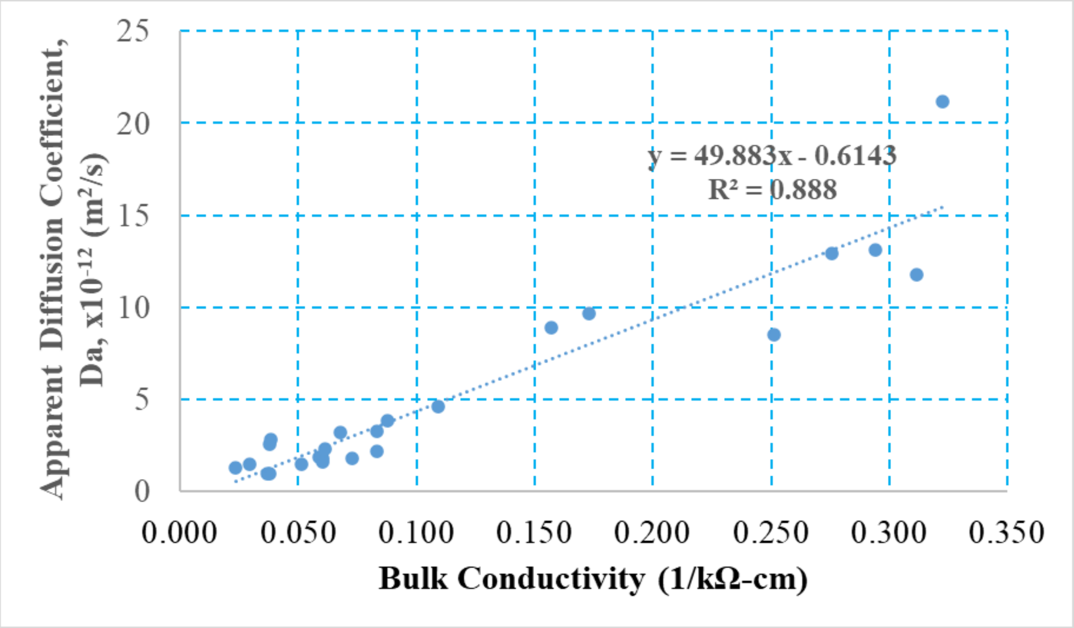


Figure 55. Correlation Between Bulk Conductivity and Apparent Diffusion Coefficient (D_a)

Since both conductivity and resistivity results show good correlation with apparent diffusion coefficients, the correlation between conductivity and apparent diffusion coefficients were used to predict the SR and BR thresholds for a service life of 75 years. Table 50 shows proposed SR and BR thresholds for different structural components.

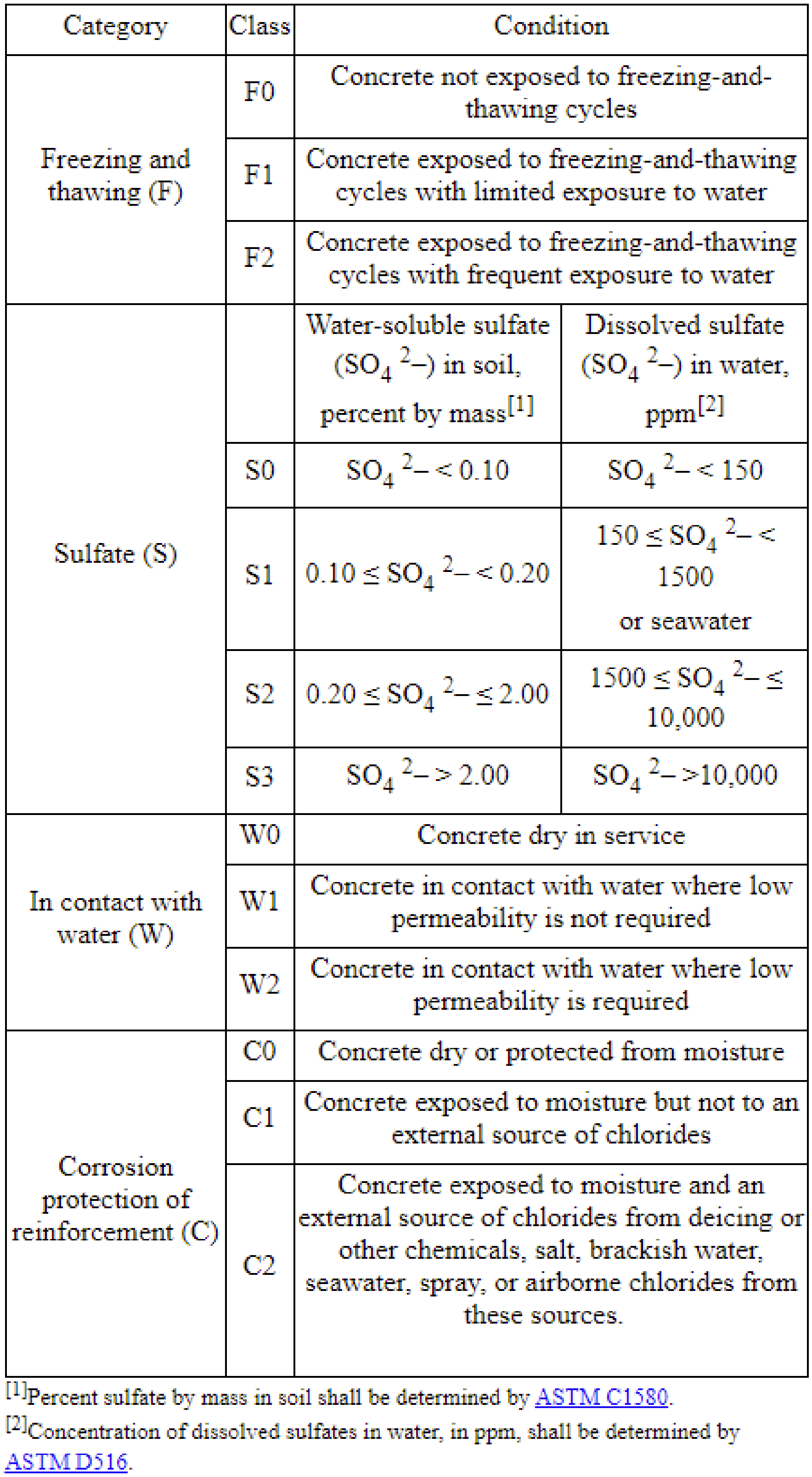
Table 50. Proposed SR and BR thresholds (Extremely aggressive environment)

Structural Component	Cover, inches (mm)	SR Threshold (kΩ-cm) at 28 days	BR Threshold (kΩ-cm) at 28 days
End bent	4” (101.6 mm)	55	21
Piers in contact with water	4.5” (114.3 mm)	42	17
Piers not in contact with water	4” (101.6 mm)	55	21
Retaining walls	3” (76.2 mm)	106	31
Pier cap and intermediate bent	4” (101.6 mm)	55	21

5.2 THRESHOLDS FOR RSPT TEST

Neville (1995) concluded that sulfates react with the Ca (OH)2 and the calcium aluminate hydrates, thus causing expansive reactions which may result in spalling and cracking, and the loss of bond strength between the cement paste and aggregate. ACI 318-25 (2025) designates exposure classes based on water-soluble sulfate in soil or dissolved sulfate in water. As shown in Table 51, while the criteria conditions are similar to current FDOT specification, ACI specifies a “S3” class with 2% sulfate content for soil and 10,000 ppm for water. “S2” class in ACI 318-25 has the same criteria as “Extremely Aggressive” condition class in FDOT SDG.

Table 51. Exposure categories and classes (ACI 318-25 Table 19.3.1.1)



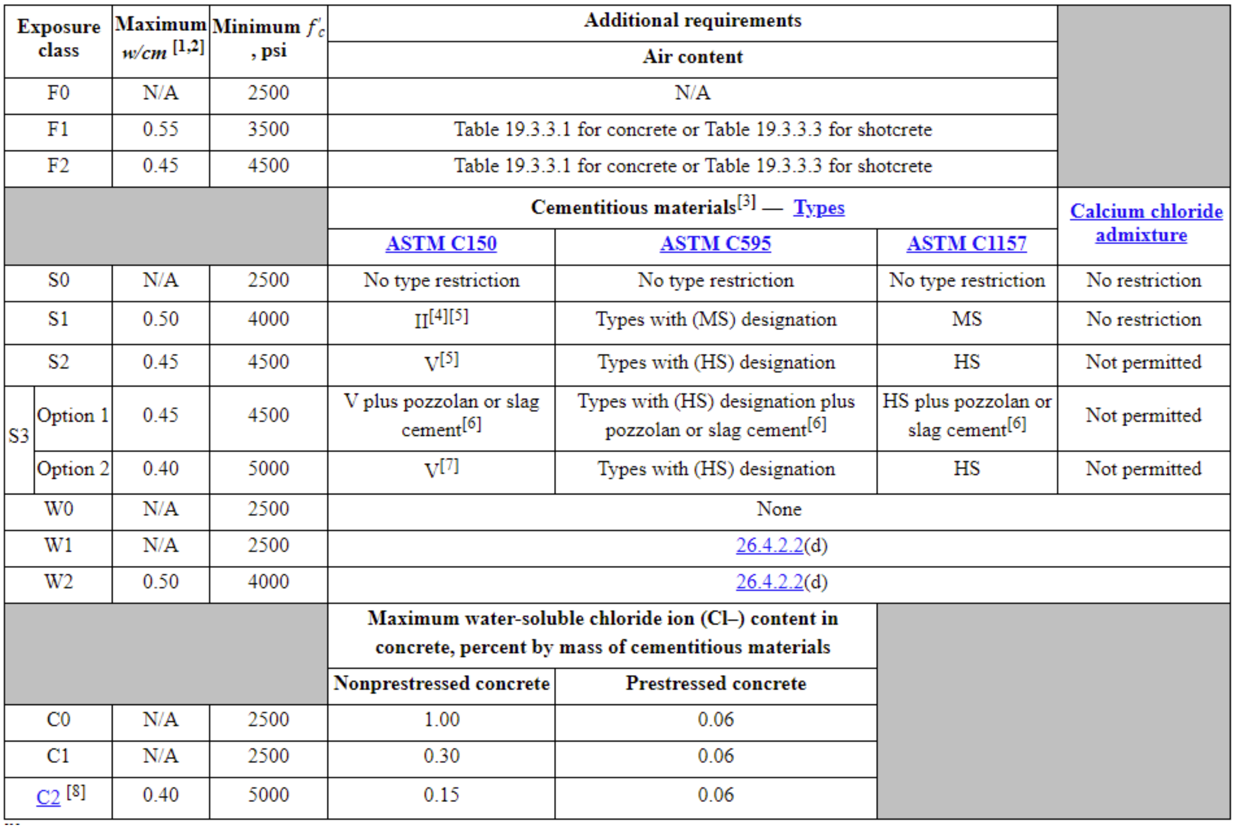
Category	Class	Condition	
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles	
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water	
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water	
Sulfate (S)		Water-soluble sulfate ($SO_4{}^{2-}$) in soil, percent by mass[1]	Dissolved sulfate ($SO_4{}^{2-}$) in water, ppm[2]
	S0	$SO_4{}^{2-} < 0.10$	$SO_4{}^{2-} < 150$
	S1	$0.10 \leq SO_4{}^{2-} < 0.20$	$150 \leq SO_4{}^{2-} < 1500$ or seawater
	S2	$0.20 \leq SO_4{}^{2-} \leq 2.00$	$1500 \leq SO_4{}^{2-} \leq 10{,}000$
	S3	$SO_4{}^{2-} > 2.00$	$SO_4{}^{2-} > 10{,}000$
In contact with water (W)	W0	Concrete dry in service	
	W1	Concrete in contact with water where low permeability is not required	
	W2	Concrete in contact with water where low permeability is required	
Corrosion protection of reinforcement (C)	C0	Concrete dry or protected from moisture	
	C1	Concrete exposed to moisture but not to an external source of chlorides	
	C2	Concrete exposed to moisture and an external source of chlorides from deicing or other chemicals, salt, brackish water, seawater, spray, or airborne chlorides from these sources.	

[1] Percent sulfate by mass in soil shall be determined by ASTM C1580.

[2] Concentration of dissolved sulfates in water, in ppm, shall be determined by ASTM D516.

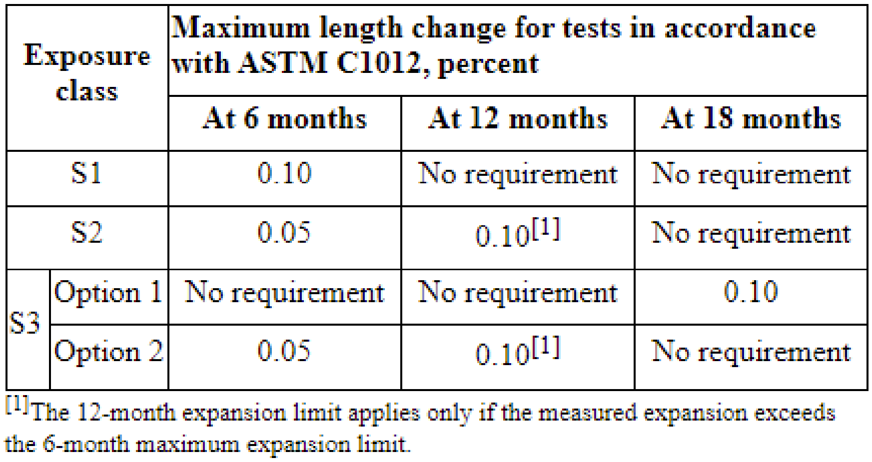
ACI 318-25 specifies both prescriptive measures as well as performance-based measures to minimize sulfate attack. Table 52 shows the requirements for concrete by exposure class in terms of maximum w/c ratio, minimum compressive strength, and types of cementitious materials. For concrete mixes using alternative combinations of cementitious materials to those listed in Table 52, Table 53 presents the requirements based on ASTM C1012.

Table 52. Requirements for concrete by exposure class (ACI 318-25 Table 19.3.2.1)



Exposure class	Maximum w/cm [1,2]	Minimum f'_c, psi	Additional requirements			
			Air content			
F0	N/A	2500	N/A			
F1	0.55	3500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			
F2	0.45	4500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			
			Cementitious materials[3] — Types			Calcium chloride admixture
			ASTM C150	ASTM C595	ASTM C1157	
S0	N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1	0.50	4000	II[4][5]	Types with (MS) designation	MS	No restriction
S2	0.45	4500	V[5]	Types with (HS) designation	HS	Not permitted
S3 Option 1	0.45	4500	V plus pozzolan or slag cement[6]	Types with (HS) designation plus pozzolan or slag cement[6]	HS plus pozzolan or slag cement[6]	Not permitted
Option 2	0.40	5000	V[7]	Types with (HS) designation	HS	Not permitted
W0	N/A	2500	None			
W1	N/A	2500	26.4.2.2(d)			
W2	0.50	4000	26.4.2.2(d)			
			Maximum water-soluble chloride ion (Cl–) content in concrete, percent by mass of cementitious materials			
			Nonprestressed concrete	Prestressed concrete		
C0	N/A	2500	1.00	0.06		
C1	N/A	2500	0.30	0.06		
C2 [8]	0.40	5000	0.15	0.06		

Table 53. Requirements for establishing suitability of combinations of cementitious materials for Exposure Category S (ACI 318-25 Table 26.4.2.2(b))

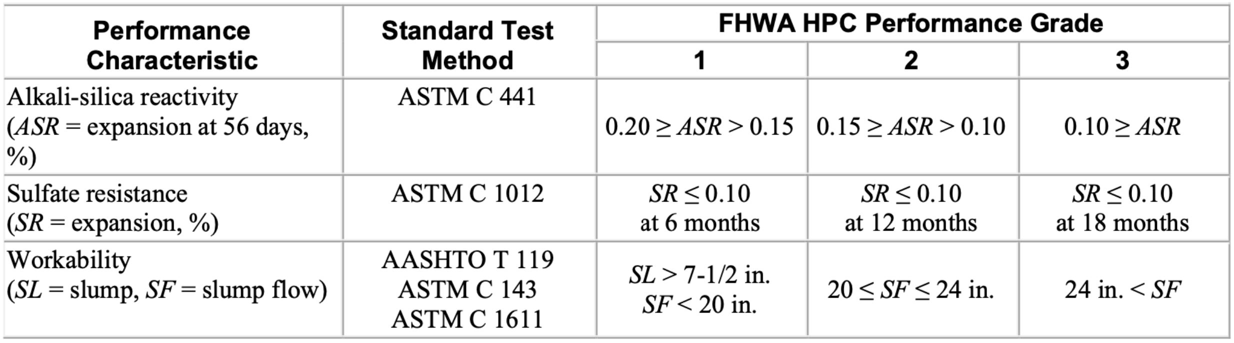


Exposure class		Maximum length change for tests in accordance with ASTM C1012, percent		
		At 6 months	At 12 months	At 18 months
S1		0.10	No requirement	No requirement
S2		0.05	0.10[1]	No requirement
S3	Option 1	No requirement	No requirement	0.10
	Option 2	0.05	0.10[1]	No requirement

[1] The 12-month expansion limit applies only if the measured expansion exceeds the 6-month maximum expansion limit.

Similar to ACI 318-25, Russell and Ozyildirim (2006) proposed grades for sulfate resistance based on ASTM C1012. As shown in Table 54, for grade 3 that applies to severe exposure conditions (water with sulfates over 1500 ppm), the expansion percentage should be less than 0.1 at 18 months (72 weeks).

Table 54. Additional grades of performance characteristics (Russell and Ozyildirim, 2006)



Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade		
		1	2	3
Alkali-silica reactivity (ASR = expansion at 56 days, %)	ASTM C 441	$0.20 \geq ASR > 0.15$	$0.15 \geq ASR > 0.10$	$0.10 \geq ASR$
Sulfate resistance (SR = expansion, %)	ASTM C 1012	$SR \leq 0.10$ at 6 months	$SR \leq 0.10$ at 12 months	$SR \leq 0.10$ at 18 months
Workability (SL = slump, SF = slump flow)	AASHTO T 119 ASTM C 143 ASTM C 1611	$SL >$ 7-1/2 in. $SF <$ 20 in.	$20 \leq SF \leq 24$ in.	24 in. $< SF$

Sirivivatnanon and Lucas (2011) conducted a similar study by testing samples from 19 concrete mixes including six sulfate-resisting cements. They concluded threshold of 2000 coulombs for rapid sulfate permeability is adequate to resist both neutral and acidic sulfate conditions.

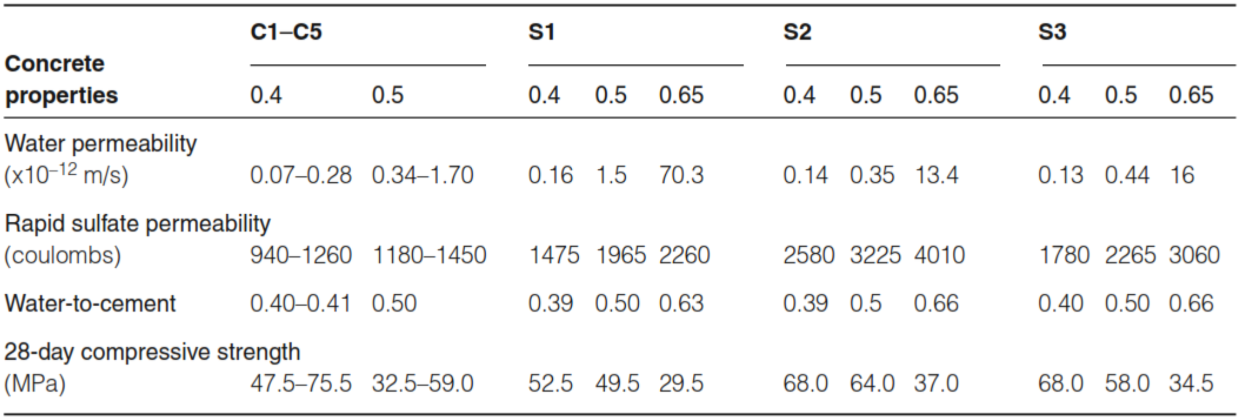
Cement Concrete & Aggregates (CCAA) Australia proposed the long-term performance and possible specifications (CCAA, 2011) as shown in Table 16. C1-C5 and S1 are mix designs with Type SR sulfate-resisting cements while S2 and S3 are mix designs with non-sulfate-resisting cements. In general, they proposed semi-prescriptive and performance-based specifications for sulfate-resisting concrete as follows:

(3) Type SR cement and water-cement ratio ≤ 0.5, and

(4) Type SR cement and a water permeability coefficient ≤ 2×10^{-12}m/s or rapid sulfate permeability ≤ 2000 coulombs.

Since the recommendations from CCAA (2011) are developed based on Sirivivatnanon and Lucas (2011), their conclusions are similar.

Table 55. Summary of long-term performance and possible specifications (CCAA, 2011)



Concrete properties	**C1–C5**		**S1**			**S2**			**S3**		
	0.4	0.5	0.4	0.5	0.65	0.4	0.5	0.65	0.4	0.5	0.65
Water permeability ($\times 10^{-12}$ m/s)	0.07–0.28	0.34–1.70	0.16	1.5	70.3	0.14	0.35	13.4	0.13	0.44	16
Rapid sulfate permeability (coulombs)	940–1260	1180–1450	1475	1965	2260	2580	3225	4010	1780	2265	3060
Water-to-cement	0.40–0.41	0.50	0.39	0.50	0.63	0.39	0.5	0.66	0.40	0.50	0.66
28-day compressive strength (MPa)	47.5–75.5	32.5–59.0	52.5	49.5	29.5	68.0	64.0	37.0	68.0	58.0	34.5

Based on the previous research and current code specifications, the research team proposes to use 0.1% expansion at 18 months (72 weeks) as the criteria for an extremely aggressive environment. To choose the thresholds for the RSPT test, we need to establish the correlation between the length change test data according to ASTM C1012 and the RSPT test results. However, so far, we only have 4 mixes that with 18 months (72 weeks) length change test data available. In order to have more 18 months (72 weeks) length change test data, the linear regression prediction equation as shown in Figure 36 through Figure 46 were used to predict the 18 months (72 weeks) length change results. For data quality control purposes, the negative value are excluded from this analysis. As shown in Figure 56, the correlation is poor between RSPT results at 28 days and expansion percentage at 18 months with R^2=0.1807. Using this linear regression prediction equation, the RSPT threshold for a 0.1% expansion is 2153 coulomb.

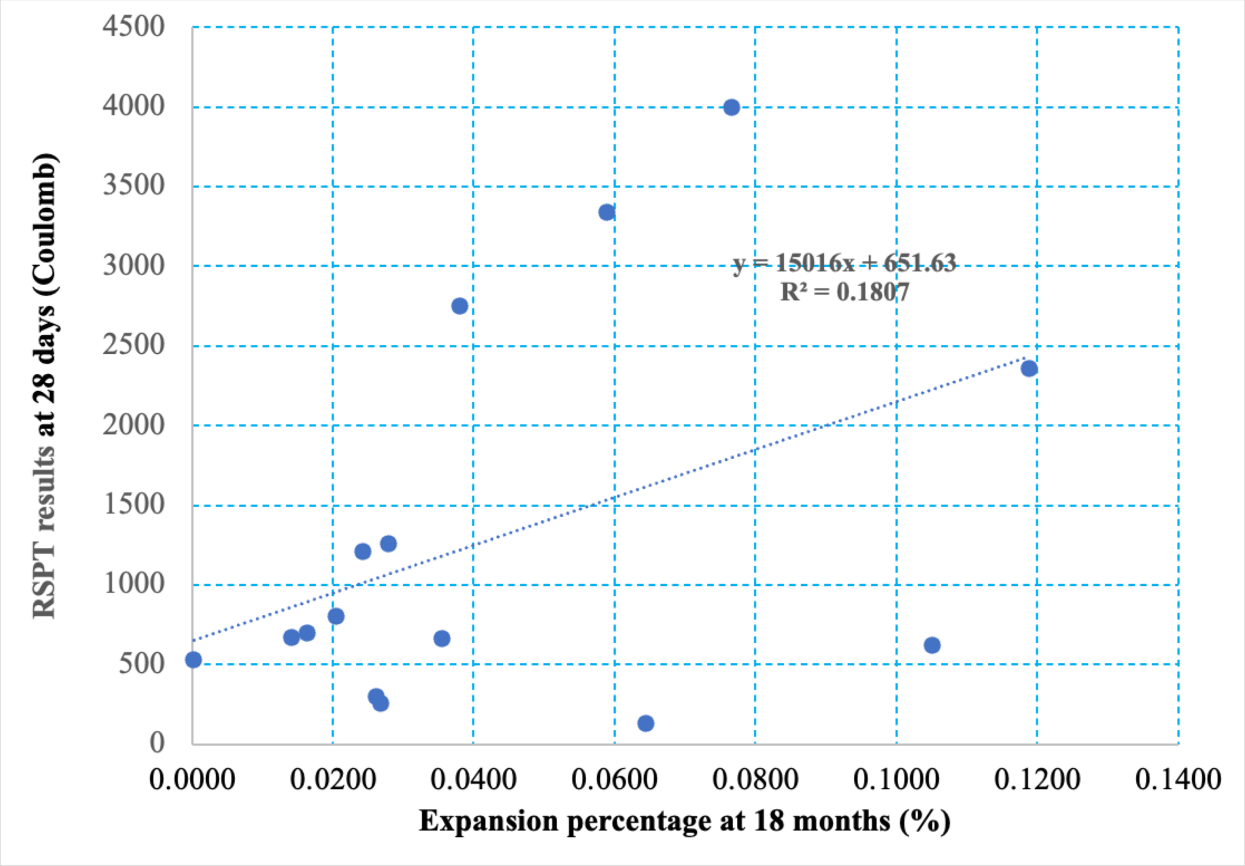


Figure 56. Correlation between RSPT results at 28 days and expansion percentage at 18 months

5.3 CORRELATIONS BETWEEN 28-DAYS AND 56-DAYS RESULTS

Based on the 28-days and 56-days testing results and their correlations as shown in Figure 28 and Figure 31 for SR test and BR test, respectively, the equations below are proposed to be used to predict the 56-days SR and BR results. As shown in Figure 57 and Figure 58, the prediction yielded in good accuracy with mean absolute error of 9.3% and 10.6% for SR and BR, respectively.

$$SR_{56} = SR_{28} \cdot \left(1 + \frac{FA}{60} + \frac{SG}{800} + \frac{SF}{20} + \frac{MK}{2000} + \frac{wc}{10}\right) \qquad \text{Eq. (2)}$$

$$BR_{56} = BR_{28} \cdot (1 + \frac{FA}{80} + \frac{SG}{2000} + \frac{SF}{40} + \frac{MK}{2000} + \frac{wc}{5}) \quad \text{Eq. (3)}$$

which FA, SG, SF, and MK are the percentage of fly ash, slag, silica fume, and metakaolin, wc is the water to cement ratio.

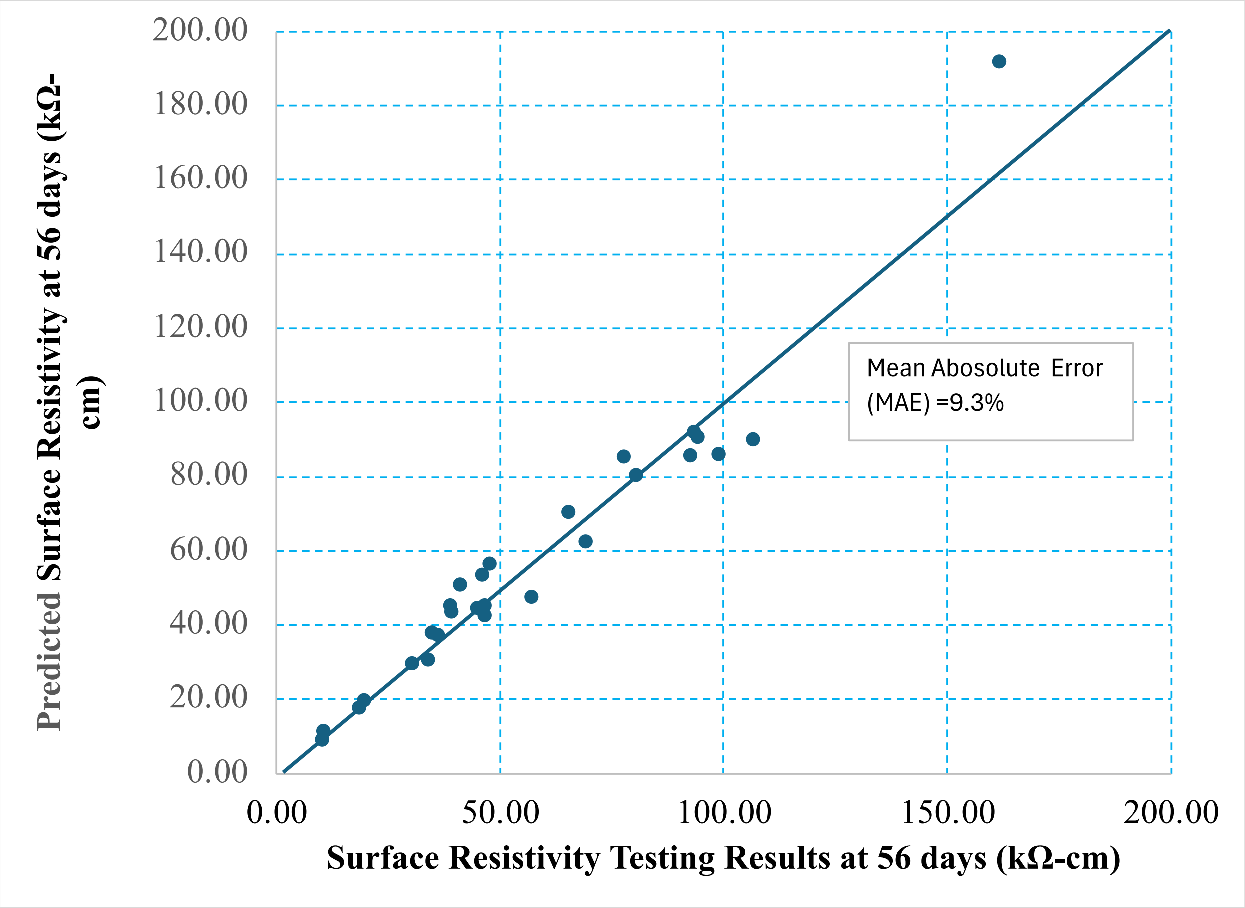


Figure 57. SR testing results vs. SR predicted

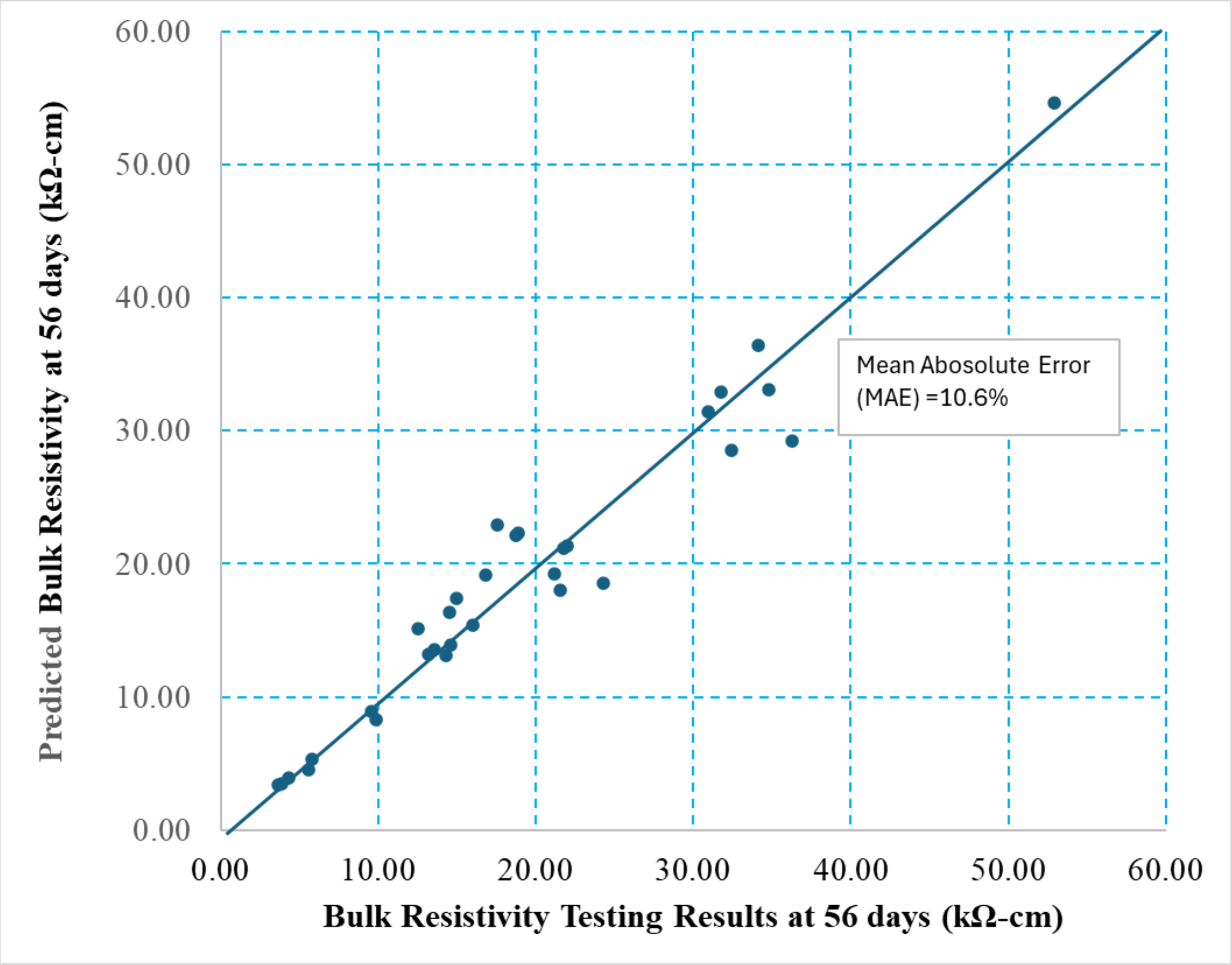


Figure 58. BR testing results vs. BR predicted

For RSPT, as shown in Figure 35, the correlation between 28-days and 56-days results are not very strong (R^2=0.8267). The equation below is proposed to predict 56-days RSPT result but the accuracy is not as good as SR or BR results with a mean absolute error of 28.1%.

$$RSPT_{56} = RSPT_{28} \cdot (1 - \frac{FA}{200} - \frac{SG}{2000} - \frac{SF}{60} - \frac{MK}{45} - \frac{wc}{2}) \qquad \text{Eq. (3)}$$

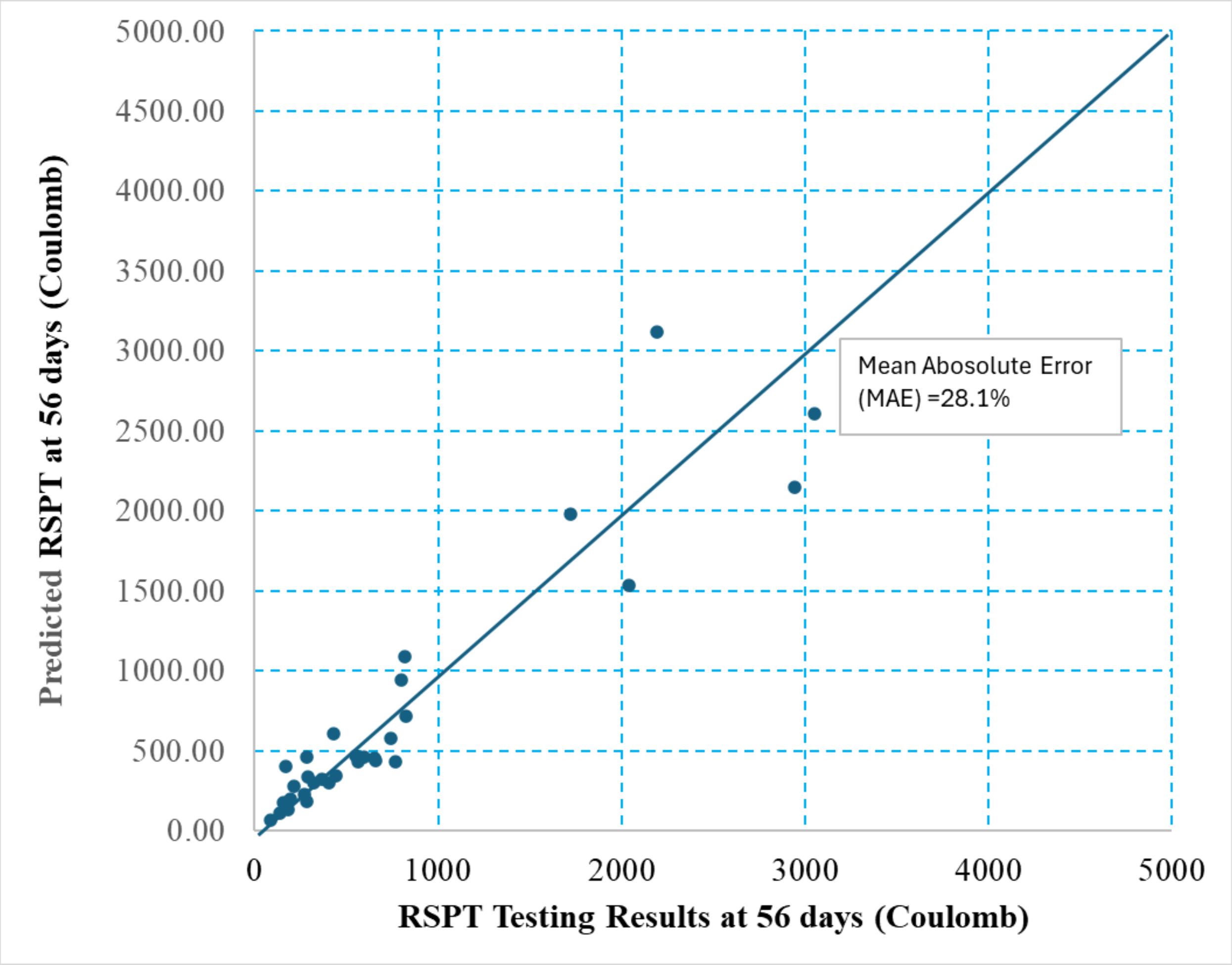


Figure 59. RSPT testing results vs. RSPT predicted

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7 APPENDIX A: DATA SCREENING AND PREPARATION PROCEDURE FOR DATA CONSOLIDATION

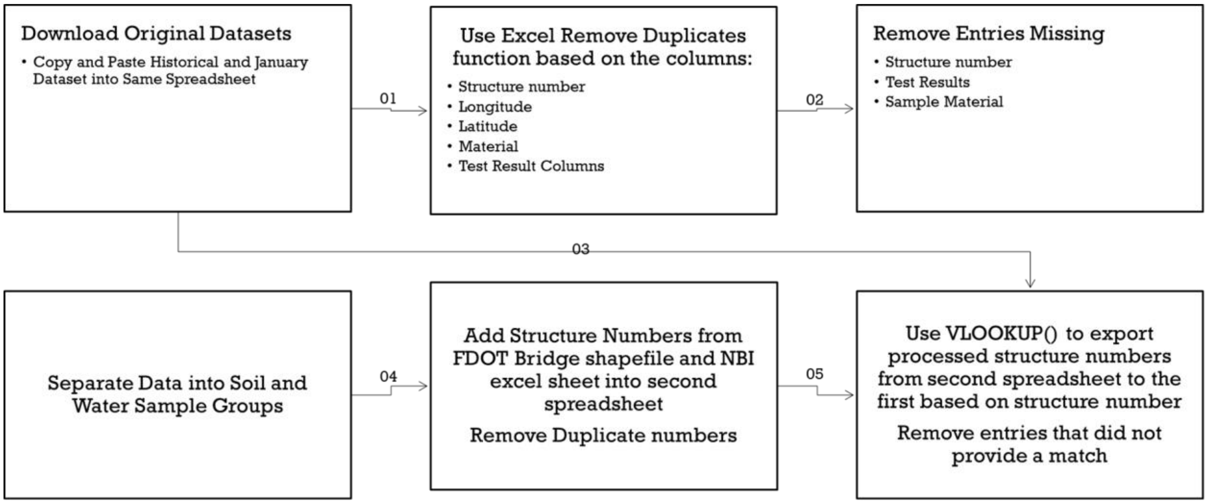


Figure A - 1. Data Validation Procedure

Figure A - 1 summarizes the procedural Microsoft Excel processes used to merged and validate the January 2022 dataset and Historical data together to resolve limitation found during initial analysis attempts. The consolidated data set was then separated into its prospective test sample categories of water and soil. Once again Microsoft excel processes were used to remove entries that were deemed invalid. The entries had to fail any one of the following to be deemed invalid for the analysis of bridge structures:

a) Have a sample material named
b) Have a structure number associated with a bridge*

*The FDOT Bridge shapefile was used in conjunction with the National Bridge Inventory (NBI) to account for any bridges that were not included in the FDOT shapefile and vice versa to provide an accurate analysis of Florida bridges.

c) Have results for ALL four test categories,

For extreme chloride and sulfate analysis of bridge structure the following criteria was added:

d) Has at least one extreme test result

The first three criterion were chosen to better provide accurate data and the fourth was added to determine if there is any correlation between extreme test results, especially chloride and sulfate. These two sets of criteria allowed for the comparison of test results for extremely aggressive environments and the collective sample of bridge environments tested.

8 APPENDIX B: SCREENING AND PREPERATION PROCEDURE FOR GIS MAPPING

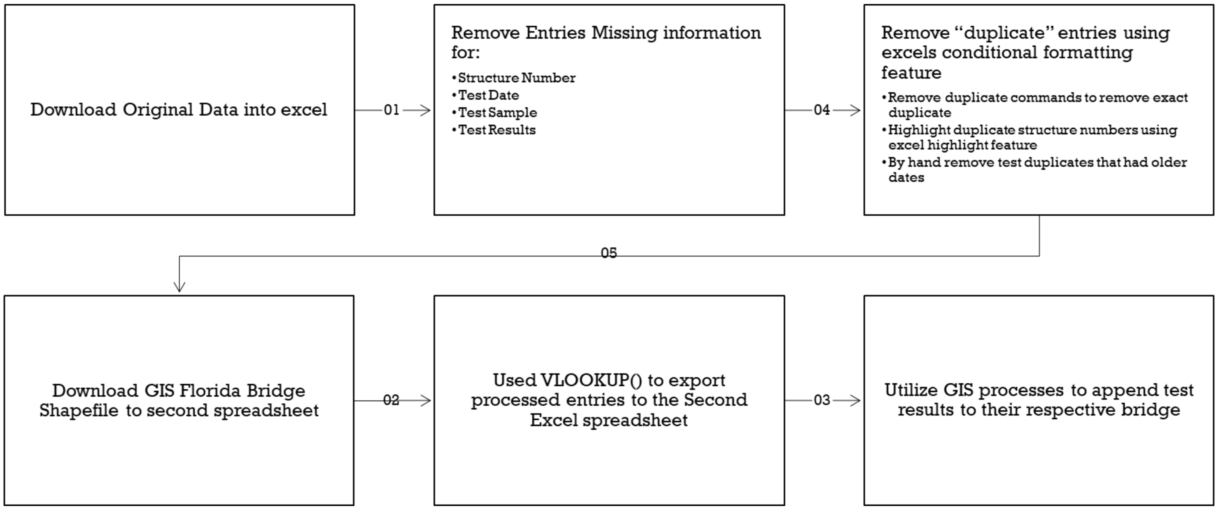


Figure B - 1. Data validation of mappable sites

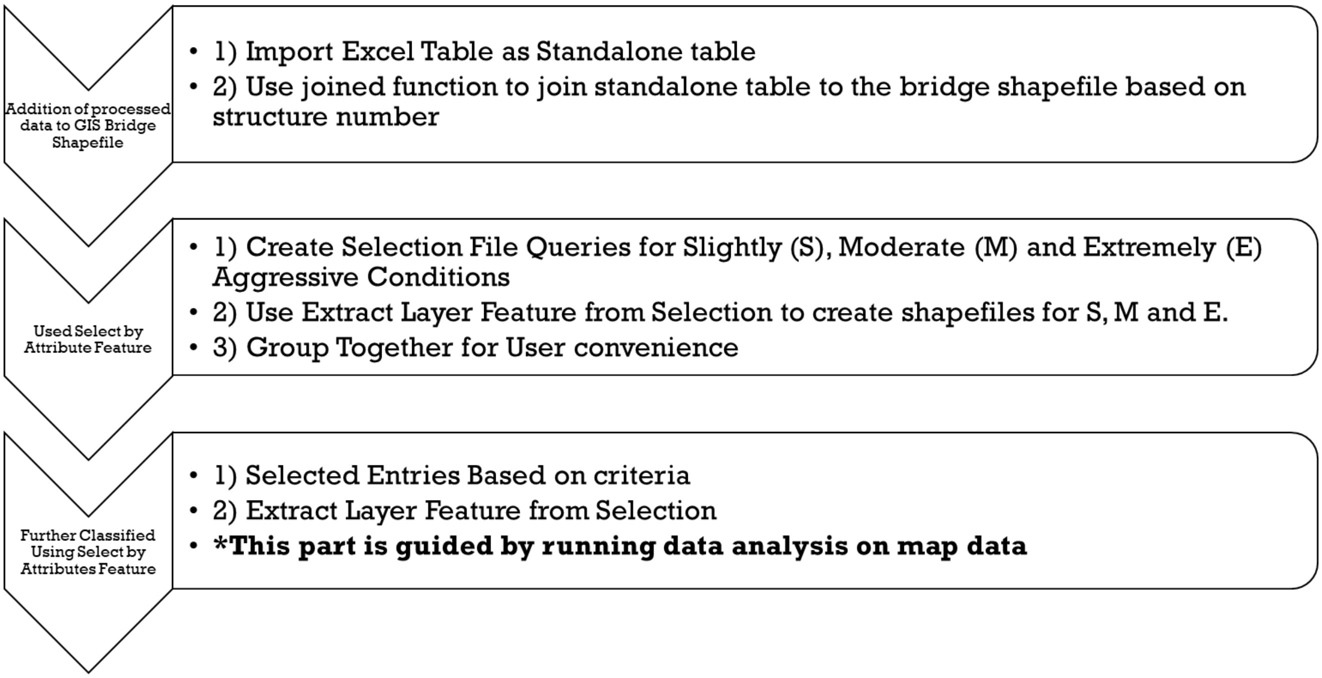
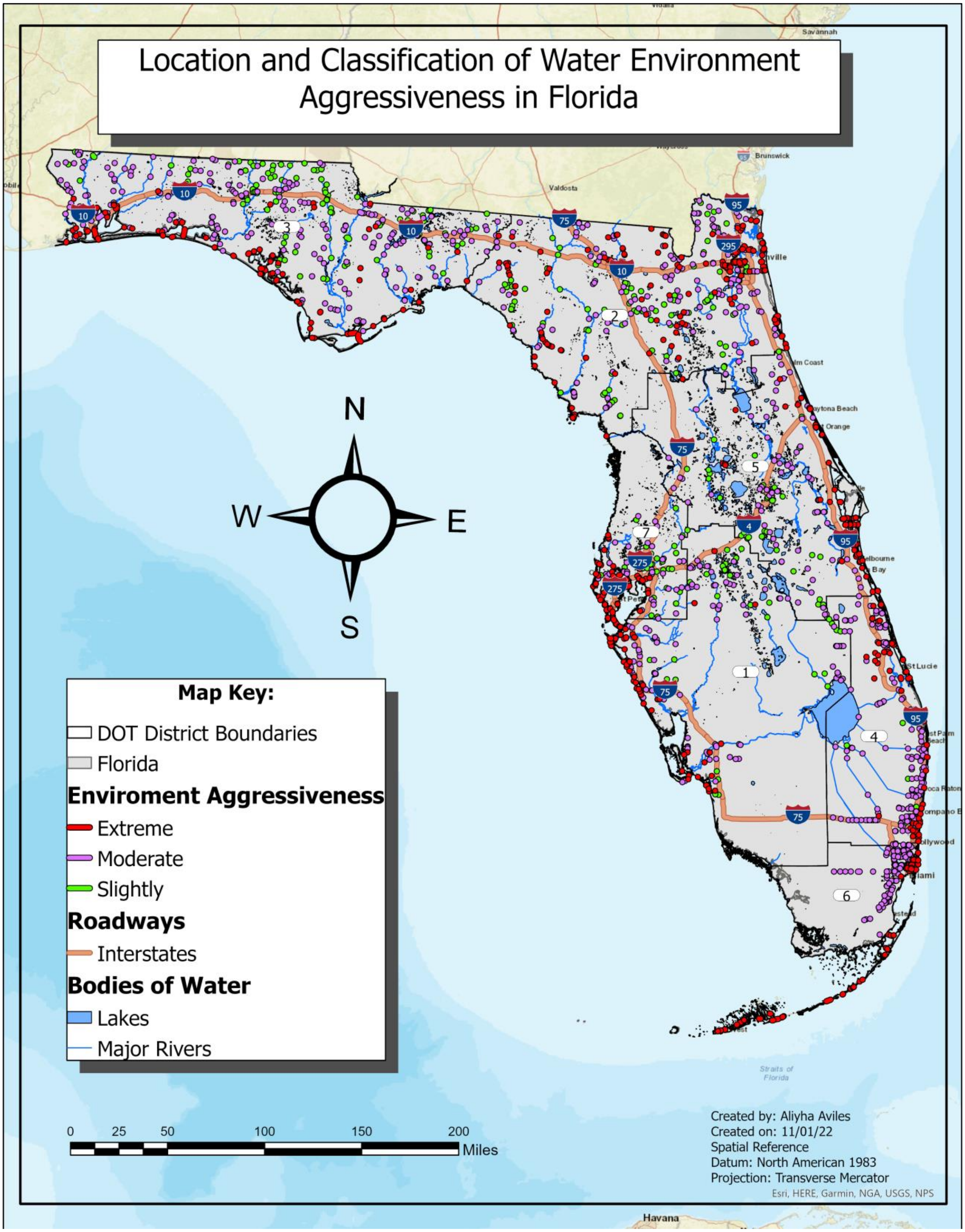
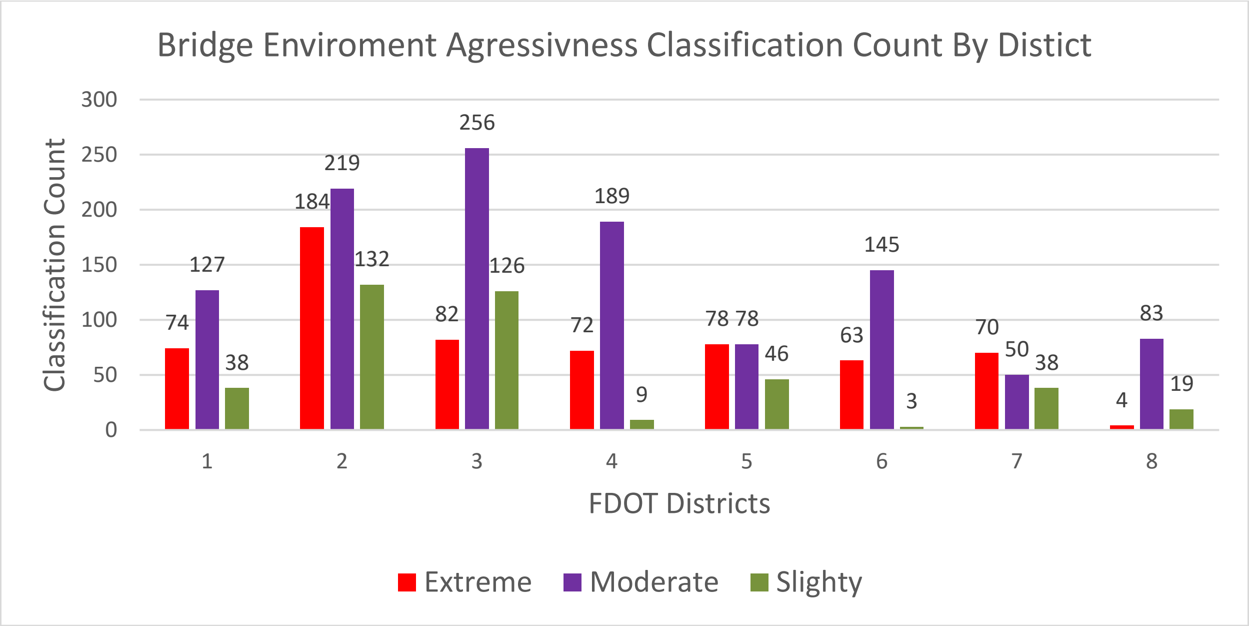
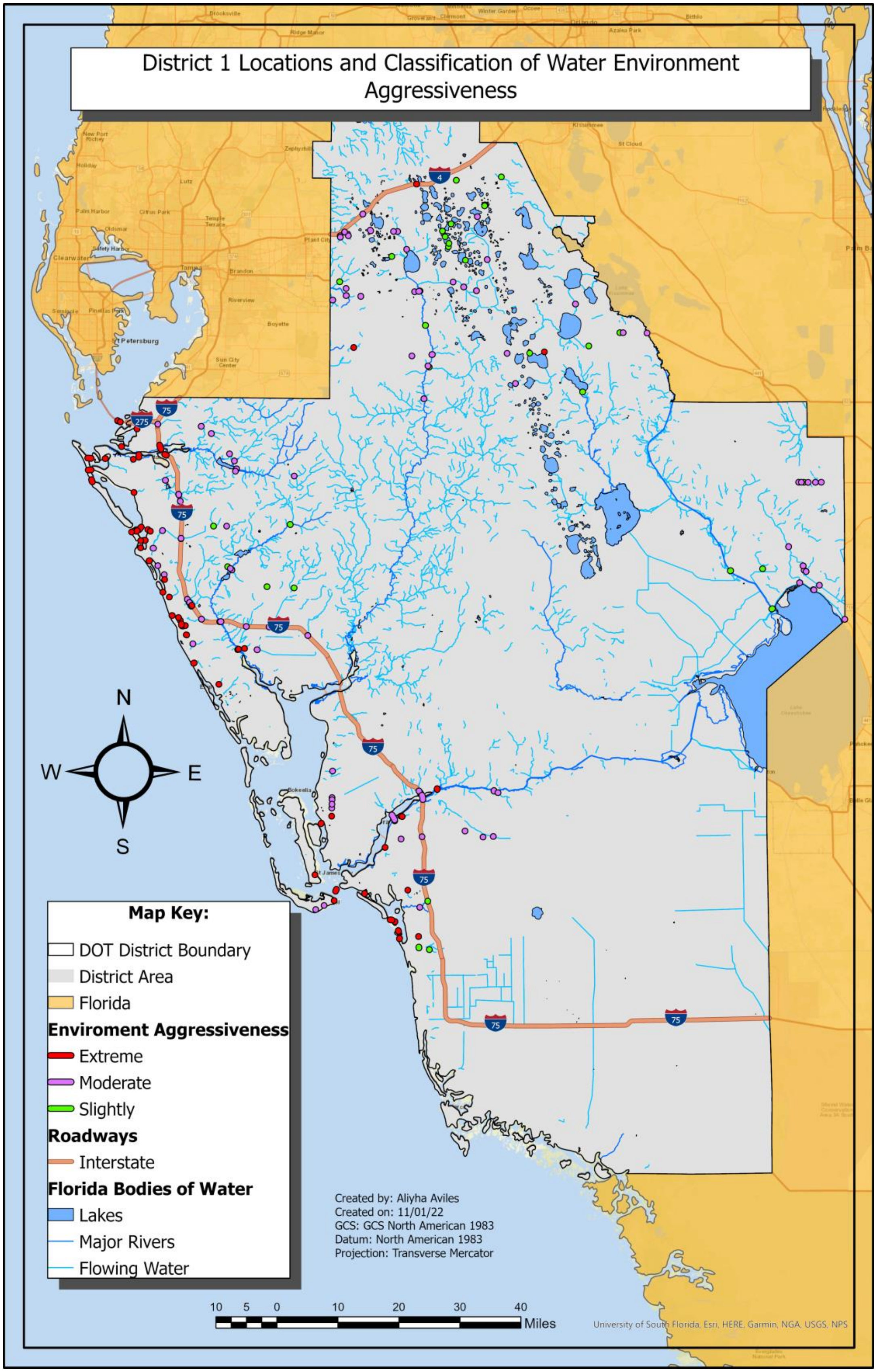


Figure B - 2. GIS selection process for criterion mapping

9 APPENDIX C: GIS MAPS

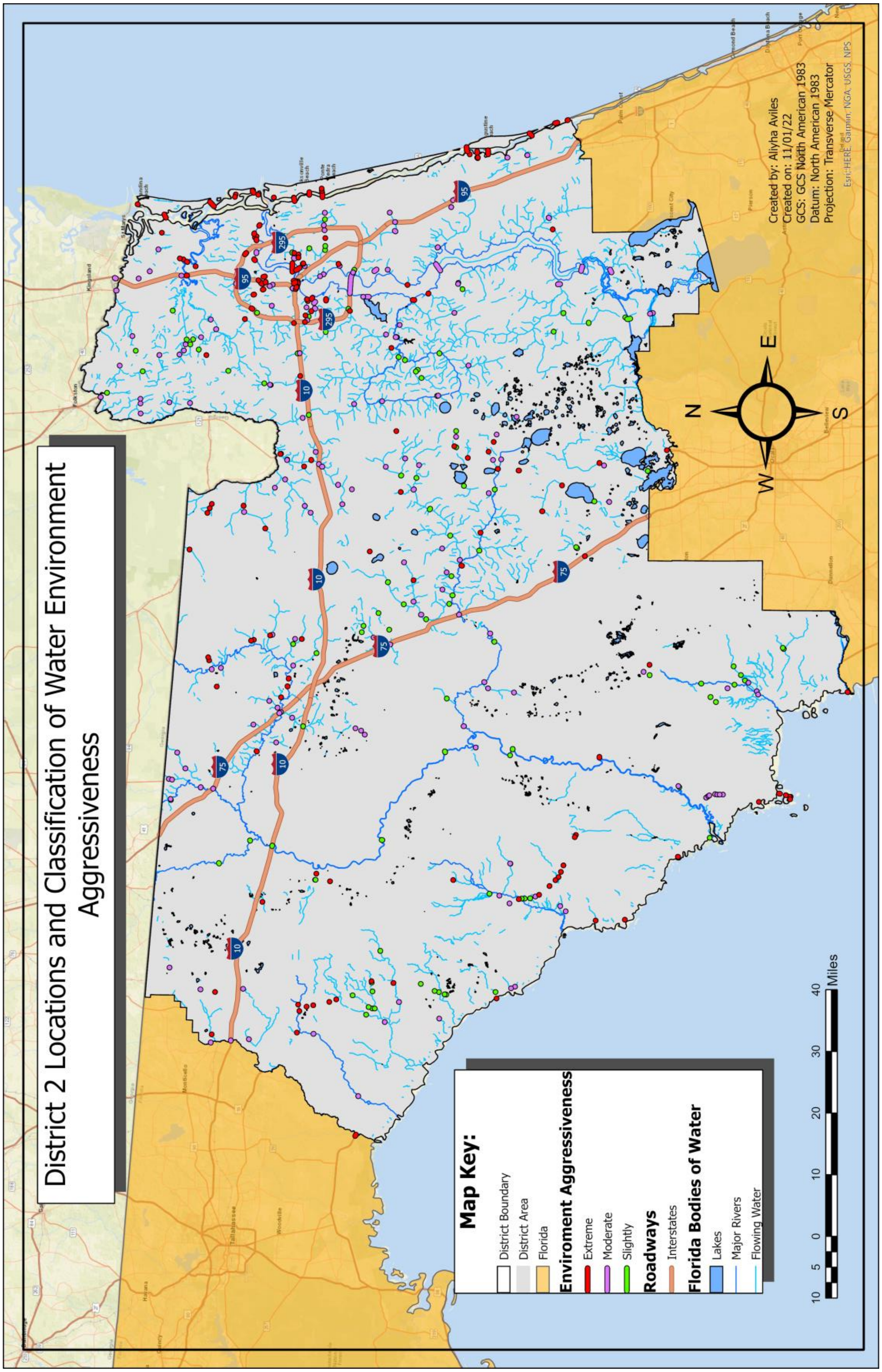


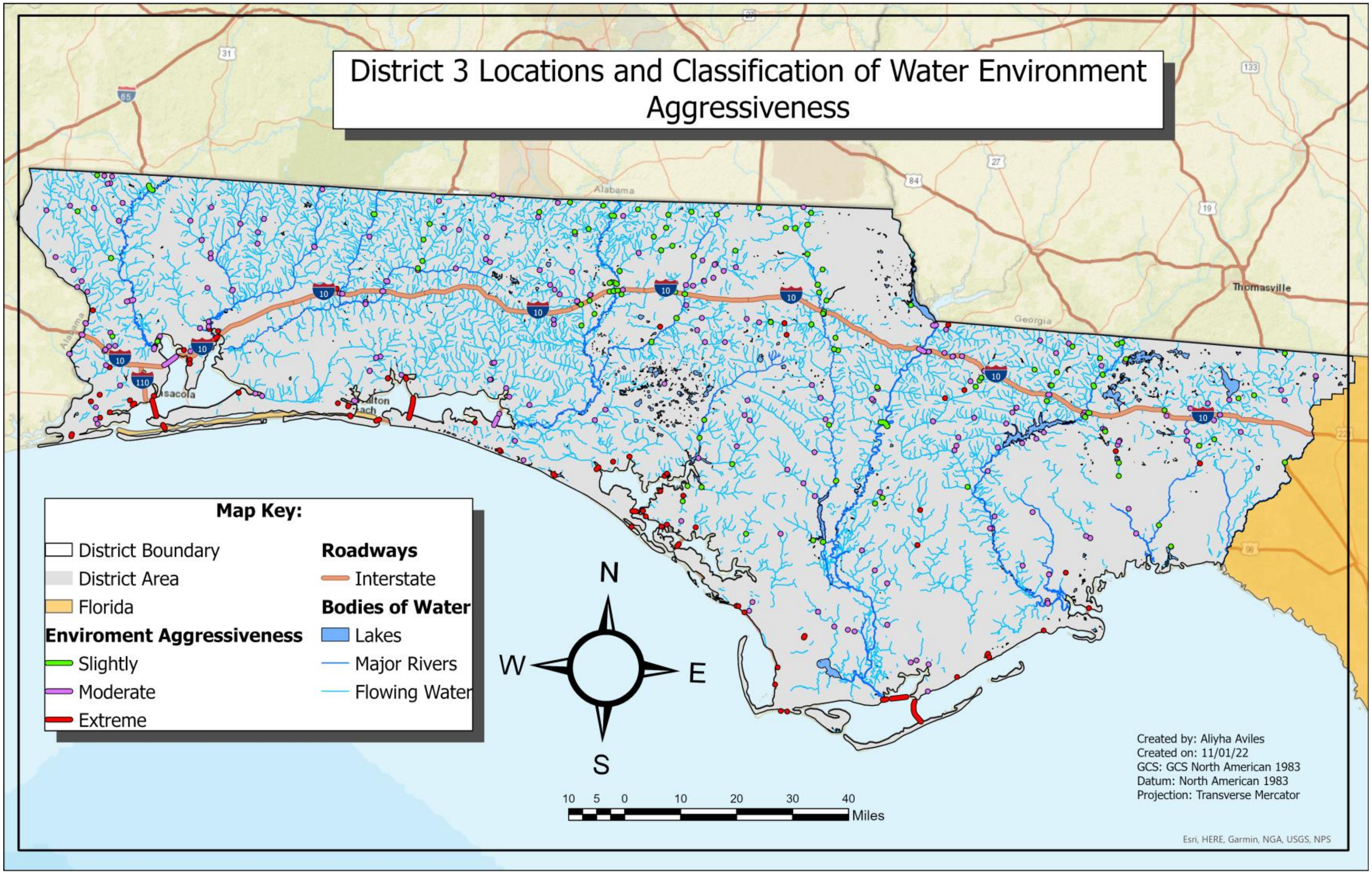

Bridge Enviroment Agressivness Classification Count By Distict
Classification Count
300
250
200
150
100
50
0
74
127
38
184
219
132
82
256
126
72
189
9
78
78
46
63
145
3
70
50
38
4
83
19
1
2
3
4
5
6
7
8
FDOT Districts
Extreme
Moderate
Slighty


District 1 Locations and Classification of Water Environment Aggressiveness

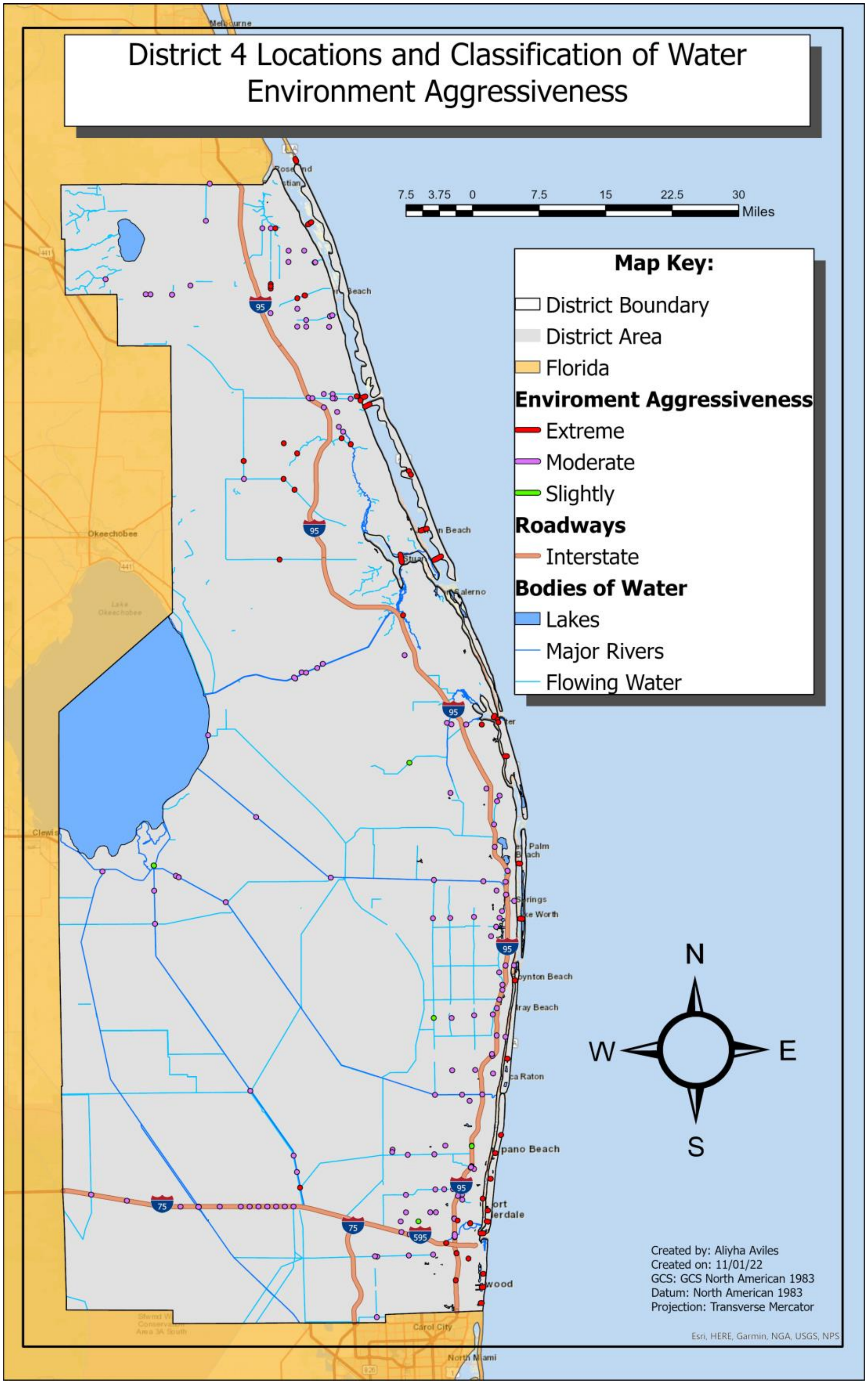
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator

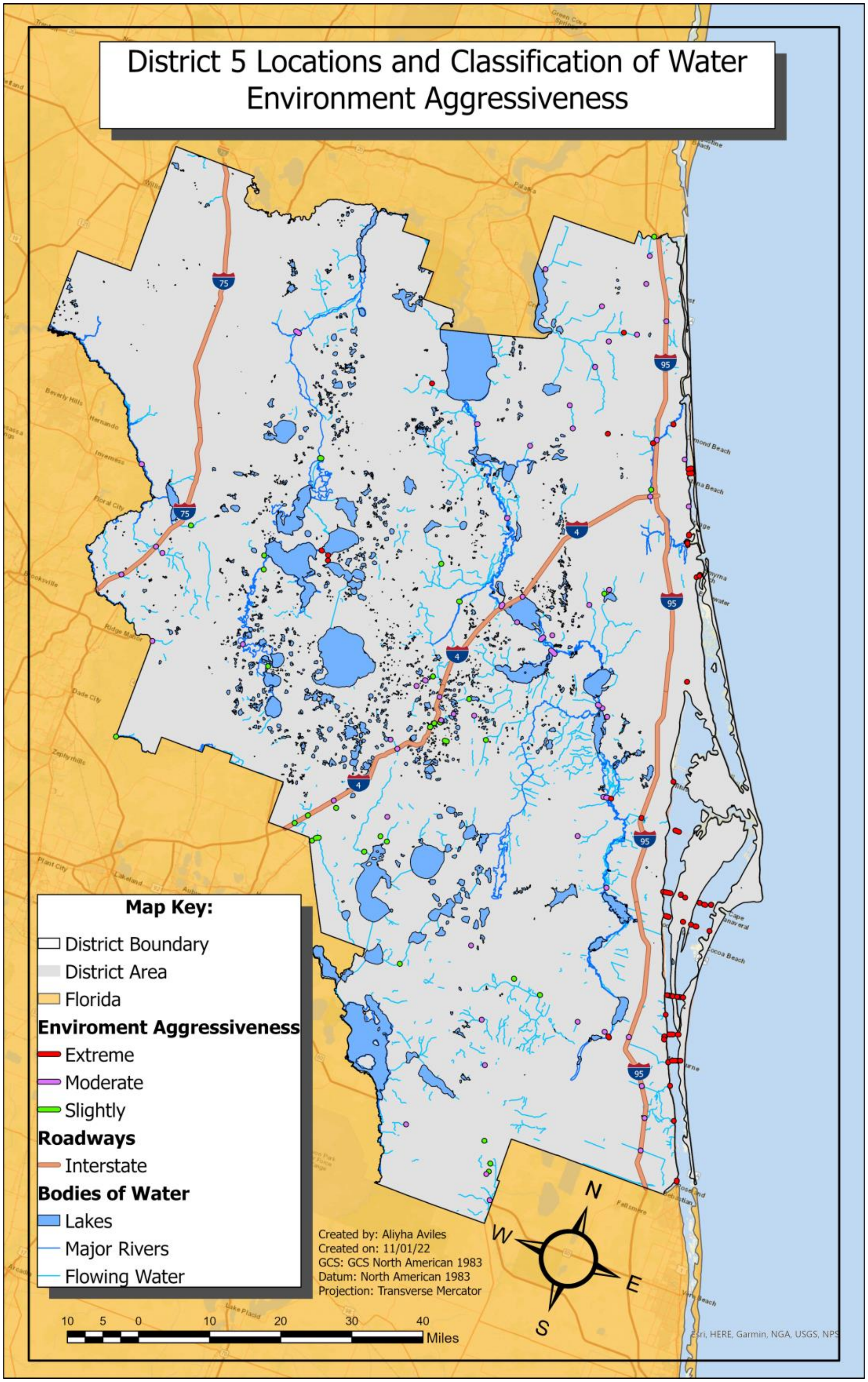
University of South Florida, Esri, HERE, Garmin, NGA, USGS, NPS


District 2 Locations and Classification of Water Environment Aggressiveness



District 3 Locations and Classification of Water Environment Aggressiveness


District 4 Locations and Classification of Water Environment Aggressiveness
7.5 3.75 0 7.5 15 22.5 30
Miles
Map Key:
District Boundary
District Area
Florida
Enviroment Aggressiveness
Extreme
Moderate
Slightly
Roadways
Interstate
Bodies of Water
Lakes
Major Rivers
Flowing Water
N
S
E
W
95
75
595
Melbourne
Okeechobee
Lake Okeechobee
Clewiston
Stuart
Palm Beach
Lake Worth
Boynton Beach
Delray Beach
Boca Raton
Pompano Beach
Fort Lauderdale
Hollywood
Carol City
North Miami
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS



District 5 Locations and Classification of Water Environment Aggressiveness

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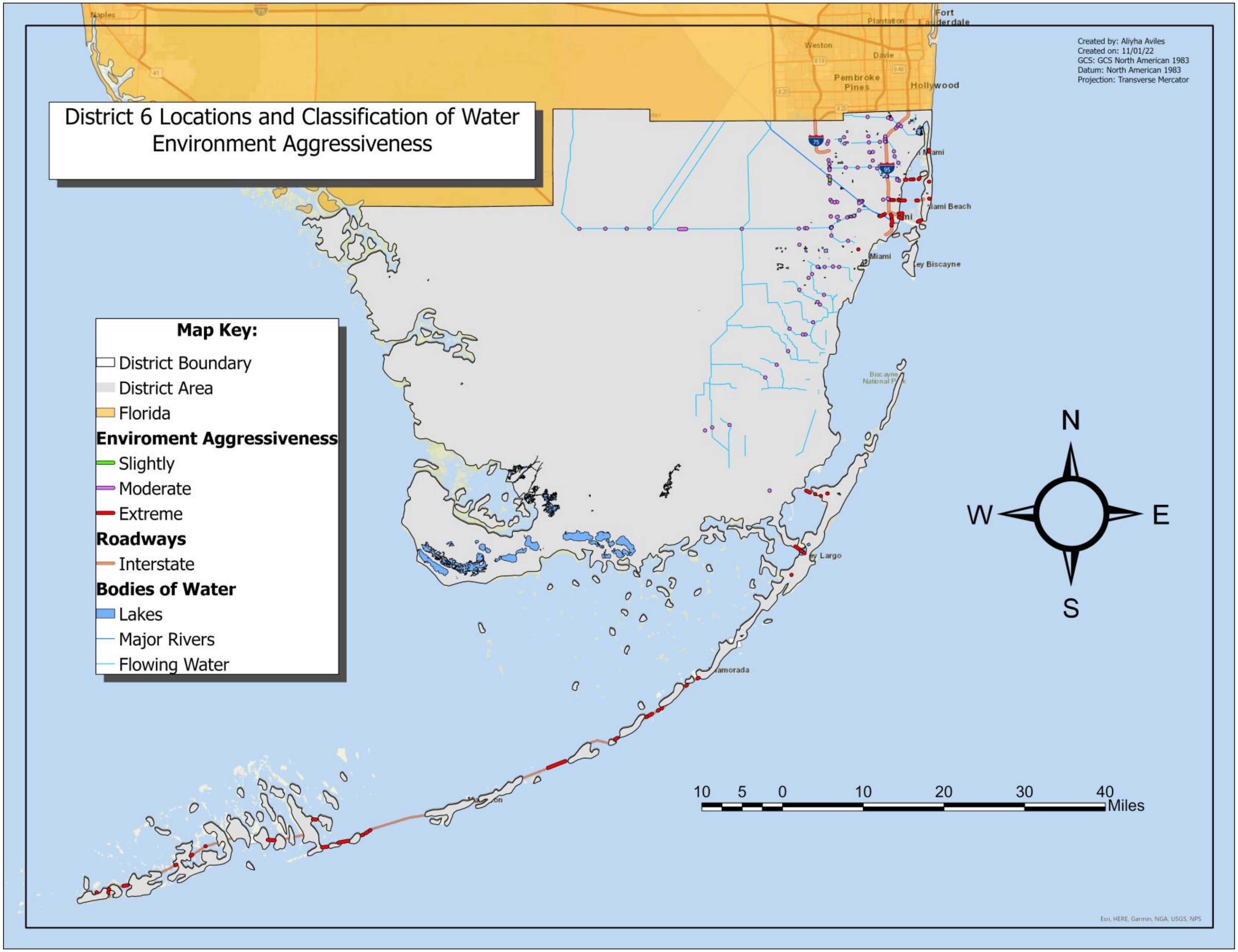
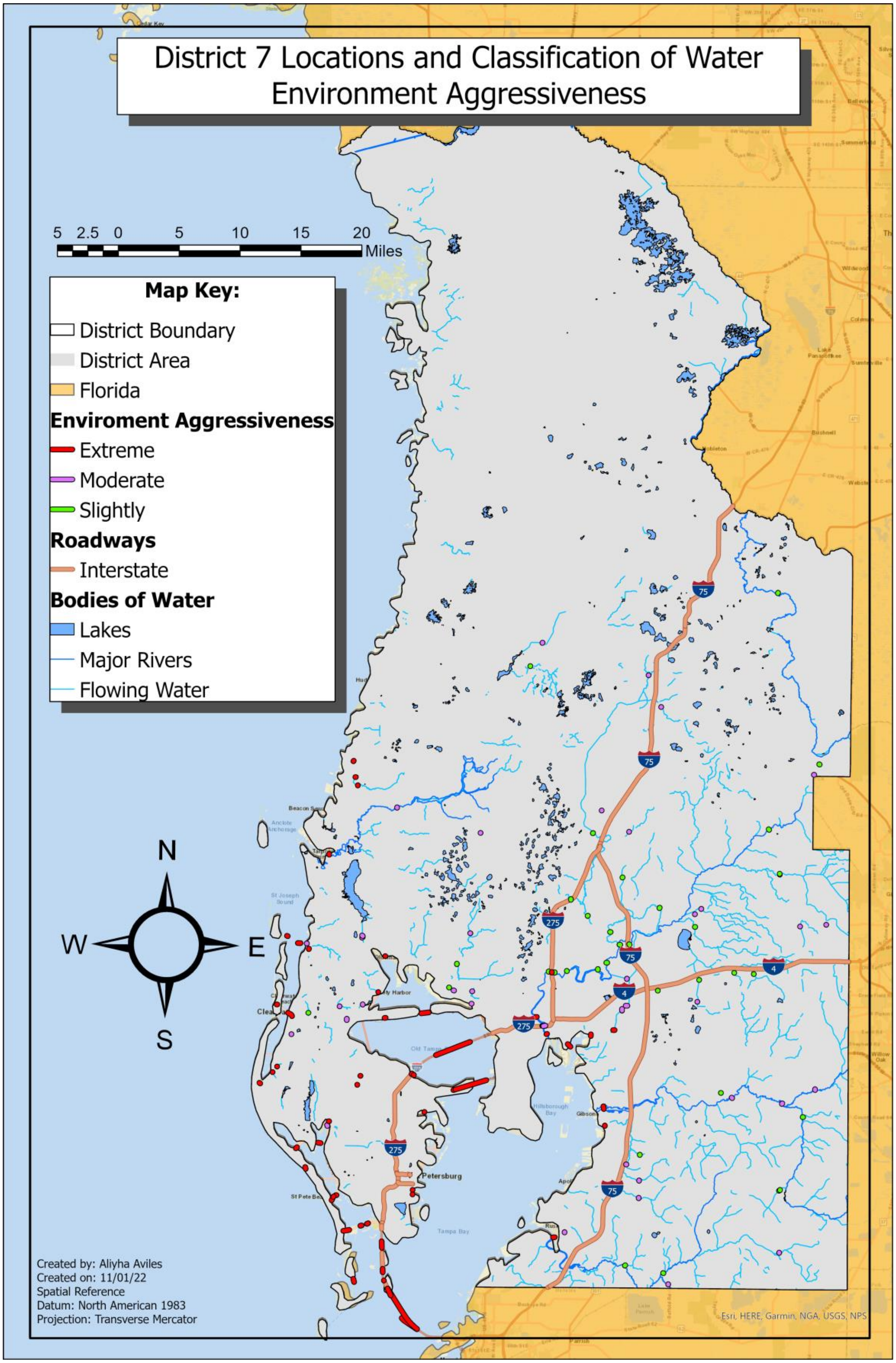
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator


District 6 Locations and Classification of Water Environment Aggressiveness

Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator

Esri, HERE, Garmin, NGA, USGS, NPS


District 7 Locations and Classification of Water Environment Aggressiveness
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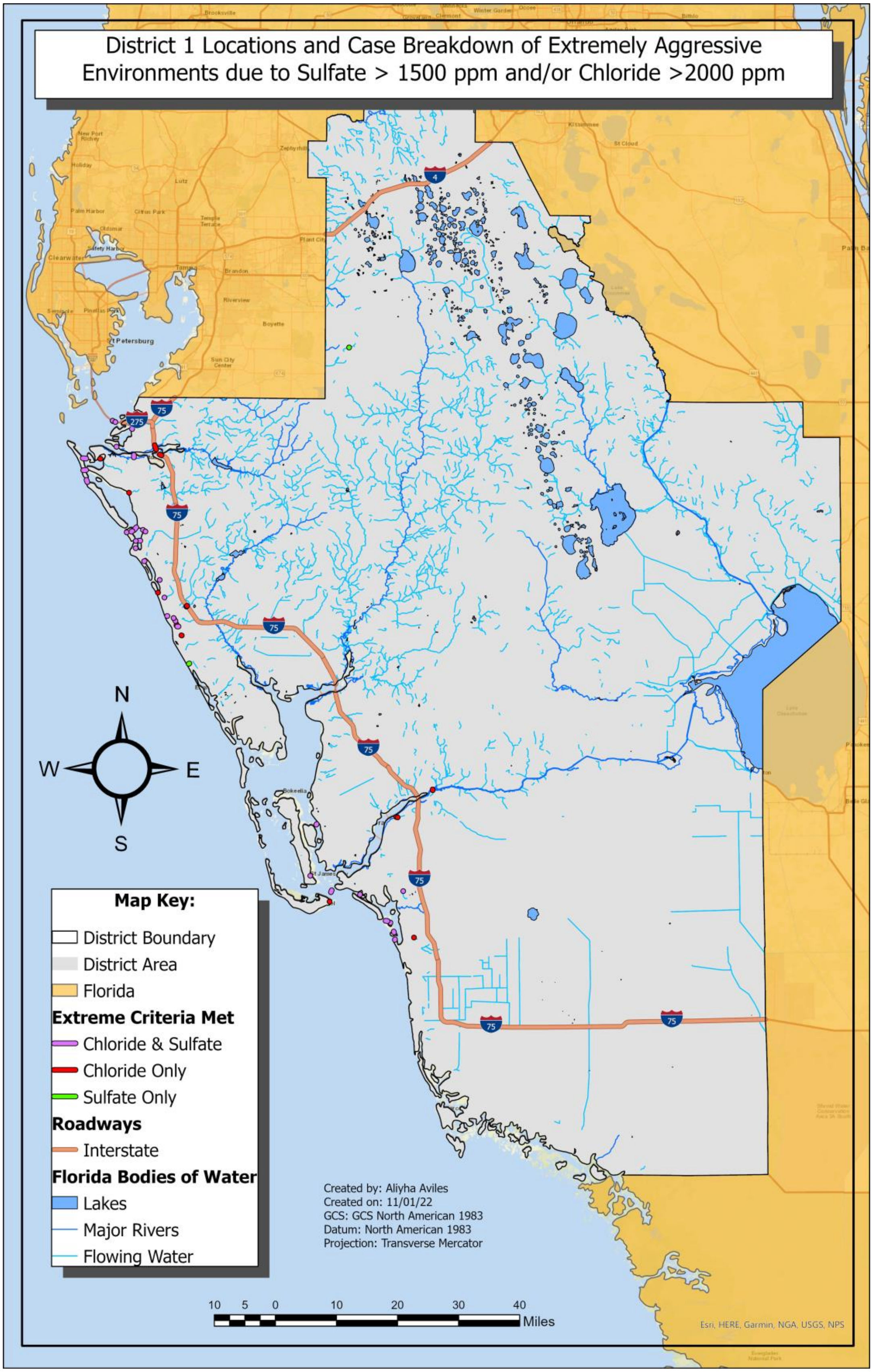
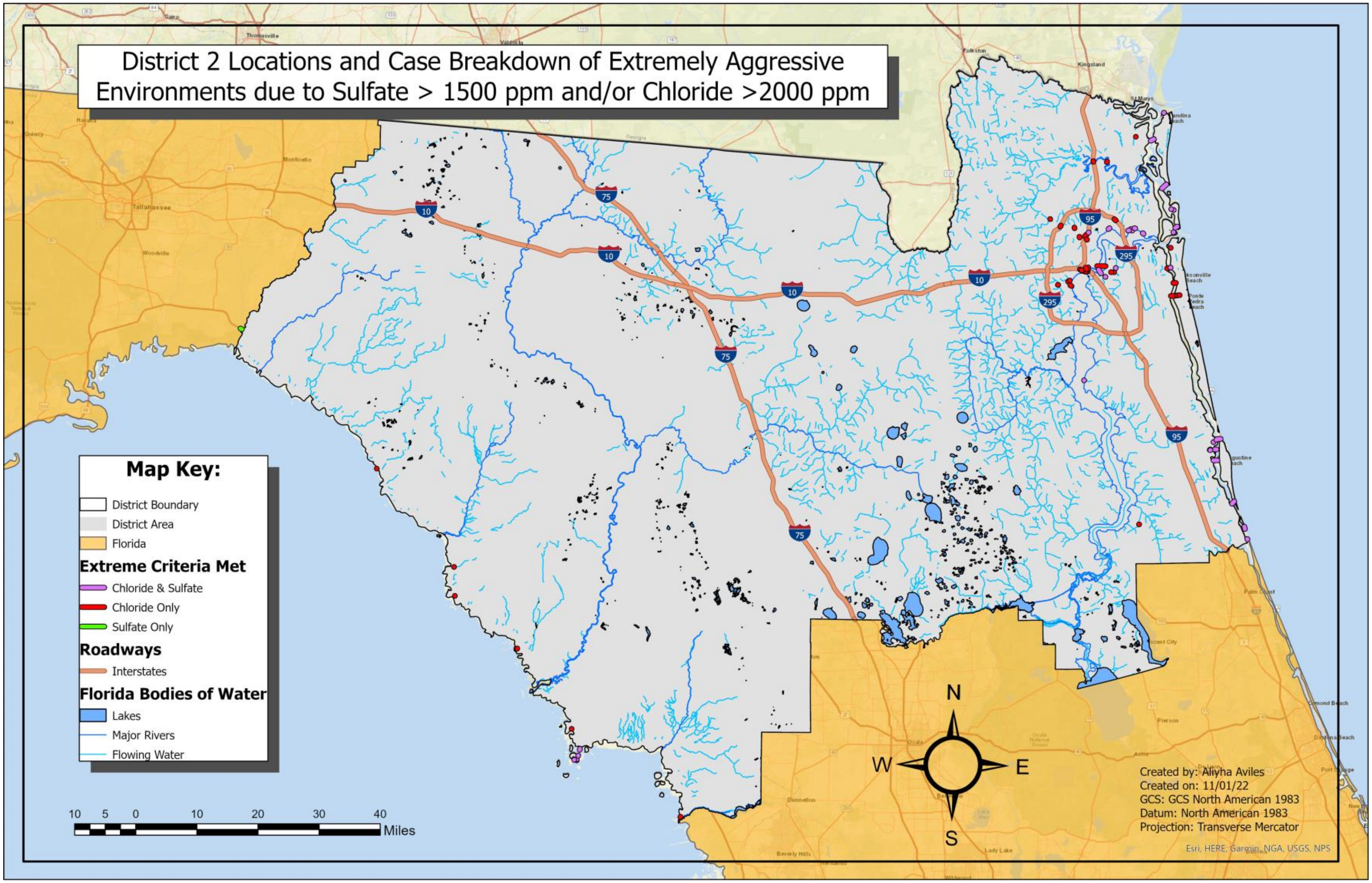
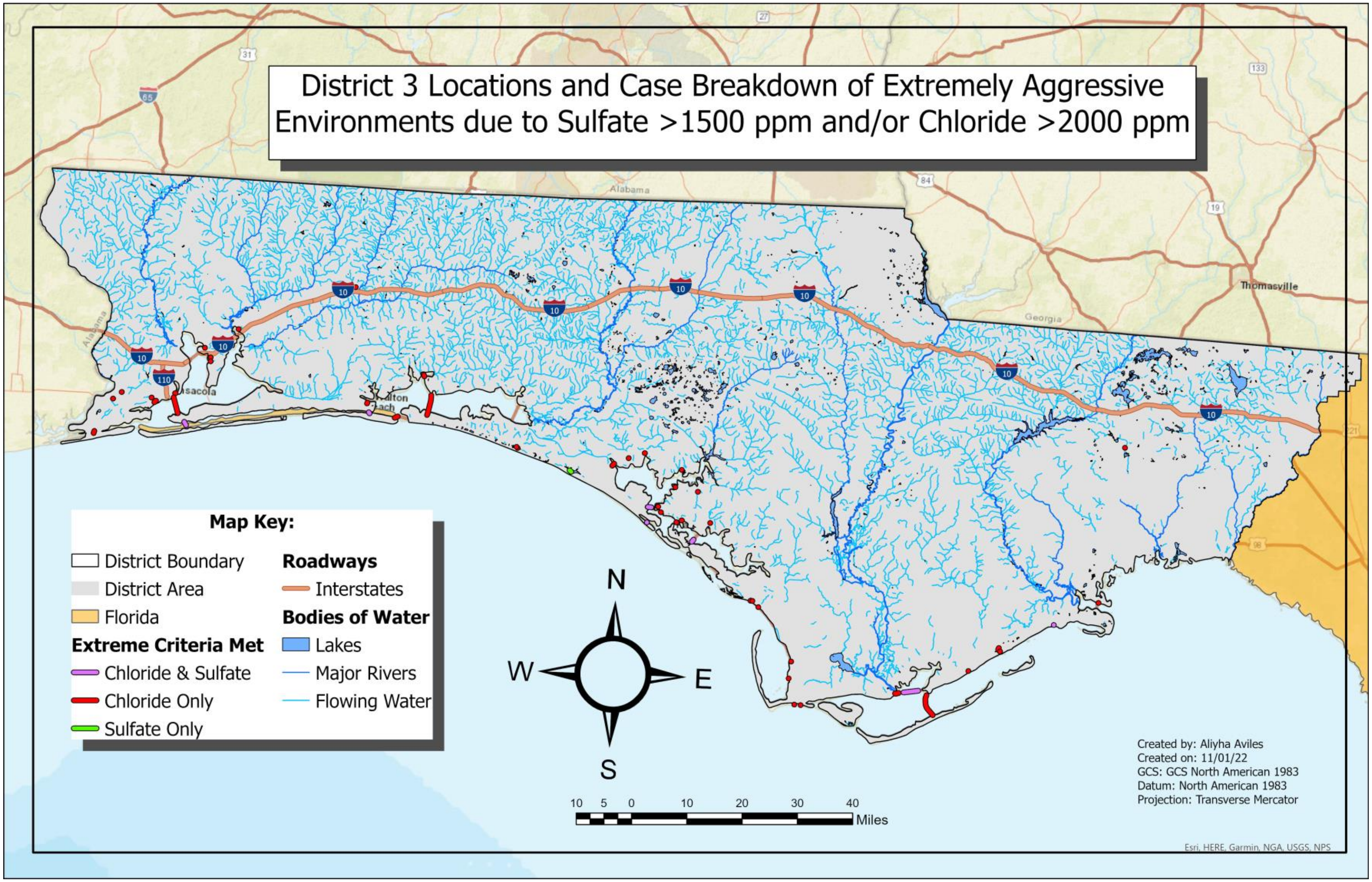
Miles
Map Key:
District Boundary
District Area
Florida
Enviroment Aggressiveness
Extreme
Moderate
Slightly
Roadways
Interstate
Bodies of Water
Lakes
Major Rivers
Flowing Water
N
W
E
S
75
275
4
Old Tampa
Hillsborough Bay
Petersburg
Tampa Bay
Gibsonton
Created by: Aliyha Aviles
Created on: 11/01/22
Spatial Reference
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS


District 1 Locations and Case Breakdown of Extremely Aggressive Environments due to Sulfate > 1500 ppm and/or Chloride >2000 ppm
New Port Richey
Holiday
Lutz
Zephyrhills
Palm Harbor
Citrus Park
Temple Terrace
Oldsmar
Safety Harbor
Plant City
Clearwater
Tampa
Brandon
Riverview
Seminole
Pinellas Park
Boyette
St Petersburg
Sun City Center
Kissimmee
St Cloud
Palm Bay
Bokeelia
St James
4
275
75
N
W
E
S
Map Key:
District Boundary
District Area
Florida
Extreme Criteria Met
Chloride & Sulfate
Chloride Only
Sulfate Only
Roadways
Interstate
Florida Bodies of Water
Lakes
Major Rivers
Flowing Water
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator
10 5 0 10 20 30 40
Miles
Esri, HERE, Garmin, NGA, USGS, NPS



District 2 Locations and Case Breakdown of Extremely Aggressive Environments due to Sulfate > 1500 ppm and/or Chloride >2000 ppm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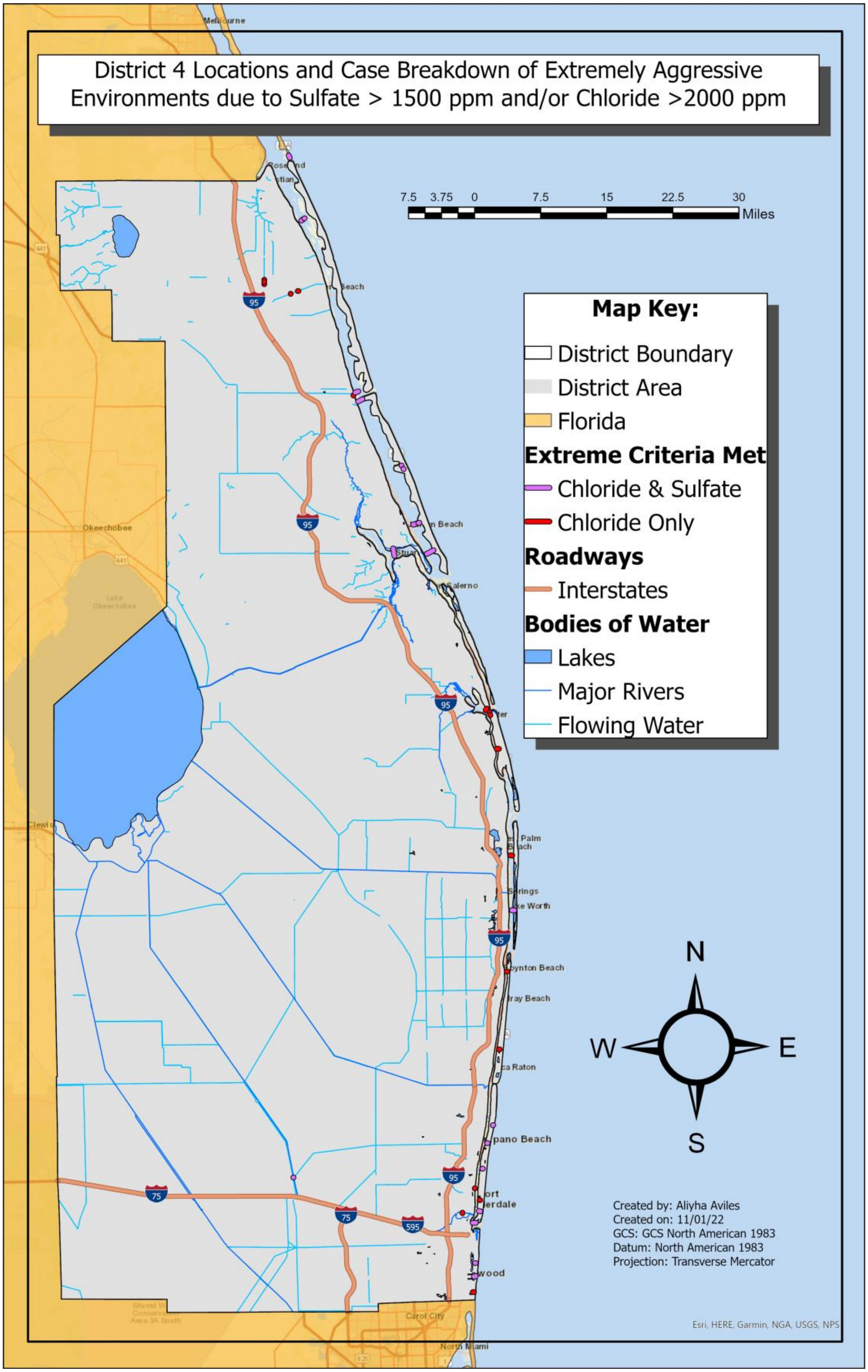
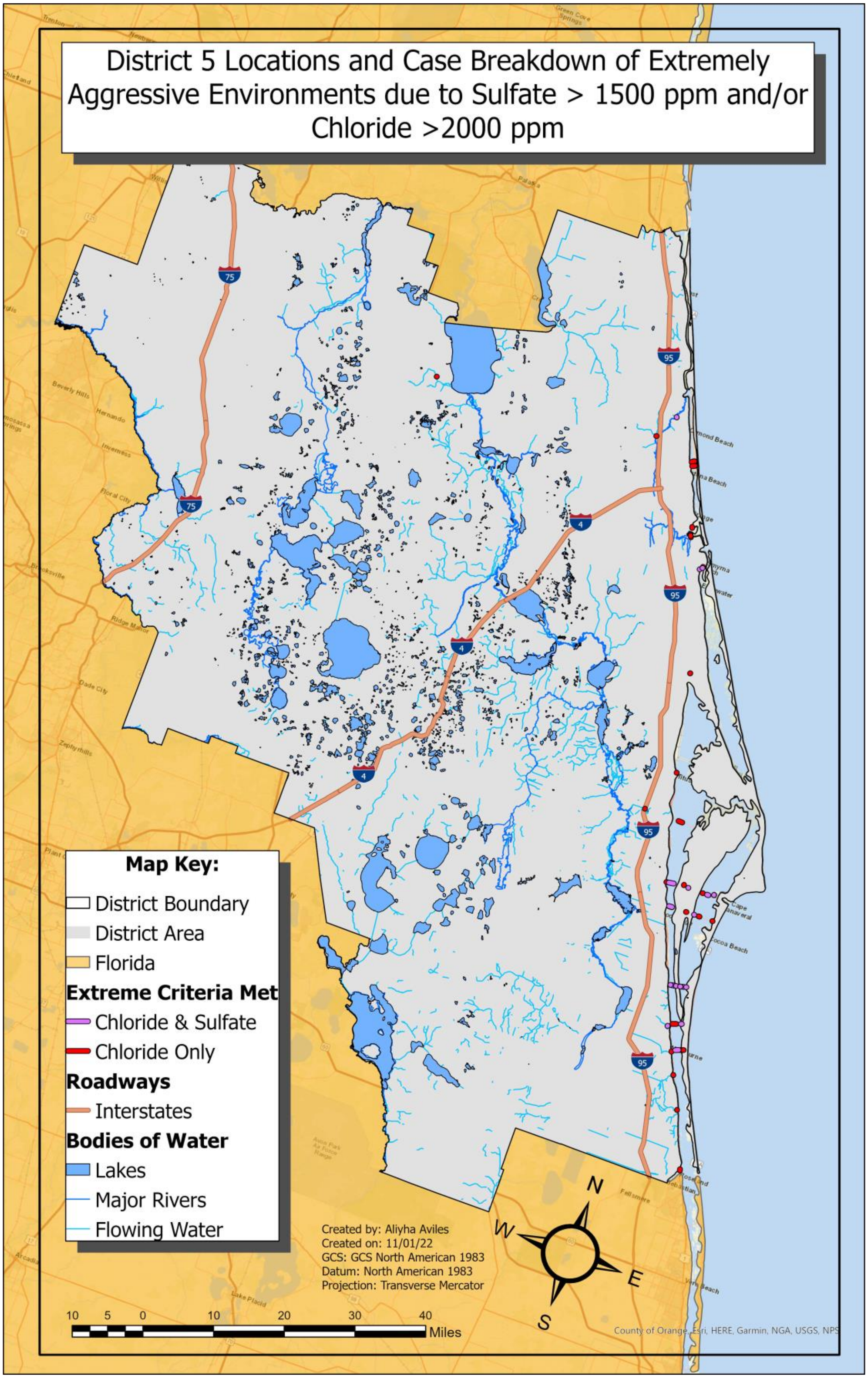
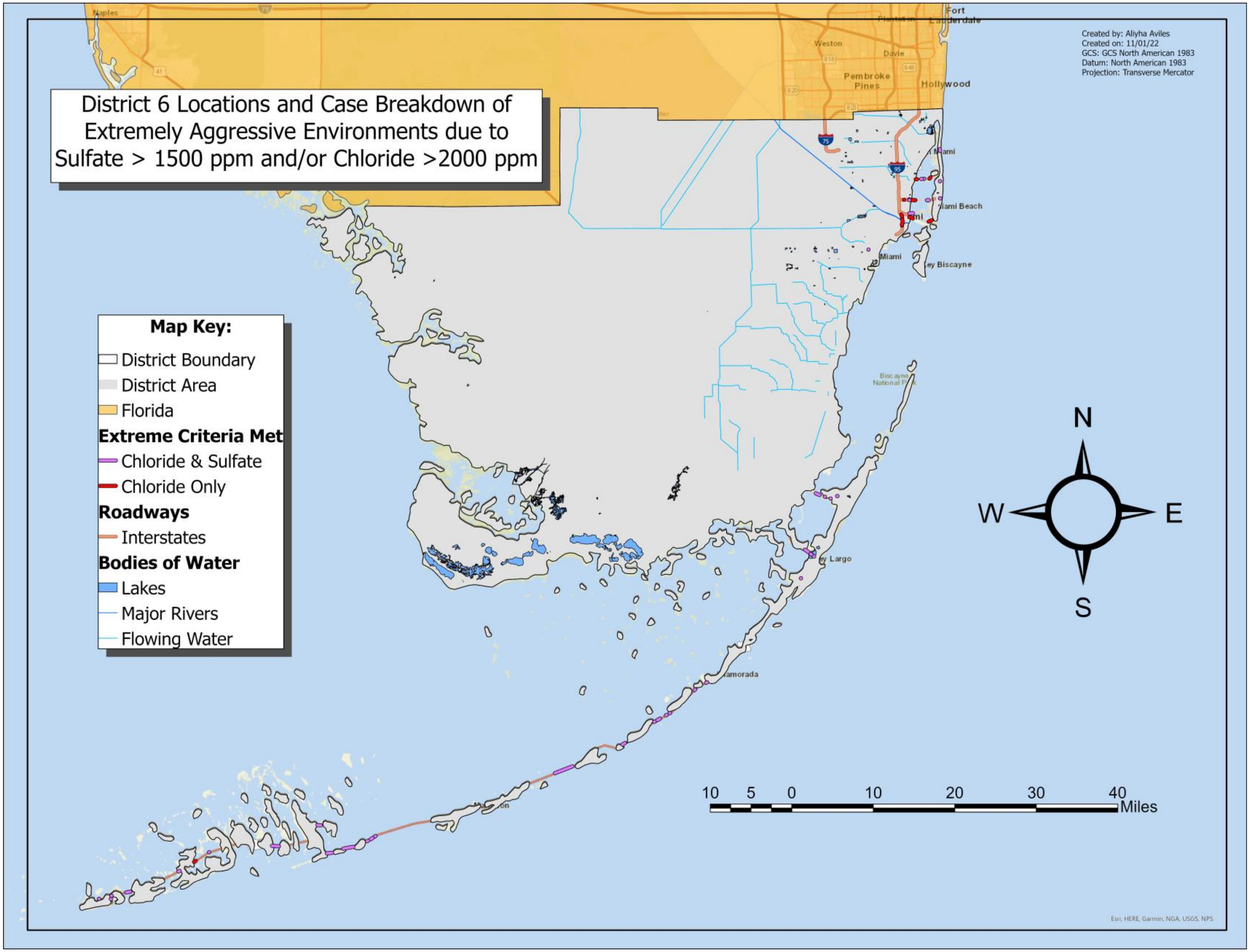

District 4 Locations and Case Breakdown of Extremely Aggressive Environments due to Sulfate > 1500 ppm and/or Chloride >2000 ppm
7.5 3.75 0 7.5 15 22.5 30
Miles
Map Key:
District Boundary
District Area
Florida
Extreme Criteria Met
Chloride & Sulfate
Chloride Only
Roadways
Interstates
Bodies of Water
Lakes
Major Rivers
Flowing Water
N
W
E
S
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS
Melbourne
Okeechobee
Lake Okeechobee
Salerno
Springs
Lake Worth
Boynton Beach
Delray Beach
Boca Raton
Pompano Beach
Fort Lauderdale
Carol City
North Miami
95
75
595
441



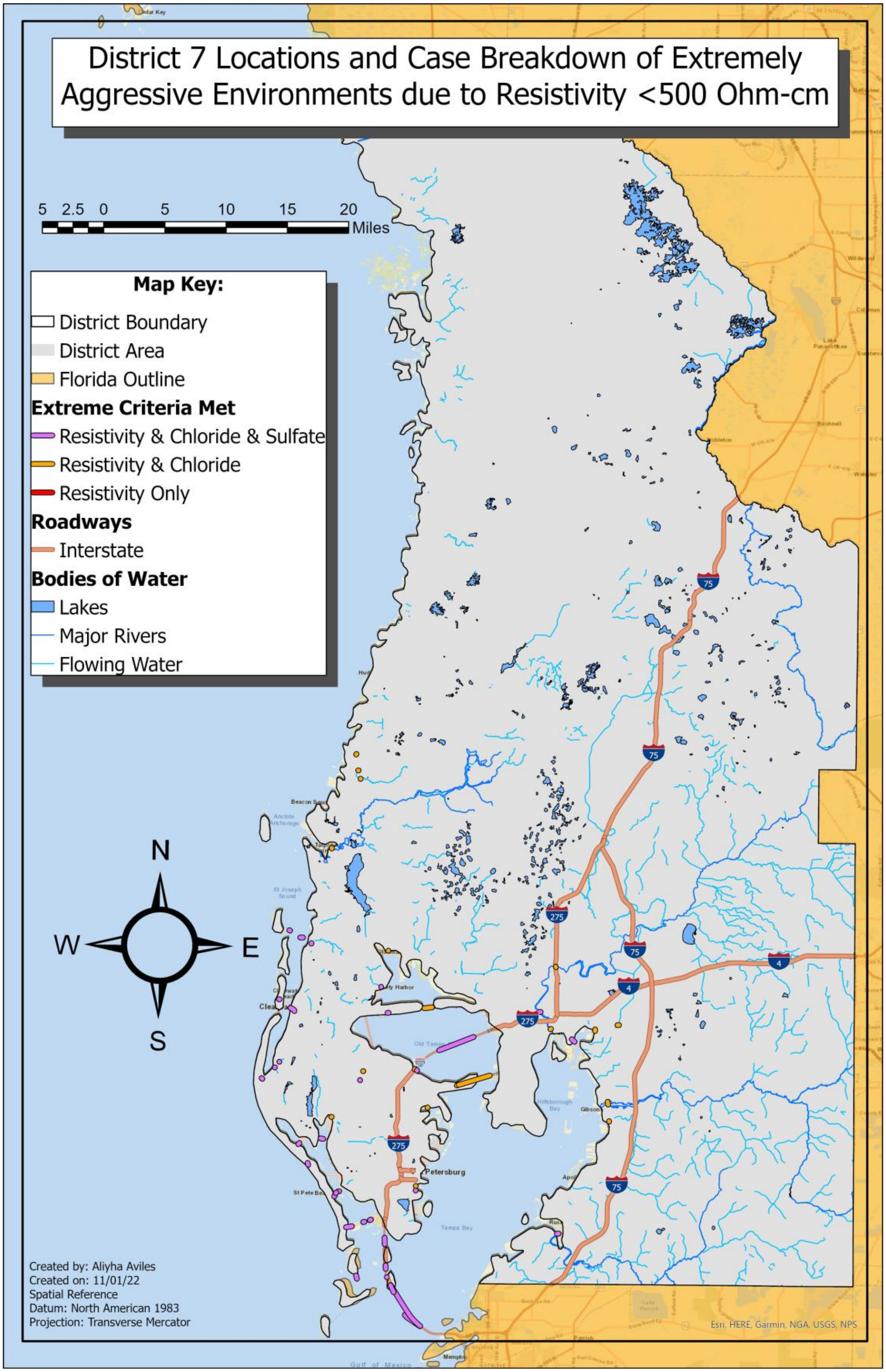
District 5 Locations and Case Breakdown of Extremely Aggressive Environments due to Sulfate > 1500 ppm and/or Chloride >2000 ppm

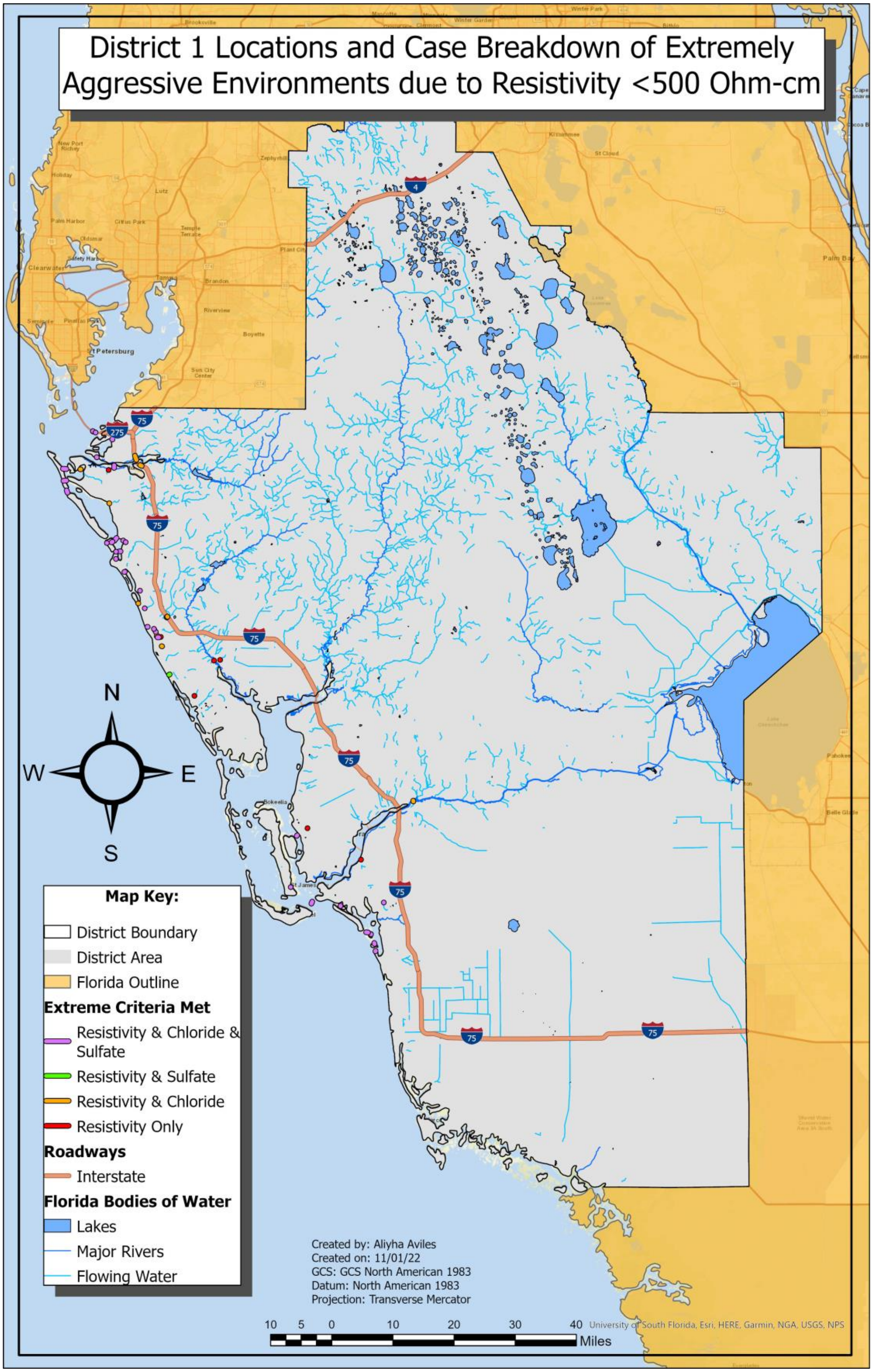
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator

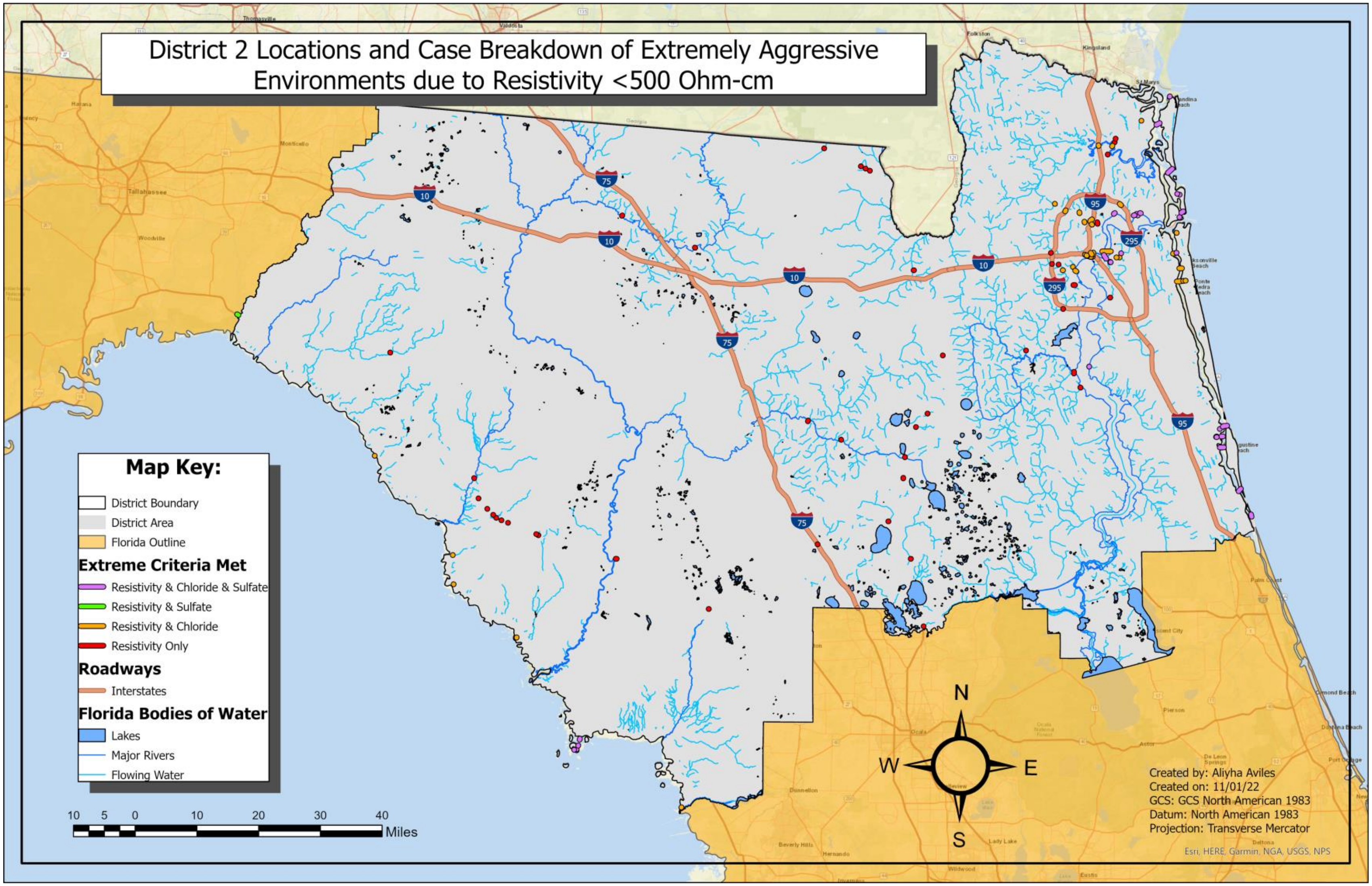
County of Orange, Esri, HERE, Garmin, NGA, USGS, NPS



District 6 Locations and Case Breakdown of Extremely Aggressive Environments due to Sulfate > 1500 ppm and/or Chloride >2000 ppm


District 7 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm
5 2.5 0 5 10 15 20
Miles
Map Key:
District Boundary
District Area
Florida Outline
Extreme Criteria Met
Resistivity & Chloride & Sulfate
Resistivity & Chloride
Resistivity Only
Roadways
Interstate
Bodies of Water
Lakes
Major Rivers
Flowing Water
N
W
E
S
75
275
4
Cedar Key
Bushnell
Webster
Beacon Sq
Anclote Anchorage
St Joseph Sound
Safety Harbor
Old Tampa
Hillsborough Bay
Gibson
Petersburg
St Pete Be
Tampa Bay
Gulf of Mexico
Memphis
Created by: Aliyha Aviles
Created on: 11/01/22
Spatial Reference
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS


District 1 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm
Map Key:
District Boundary
District Area
Florida Outline
Extreme Criteria Met
Resistivity & Chloride & Sulfate
Resistivity & Sulfate
Resistivity & Chloride
Resistivity Only
Roadways
Interstate
Florida Bodies of Water
Lakes
Major Rivers
Flowing Water
N
W
E
S
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator
10 5 0 10 20 30 40
Miles
University of South Florida, Esri, HERE, Garmin, NGA, USGS, NPS
4
75
275
St Petersburg
Tampa
Clearwater
Bokeelia



District 2 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm

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Created on: 11/01/22
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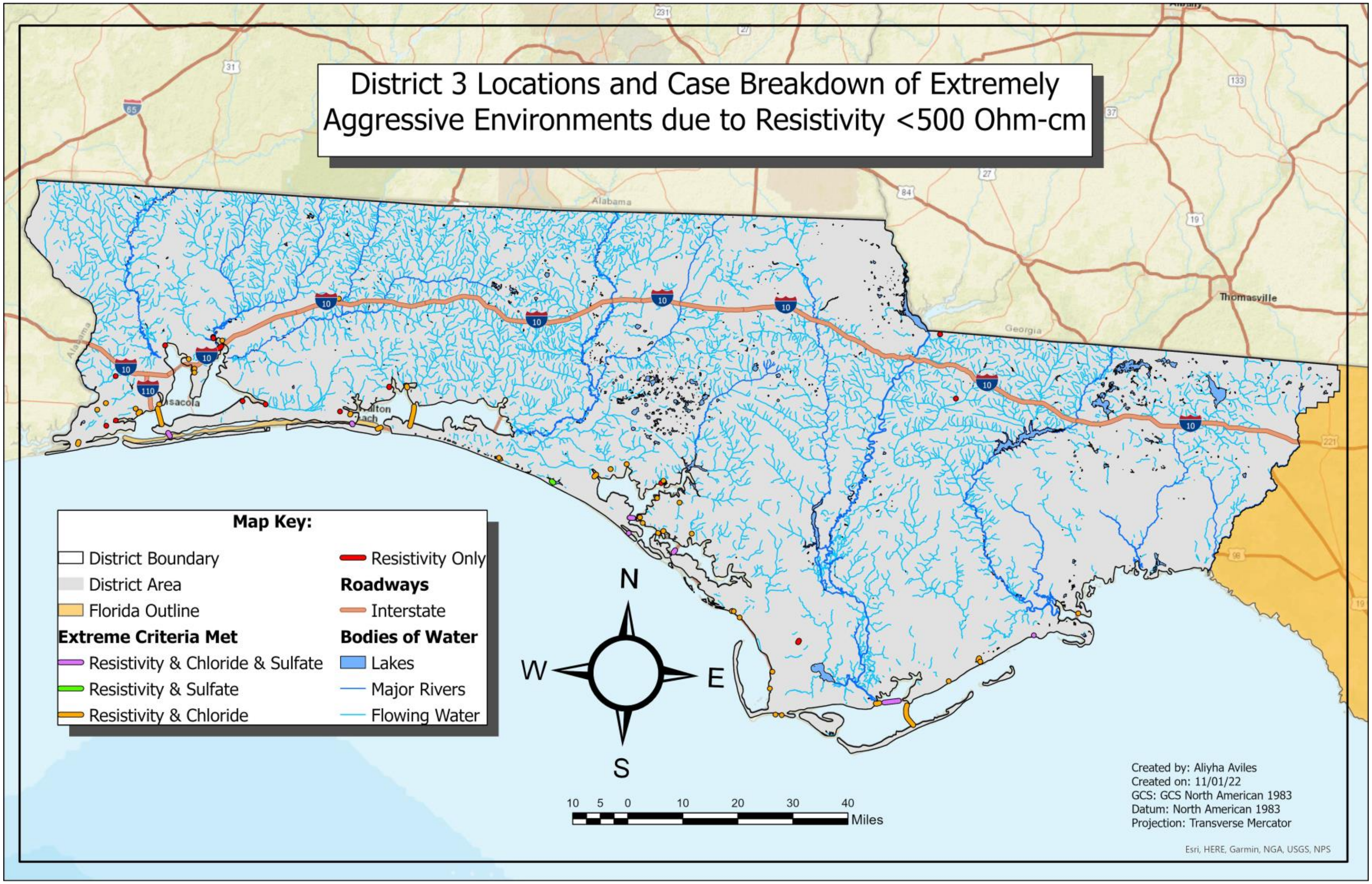
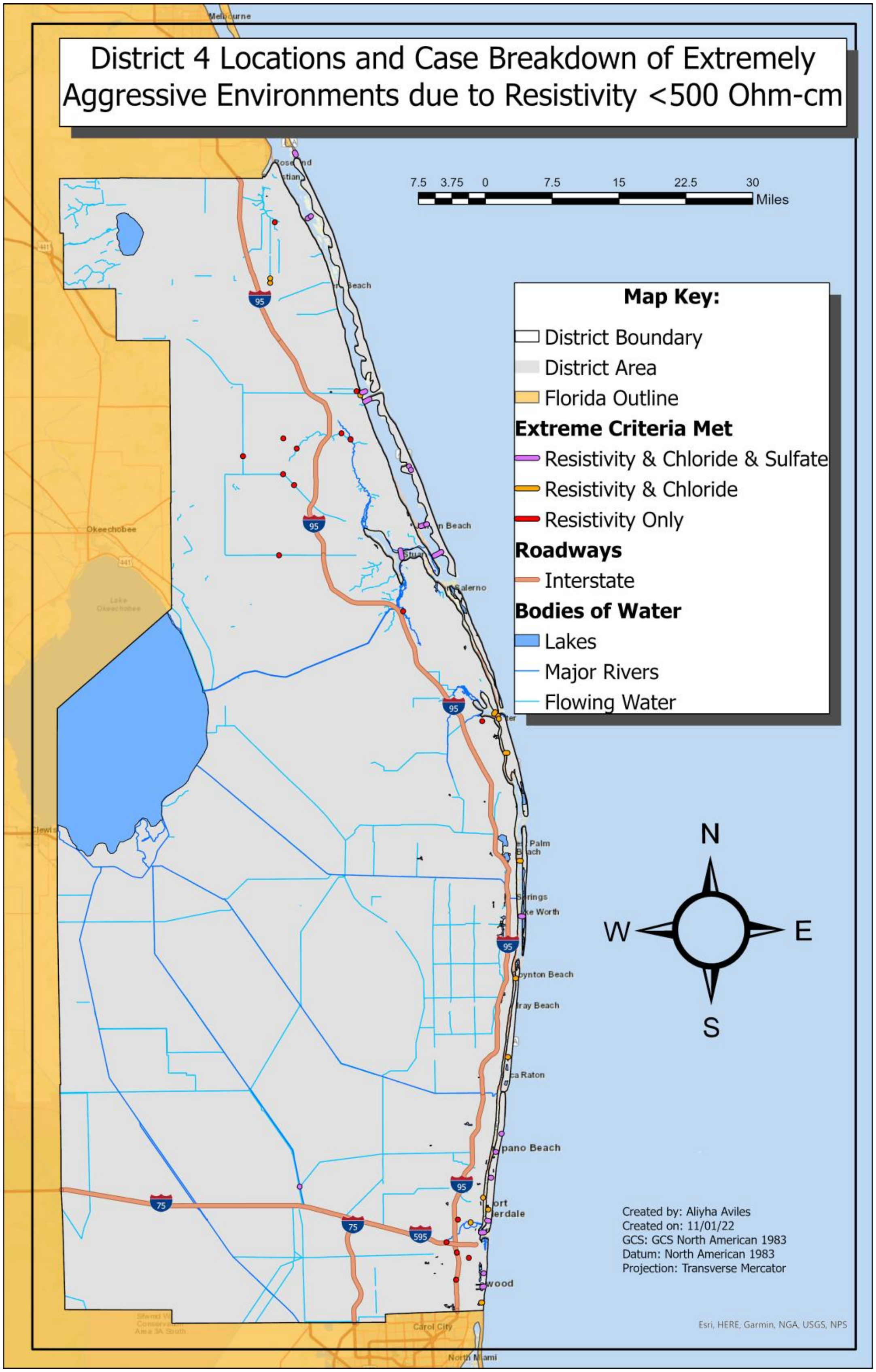
Datum: North American 1983
Projection: Transverse Mercator



District 3 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm

Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator

Esri, HERE, Garmin, NGA, USGS, NPS


District 4 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm
Map Key:
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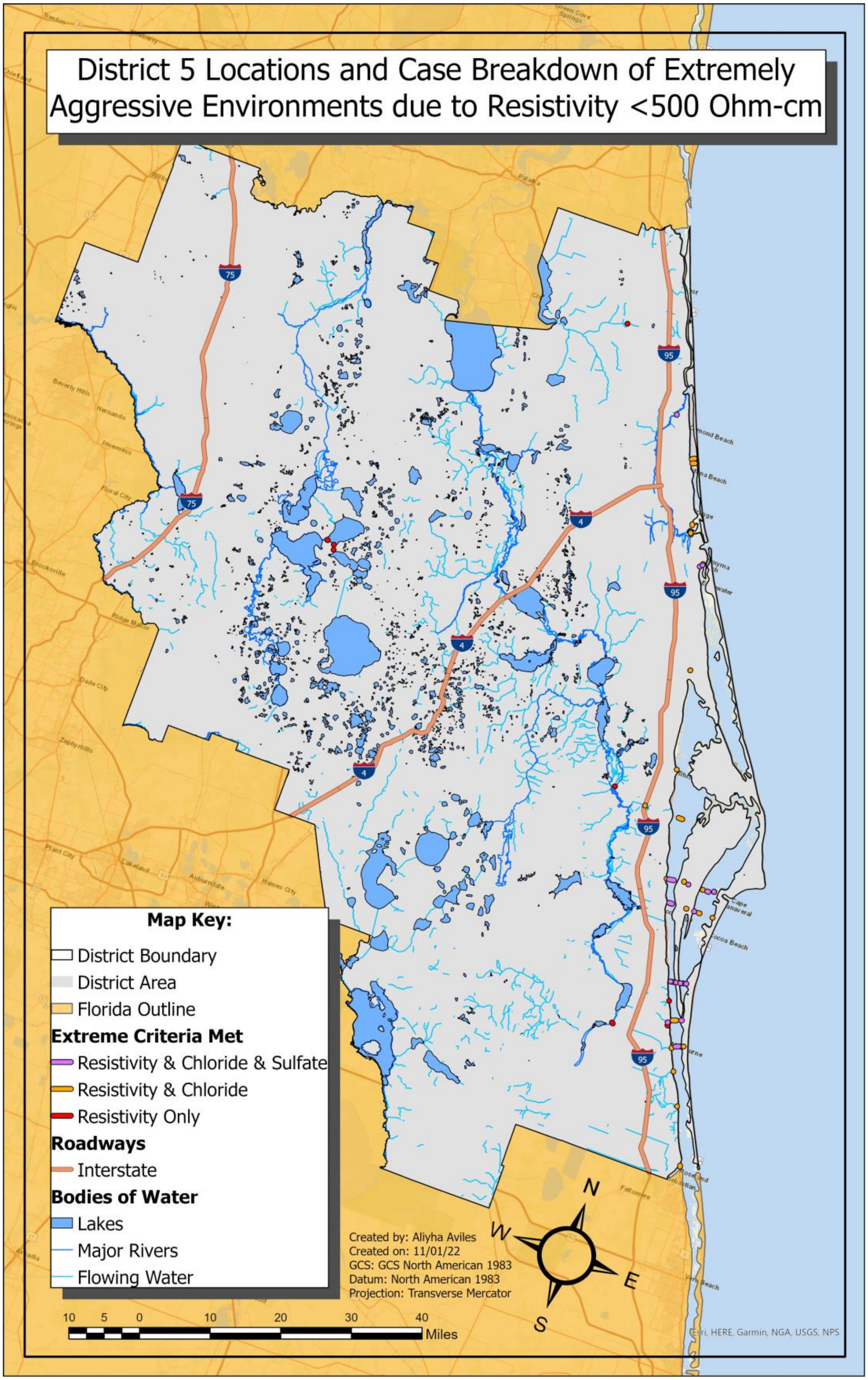
District Area
Florida Outline
Extreme Criteria Met
Resistivity & Chloride & Sulfate
Resistivity & Chloride
Resistivity Only
Roadways
Interstate
Bodies of Water
Lakes
Major Rivers
Flowing Water
7.5 3.75 0 7.5 15 22.5 30
Miles
N
W
E
S
95
75
595
Melbourne
Okeechobee
Palm Beach
Boynton Beach
Delray Beach
Boca Raton
Pompano Beach
Fort Lauderdale
Hollywood
Carol City
North Miami
Stuart
Salerno
Created by: Aliyha Aviles
Created on: 11/01/22
GCS: GCS North American 1983
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS



District 5 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm

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Created on: 11/01/22
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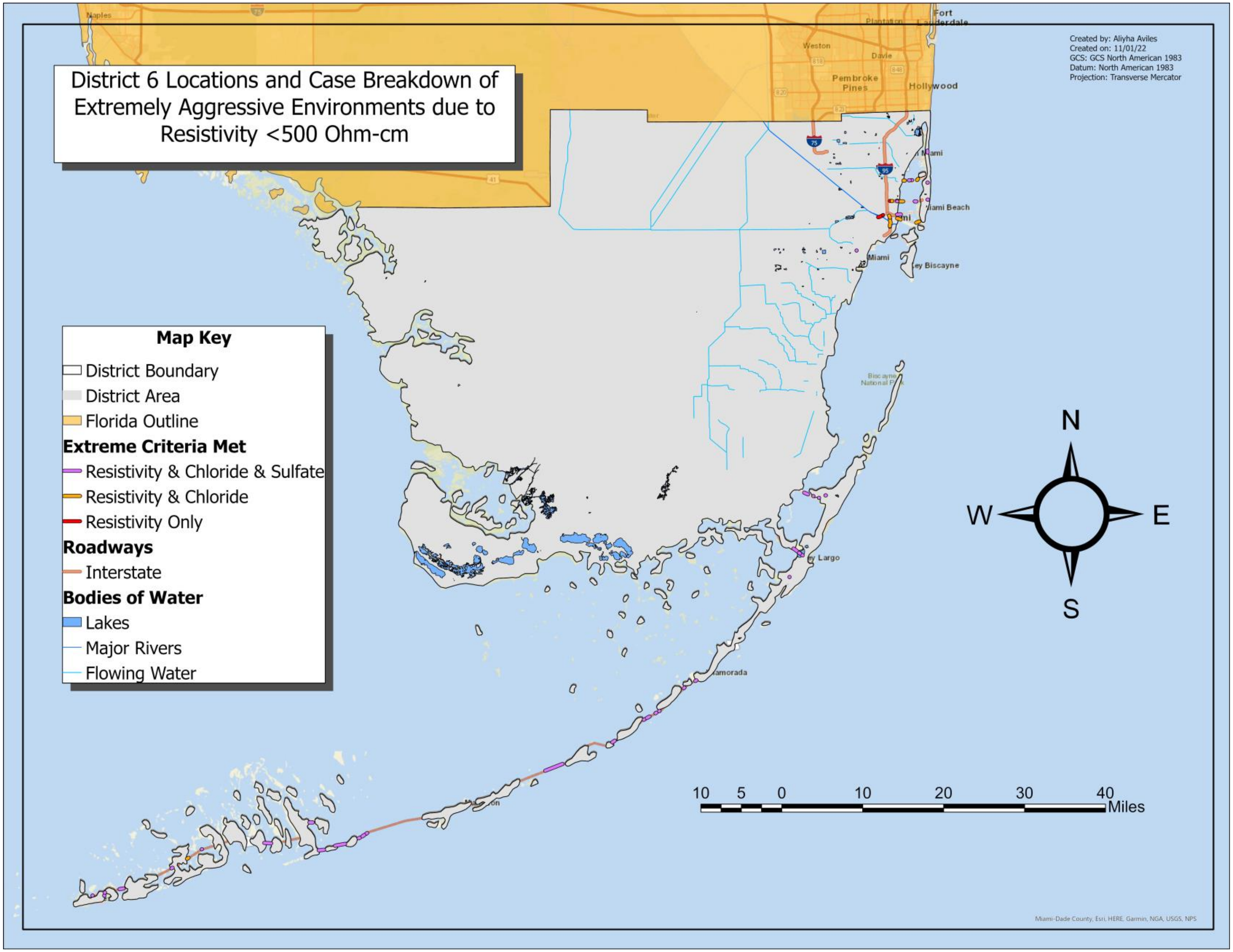
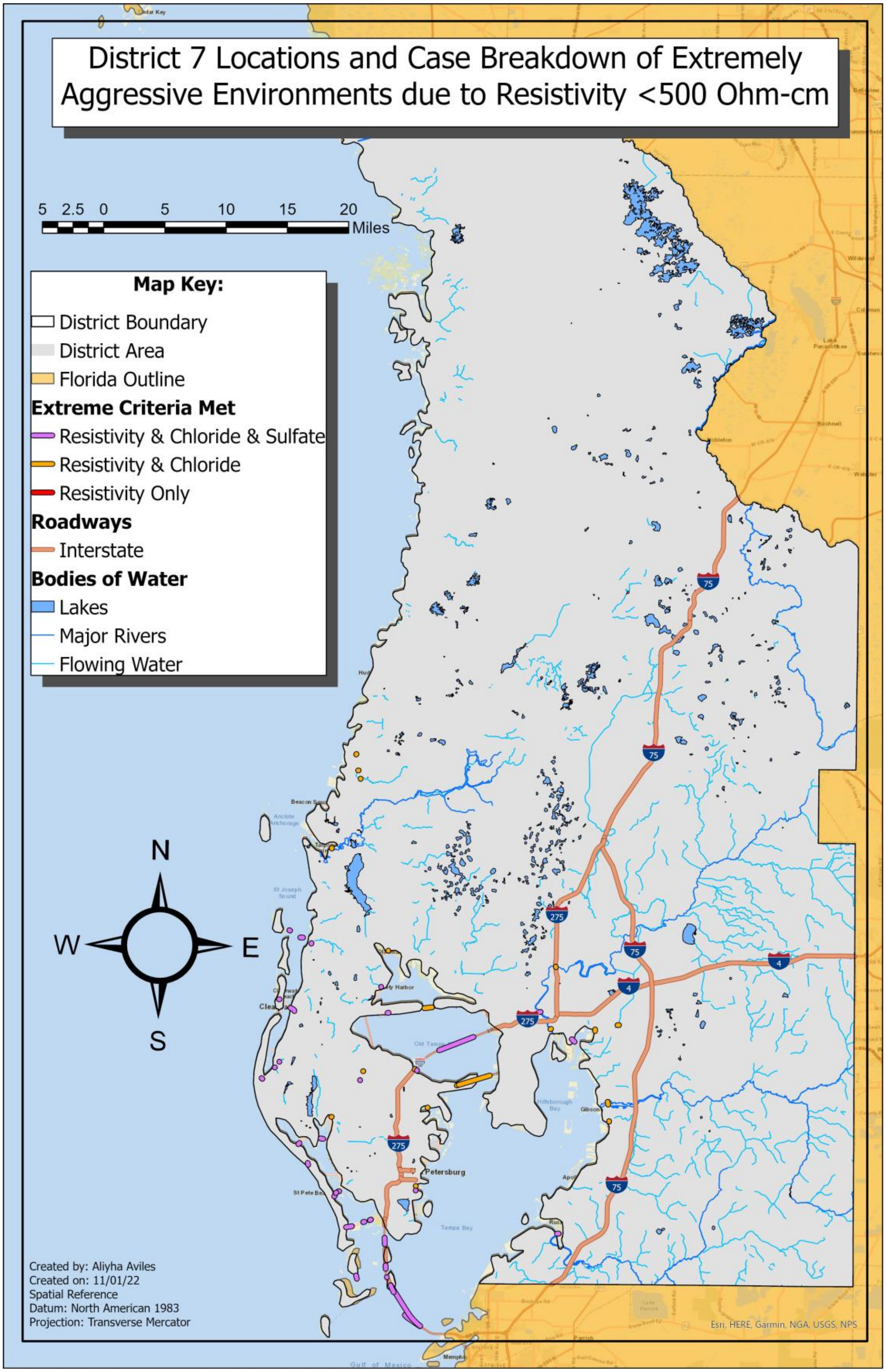
Datum: North American 1983
Projection: Transverse Mercator



District 6 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm


District 7 Locations and Case Breakdown of Extremely Aggressive Environments due to Resistivity <500 Ohm-cm
5 2.5 0 5 10 15 20
Miles
Map Key:
District Boundary
District Area
Florida Outline
Extreme Criteria Met
Resistivity & Chloride & Sulfate
Resistivity & Chloride
Resistivity Only
Roadways
Interstate
Bodies of Water
Lakes
Major Rivers
Flowing Water
N
W
E
S
75
275
4
Petersburg
Tampa Bay
Hillsborough Bay
Old Tampa
Gulf of Mexico
Created by: Aliyha Aviles
Created on: 11/01/22
Spatial Reference
Datum: North American 1983
Projection: Transverse Mercator
Esri, HERE, Garmin, NGA, USGS, NPS