Lightweight Concrete for Tennessee Bridge Decks

Final Report

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16. Abstract

The major focus of the research performed on the project described in this Final Report was directed toward learning more about the effective use of a ternary blend mix for lightweight concrete, including the identification of an surface resistivity (SR) value that could be reasonably chosen as a lower limit expectation for bridge deck concrete.

Based on available literature, the choice of expanded slate as the lightweight coarse aggregate, rather than expanded shale or expanded clay is a sound one. However, there are some special considerations that affect the use of lightweight concrete (LWC) and which have some influence on any chosen acceptance criteria. Based both on research reported in available literature and experience on this project, one can argue that proper aggregate saturation is the primary quality control concern for LWC. The positive effect of internal curing only occurs with properly saturated aggregate. Poorly saturated aggregate leads to difficulty in pumping.

One motivating objective of this project was to identify a reasonable minimum SR value to specify for mix designs to achieve an adequate resistance to chloride ion penetration. Work to accomplish this objective evolved into a study of the effects several variables have on Surface Resistivity. However, the surprising discovery of the large effect that cement brand had on the test results, coupled with the differences between lab and field mixes, made the specification of a lower bound SR value essentially impossible. The report also found that shrinkage of properly saturated lightweight concrete is not appreciably different from that of normal weight concrete.

The inspection of five bridge decks indicated only minor cracking but raised potential concerns because of one difference between lightweight and normal weight aggregates. Lightweight aggregate tends to float closer to the top than normal weight, a phenomenon which is particularly exacerbated by improper aggregate saturation. The grinding exposes the lightweight aggregate near the surface which is then ground smooth. This aggregate exposure is a potential issue for porous aggregate as the pore connectivity potentially allows some chloride ion penetration into the deck. Whether or not this is a problem was not reviewed as part of this report.

17. Key Words
Lightweight Concrete, LWC, Surface Resistivity, Mix Design, Chloride Ion Penetration

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DISCLAIMER

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ACKNOWLEDGEMENT

The research reported herein was sponsored by the Tennessee Department of Transportation and the Federal Highway Administration; their support is acknowledged with appreciation. This project grew out of an earlier project—actually two, two-year projects—involving testing of sample cylinders collected from actual bridge deck placements. The project would never have seen the light of day but for the insight and interest of Ed Wasserman. So, once again, special thanks are extended to Edward Wasserman, retired long-time Director of Structures, for the initiation of the research that led to this project and for his continuous support and encouragement over the past two decades. Funding for this project would not have occurred without the specific involvement and support of Wayne Seger, current Director of Structures, who is continuing the tradition begun many years ago by Henry Derthick and extending through the long tenure of Ed Wasserman, a tradition of innovation and foresight and support of research. We appreciate very much his support and continued cooperation. Appreciation is also extended particularly to Brian Egan and Danny Lane. Danny got the earlier project started and supported it throughout its four year duration. Brian Egan, first as Director of Construction and, currently, as Director of Materials and Tests has been a key source of assistance and support throughout the past six years. John Steele with FHWA has been a constant supporter of this research, for which he is very much appreciated. Darrell Bost, Joseph Kerstetter, Jamie Waller, and Heather Purdy have all been involved in one way or another. Stephanie Vincent continues to be at once competent, supportive, and simply on top of what's going on, not only on this project but on the previous projects. She is a genuine treasure.

The success of the project depended heavily on the cooperation of both field personnel and TDOT Region 1 personnel, almost too many to mention. At the risk of leaving out someone who played a key role, lab personnel, particularly Billy Goins, at Region 1, kept it going. Joseph Kerstetter in the materials division at TDOT headquarters was most helpful in providing information on the concrete mixes used on the individual deck pours. Pam Porter has been a reliable source of help and advice when needed.

The folks involved in the deck replacement for the I-40 Bridge over the French Broad River were extremely helpful. Again, at the risk of leaving out somebody who should be included, the following people clearly should be thanked: Mike Miller, Thompson Engineering; Jeff Walker, Ray Bell Construction; Andy Smith, Ready Mix USA; Tracie Widner, TDOT; and Jeremiah Davis, AMEC.

Most of the work on any research project is done by graduate research assistants (GRAs). Darren Haun was the first, followed by Marvin Martinez and Andrew Wagner. Andrew in particular deserves a high portion of credit for his work, his intense interest, and his unflagging energy in every facet of the research. Tyler Henderson, who was supported by another assistantship, volunteered a significant amount of time in the summer of 2015 assisting Andrew in inspecting five bridges.

Finally, a disclaimer is in order, namely that the opinions stated herein are those of the researchers and do not necessarily reflect those of either TDOT or FHWA.

PERSONAL ACKNOWLEDGEMENT

The preceding "Acknowledgement" represents a genuine effort to acknowledge, in a professional way, the researchers' appreciation to those people who played important roles in the research just completed. This "Personal Acknowledgment", on the other hand, is my—Ed Burdette's—attempt to convey my genuine and heartfelt appreciation to those people whose support for a long time has played an important part in my professional life. As this is almost certainly the last Final Report to TDOT that I will write, I feel a personal need to close out my research career by saying thanks.

My research with TDOT (then the Tennessee Highway Department) began in 1969 with the beginning of Full Scale Bridge Testing, a project that culminated in 1970 with the tests to failure of four highway bridges in Franklin County. That research project was arguably the most important in my career—and I thank Henry Derthick in particular for his support, criticism, and insight. I was a bit awed by Henry early on—a sort of "fear of God" feeling; later along the way he became and remains a personal friend. I look back with much appreciation for the contribution he made to my professional career and with admiration for him as a person.

Then, some years later, Ed Wasserman began to play a similar role: supporter, advocate, critic, advisor, and personal friend. Ed became, and still is, a widely recognized, highly respected member of the professional bridge design community, a fact that became particularly apparent to me when, at his request, I presented results of our research to a TRB committee that Ed was a member of, and even more so when I attended a panel discussion on Integral Abutment Jointless Bridges at a conference in Baltimore. The "panel" may as well have been one person; all questions were directed to Ed! He has brought a national reputation of innovative excellence to TDOT. It has been a personally rewarding experience to have been associated with him and to enjoy his friendship for many years.

As I type this I realize that I could write an entire tome about various TDOT people that I have come to know and to whom I owe a debt of gratitude. But I won't. Many of those TDOT folks are mentioned in the "Acknowledgment" above. So I close with a genuine thanks to a number of people at the Center for Transportation Research (CTR). Tammy Enix and Carol Hatmaker have tried very hard to keep me out of trouble by being sure that I touch all the right bases and don’t overspend the budget. Stephanie Vincent, mentioned above, played a similar role at TDOT. I have had a rewarding and, I would like to think, productive relationship with TDOT for several decades. So to all the people mentioned in these acknowledgments, as well as to several people that I probably have forgotten to mention: THANKS.

Executive Summary

The research project which is the subject of this Final Report grew out of two, two-year projects which were directed toward evaluating the quality of concrete being placed on Tennessee bridge decks in terms of the ability of the concrete to resist the penetration of chloride ions. This resistance was measured by the conventional method known as the Rapid Chloride Ion Penetration Test (RCP Test) and the newer Surface Resistivity Test (SR Test). Near the end of that testing, the deck of the SR 56 Bridge over the Caney Fork River, the Hurricane Bridge, in Dekalb County was being replaced with lightweight concrete. Coincidentally, a lightweight concrete replacement deck for the I-40 Bridge over the French Broad River in East Tennessee was about to get started. Both of these decks were slated to be cast with a ternary blend concrete with cementitious material consisting of cement, ground granulated blast furnace slag, and fly ash. As a motivating factor to achieve a concrete with high resistance to the penetration of chloride ions, a target value of SR was set such that a measured SR of that value or greater would result in a bonus. The major focus of the research performed on the project described in this Final Report was directed toward learning more about the effective use of a ternary blend mix for lightweight concrete, including the identification of an SR value that could be reasonably chosen as a lower limit expectation for bridge deck concrete.

Very few things on this project went smoothly. Unforeseen and for a long time undetected problems with the moist room in the new Civil Engineering Building led at once to some confusion and disappointing results and to some potentially important information in terms of measurement and specification of SR values as a construction acceptance criterion. The details of the research are presented in this Final Report; the practical results of the research are briefly summarized in the following paragraphs.

(1) There is nothing inherent in the make-up of lightweight concrete to suggest that the use of it in either replacement decks or newly built decks is in any way inappropriate. Based on available literature, the choice of expanded slate as the lightweight coarse aggregate, rather than expanded shale or expanded clay is a sound one. However, as noted in the following paragraphs, there are some special considerations that affect the use of lightweight concrete and which have some influence on any chosen acceptance criteria for lightweight concrete (LWC).

(2) Based both on research reported in available literature and experience on this project, one can argue that proper aggregate saturation is the primary quality control concern for LWC. The positive effect of internal curing only occurs with properly saturated aggregate. Poorly saturated aggregate leads to difficulty in pumping; the pressure in the pumping process forces water into the partially open voids in the aggregate, thus reducing the amount of water available to enhance the lubricating effect of the cementitious paste.

(3) One motivating objective of this project was to identify a reasonable minimum SR value to specify for mix designs to achieve an adequate resistance to chloride ion penetration. Work to accomplish this objective evolved into a study of the effects a number of variables have on Surface Resistivity, the results of which are reported herein. However, the surprising discovery of the large effect that cement brand had on the test results, coupled with the differences between lab and field mixes, made the specification of a lower bound SR value essentially impossible. A lower bound of 18 would not be unreasonable for Buzzi mixes; based on the tests performed on this project, that lower bound would be almost unreachable for Cemex mixes.

(4) Shrinkage of properly saturated lightweight concrete is not appreciably different from that of normal weight concrete. At 28-days the shrinkage of lightweight concrete may actually be a bit lower than that of comparable normal weight concrete; however, the final shrinkage would be expected to be somewhat larger than that of normal weight. The effects of some variables on shrinkage are shown in the report in the graphs of shrinkage vs. time.

(5) The inspection of five bridge decks indicated only minor cracking but raised potential concerns because of one difference between lightweight and normal weight aggregates. Lightweight aggregate tends to float closer to the top than normal weight, a phenomenon which is particularly exacerbated by improper aggregate saturation. Although contactors have reported that it is often cheaper to get a deck finished and later grind it smooth rather than meet profile requirements, the grinding exposes the lightweight aggregate near the surface which is then ground smooth. This aggregate exposure is a potential issue for porous aggregate as the pore connectivity potentially allows some chloride ion penetration into the deck. Whether or not this is a problem is unknown.

1.0 Background and Introduction

Recognition of the need for durable concrete in bridge decks is hardly new; however, an enhanced recognition and a commitment to improve durability has increased significantly in the past two decades. Twelve years ago, research focusing on concrete durability, sponsored by the Tennessee Department of Transportation (TDOT) and the Federal Highway Administration (FHWA), was begun at The University of Tennessee (UT). A major focus of that research was developing a concrete mix that had a high resistance to the penetration of chloride ions as measured by the Rapid Chloride Ion Penetration Test, referred to herein as the RCP test. One of the conclusions from that research was that a ternary blend mix consisting of cement, ground granulated blast furnace slag, and fly ash produced a concrete with significantly higher resistance to penetration of chloride ions as indicated by lower RCP values.

As the original research was winding down, the recognition emerged that no information was available regarding the current quality of concrete, in terms of resistance to penetration of chloride ions, being used on Tennessee bridge decks. Thus was born another project, which evolved into two, two year projects, in which 13, 4” x 8” cylinders were cast at the site of bridge deck placements all over the state and sent to UT, via Region 1, for RCP testing and surface resistivity (SR) testing in order to establish a correlation between SR and RCP readings. That project ended two years ago, August 31, 2013.

Near the end of the second project, the Hurricane Bridge on State Route 56 in DeKalb County was undergoing a deck replacement which used lightweight aggregate concrete, aggregate consisting of expanded slate supplied by Carolina Stalite. Edward Wasserman, long-time Head of TDOT’s Structures Division, had just retired and was consulting with Modjeski and Masters, the firm that had the engineering and inspection contract for the bridge deck construction. Through his familiarity with the ongoing research, he worked with UT researchers, TDOT Structures (Wayne Seger), Materials (Gary Head), and Construction (Brian Egan) to specify a ternary blend lightweight aggregate mix for the replacement deck. Work on that project led to the current project which began August 1, 2013, and ends July 31, 2015. The fact that the deck replacement for the I-40 Bridge over the French Broad River was to be a ternary blend lightweight aggregate mix was a catalyst that added immediacy for more research needed on that subject. Wayne Segar had added to the concrete specifications the caveat that concrete with SR readings above a specified minimum value would receive a bonus. This caveat added incentive to the contractor to develop a high quality concrete mix.

The scope of testing on this project consisted of surface resistivity (SR) tests, RCP tests, and shrinkage tests. The compressive strength was also measured, but reaching the 4,000 psi required by the project specifications was very rarely an issue. The main focus of the research was on the chloride ion penetrability of lightweight concrete. The RCP and SR tests are electrical indications of chloride ion penetrability of concrete. High impedance to the penetration of chloride ions will better protect the reinforcing steel. These test results are, essentially, inversely proportional to each other; the SR test measures the resistivity of the specimen compared to conductance measured by the RCP. To confirm that there is a correlation between SR and RCP values for lightweight concrete, the two values were plotted and a correlation confirmed. Because of the far more user friendly test procedure for SR testing compared to RCP testing, SR tests were chosen by TDOT as the accepted measure of chloride ion penetrability.

Shrinkage measurements help to evaluate the potential for shrinkage cracking to occur. Shrinkage cracking could negatively affect the durability of the deck, as the cracks provide channels for potential hazards into the deck and closer to reinforcing steel. For the laboratory testing, accelerated shrinkage using a hot and dry environment was used.

The objectives of this research are directly quoted from the research proposal and are as follows; "The overall objective of the proposed research is to assess the effectiveness and feasibility of using lightweight concrete on Tennessee bridge decks, not only as replacement decks, but potentially as original decks in certain situations. Within this overall objective, there are three primary objectives: (1) Assess and monitor the ongoing performance of lightweight concrete decks currently in service; (2) assess, by appropriate SR and RCP tests, the quality of the concrete placed in the I-40 deck over the French Broad River and the deck on State Route 66 over the French Broad River; (3) Explore and evaluate the use of more than one lightweight coarse aggregate by performing tests on a number of lab mixes; (4) Identify a minimum SR value that can be specified in a design mix for lightweight concrete." Due partly to miscommunication and partly due to the fact that one of the SR 66 bridge decks, the later one placed, was normal weight concrete, no data were gathered from this work. Also, Objective No. 3 was deemed an inappropriate use of time and resources as Carolina Stalite's expanded slate is the aggregate of choice for lightweight decks in Tennessee. This Final Report addresses in some detail the other stated objectives.

From an environmental point of view, increasing the durability of bridge decks is important for two reasons: (1) maintenance costs are reduced and (2) this increased durability reduces the amount of cement which will be produced. As the production of Portland cement produces roughly 5% of carbon emissions in the United States, a reduction in cement production is environmentally positive. The use of a ternary blend is doubly beneficial in that fly ash and slag replace as much as 50% of the cement and, concurrently, dispose of waste products which are themselves potential polluters. Thus, while this TDOT–sponsored research, admittedly, was not born of environmental considerations, the overall result of the several years of research on concrete bridge decks done at UT is potentially significant in its potential to reduce carbon emissions in the state by some small degree.

2.0 Literature Review

Andrew Wagner, the lead Graduate Research Assistant (GRA) on the project since August 2014, conducted a thorough review of literature relating to the durability of lightweight concrete, specifically focusing on lightweight concrete used for bridge decks, and that review is included as a part of his M.S. thesis. That thesis is too long to be included with this Final Report as an attachment, but an electronic copy of the thesis has been sent to TDOT. In very brief summary, the following findings about the durability of lightweight concrete (LWC) are as follows.

(1) Expanded slate manufactured by Carolina Stalite is the lightweight aggregate of choice by TDOT; while the literature review looked at information about expanded shale and expanded clay, the focus was on expanded slate. Expanded slate's low absorbed moisture is good, indicating less pore connectivity compared to aggregates with higher absorbed moistures.

(2) While the porosity of the expanded slate is much greater than that of normal weight aggregate, the permeability of the lightweight aggregate concrete is typically about the same as that of its normal weight counterpart. Consistent with that fact is the finding that the chloride ion penetrability of LWC is not appreciably greater than that of NWC.

(3) The 28-day shrinkage of LWC generally is not greater—and may be somewhat less—than that for NWC. However, the long-term shrinkage is generally a small amount greater than the long-term shrinkage of NWC.

(4) Proper saturation of the lightweight aggregate before mixing is extremely important. Inadequate saturation of the aggregate potentially leads to difficulty pumping, to concrete that has lower resistance to the penetration of chloride ions, and potentially to higher shrinkage.

(5) The resistance of LWC to freezing and thawing is comparable to that of NWC. Both require air entrainment to assure adequate resistance to freeze-thaw cycles, and both are rendered adequate by the entrainment of the proper amount of air.

3.0 Test Results and Discussion

A series of tables and figures are presented to illustrate the results obtained in the research conducted on this project. In the interpretation of the test results, one unfortunate fact must be understood at the beginning. As described in earlier progress reports, the "moist room" for a good part of the project was inadequate. The moist room is located in the new John D. Tickle Building which opened in August 2013; the Civil and Environmental Engineering Department moved in for the beginning of the fall semester of 2013. All laboratory operations moved at that time. In the move the container for the lime bath sprung a leak that resisted repair, thus necessitating building a new container. In the meantime the new moist room, with an outside relative humidity gauge that read 100%, was used. Because of the presence of what appeared to be a state-of-the art curing facility, building a new lime bath container was not deemed an urgent priority. Unexpected readings of surface resistivity (SR) led the researchers to investigate the situation and, belatedly, they identified the source as a "moist room" with approximately 84% relative humidity. Thus, results of tests conducted on specimens cured in the inadequate moist room are labeled as MR-84 results. The SR readings for samples cured in MR-84 proved useful to illustrate the effects of curing on SR values, but they are otherwise meaningless. Samples cured in a lime bath are noted with LB. Results of surface resistivity tests are noted as SR, and tests results noted RCP are from Rapid Chloride Ion Penetration tests.

A table showing all results obtained on this research project are shown in Table 4 and Table 5, included at the end of this report. Due to the number of variables embedded in the results presented in this table, making meaningful interpretations is difficult. However, from the table it is clear that samples cured in MR-84 had much higher SR values than those cured in the lime bath, much higher than the 10% difference in SR values suggested in by the AASHTO specification.

3.1 SR versus RCP

A thorough study of the relationship between SR and RCP values was made for NWC in the two earlier projects, the second of which ended two years ago. No such comparison was intended in this project on lightweight concrete. However, because of the confusion surrounding the early results in the current project, confusion which stemmed from the inadequate moist room, a number of RCP tests were conducted for comparison with SR readings. A plot of the data from the tests of specimens cured in a lime bath is given in Figure 1. The correlation was excellent.

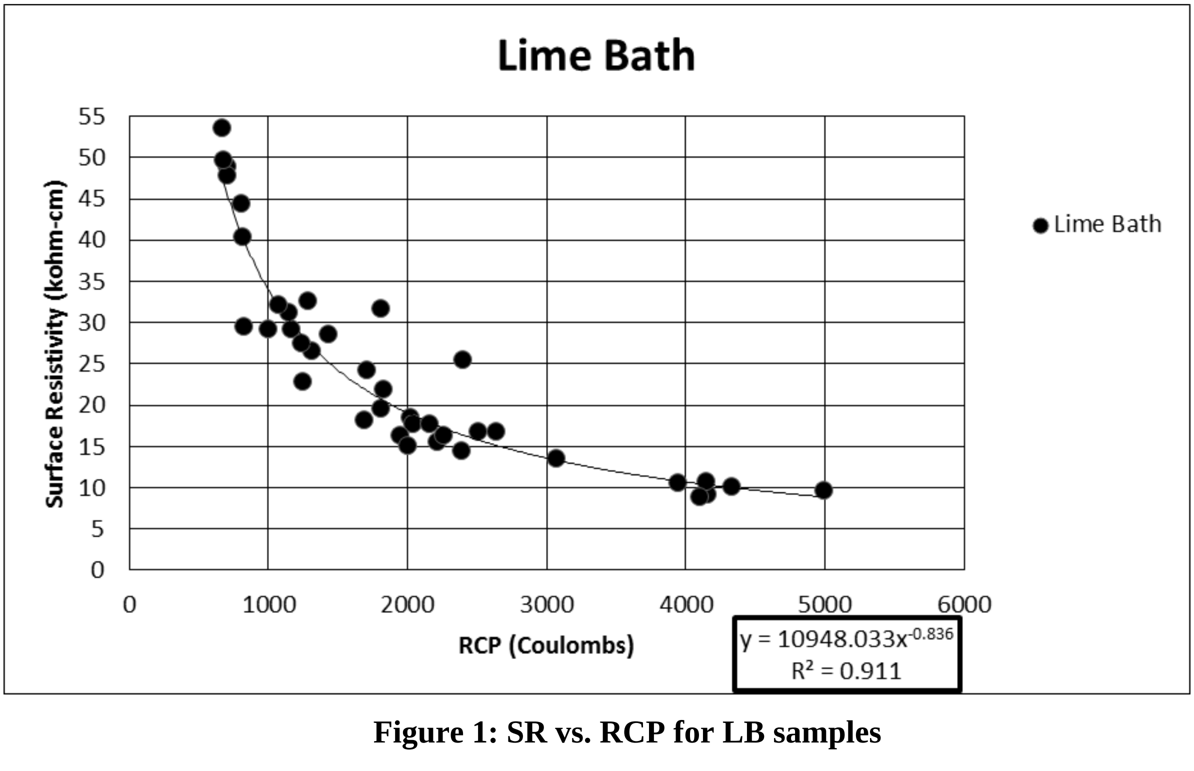

Figure 1: SR vs. RCP for LB samples

Finally, the results of this research are supported by comparison to the SR vs. RCP correlation of three other projects which tested normal weight conncrete. Due to the difficulty in comparing equations, a plot is shown in Figure 2 to compare this research graphically to that reported by Ryan, Kessler and Smith (17) for NWC specimens. As shown in Figure 1, the correlation equation obtained from the research on LB samples of LWC reported in this Final Report was

$$SR = 10948\ (RCP)^{-0.836} \text{ with } R^2 = 0.91$$

In which SR is surface resistivity (kohm-cm) and RCP is the charge passed in the 6 hour RCP test (coulombs over a 6-hour period.)

The correlation equation obtained from the research of Eric Ryan at UT on normal weight samples is

$$SR = 2982\ (RCP)^{-0.651} \text{ with } R^2 = 0.88$$

The correlation equation obtained from the research of Kessler and used by FDOT (normal weight) is

$$SR = 5801.2\ (RCP)^{-0.819} \text{ with } R^2 = 0.95$$

The correlation equation obtained from the research of Smith (normal weight) is

$$SR = 16573\ (RCP)^{-0.813} \text{ with } R^2 = 0.89$$

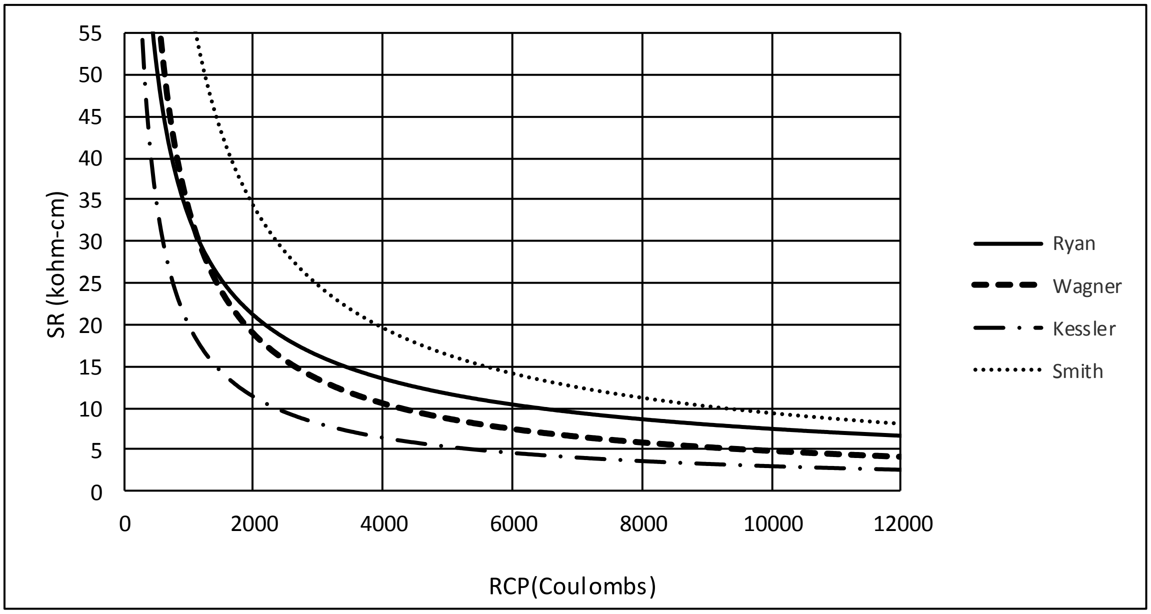

Figure 2: A Comparison to other Research Correlations

A comparison to the results obtained by Ryan, Kessler, and Smith for normal weight concrete confirms that the inverse curve relationship stays consistent for LWC using natural sand and expanded slate coarse aggregate. However, the comparison also shows the variability in these curves. As Eric Ryan notes, Kessler and Smith both used moist room curing while Ryan and Wagner, as plotted, both used LB curing. While there is no evidence to suggest that the different curing methods, properly done, lead to appreciable differences in SR or RCP results, the difference in the results from the various sources highlights the importance of developing correlation curves for concrete using aggregates consistent with those used in the area where the equation will be applied.

The curves can be expected to vary depending on mix proportions, curing method, aggregate source, and perhaps other variables not yet identified. When comparing SR values, the correlation used could significantly affect the acceptance. For example, an SR value of 11.5 is considered to have high chloride ion penetrability based on the AASTHO values shown in

Error! Reference source not found. From Kessler's correlation, the corresponding RCP value is 2,000 coulombs, indicating moderate penetrability as shown by Table 2 . From the correlation developed by Ryan's research, converting the 2,000 coulomb RCP value to an SR equivalent gives an SR score of 21.2, a value which is deemed in the AASHTO table to represent low penetrability of the concrete. The point of this example is to show that the AASHTO specification for SR is based on RCP conversions using a given correlation. When mixing is done with different materials or in a different location, a different correlation will exist and could be misleading if results are based off the AAHSTO correlation.

Table 1: Chloride Ion Penetrability Based on Surface Resistivity (AASHTO)

	SR	
Chloride Ion Penetrability	4 inch x 8 inch Cylinder	6 inch x 12 inch Cylinder
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
Werner probe tip spacing = 1.5		

Table 2: Penetrability Based on Rapid Chloride Ion Penetration Test (ASTM)

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

3.2 Effects of Curing on SR and RCP Results

The effects that curing has on these two tests is important to understand before developing a specification requiring either's use. As research on this project has demonstrated, small differences in mix designs or curing will change the correlation between SR and RCP values. Variables that have been shown to affect RCP and SR results include curing method, cement brand, and the amount of time before reaching a proper curing environment. The results also vary depending on whether the concrete was mixed in the lab or the field. Developing a specification that accounts for each variable would be extremely cumbersome. The condition of the sample, specifically the degree of sample saturation, plays a large role. This concept and data to support this concept are presented in "A Study and Comparison of the Effects of Curing on Results obtained from both Surface Resistivity and Chloride Ion Penetration Tests of Lightweight Concrete" and is included as Attachment 1 at the end of this document.

3.3 Analysis of SR Test Data

In order to identify major factors affecting impedance to the penetration of chloride ions, Table 3 separates samples into different groups based on amount of cementitious material, lab mixed or field mixed, and cement brand. Averages presented in this table are for samples cured in the lime bath to prevent any inconsistencies that could arise due to the inflated SR values caused by MR-84. These values do not contain the 1.10 factor that is recommended by AASHTO, as no justification for that specific multiplier was found from the tests conducted as a part of this research. The table shows that samples using Buzzi cement outperformed samples using Cemex cement, and lab samples outperform samples collected from the field. At 28 days, mixes with 620 lbs/cu.yd. had average SR results from lab samples that were 66.4% higher than from field samples, and for mixes with 670 lbs/cu.yd., the difference was 58.1%. Figure 3 illustrates these differences, and Figure 4 shows the differences between lab and field for all specimens tested. The value shown for concrete without slag came from an unidentified source through TDOT Region 1.

Interestingly—and unexplainably—the variable that led to the largest variation in SR values was cement brand. The difference in SR readings between samples made from Buzzi cement outperformed those made with Cemex cement by an almost absurdly large margin. The bar graphs shown in Figure 5 illustrate this difference.

Table 3: SR results for various Lightweight Mixes separated out for Comparison

		Surface Resistivity	
	Mix Description	28-Day	56-Day
Over the Entire Project	Buzzi	34.13	50.58
	Cemex	13.94	22.55
	Lab Cemex	17.18	29.74
	Field Cemex	10.30	17.27
Lab w/ Cemex Mixes Only	575 lbs/yd	16.40	27.50
	620 lbs/yd	17.37	30.74
	670 lbs/yd	16.30	22.90
Field Mixes Only	620 lbs/yd	10.47	16.90
	670 lbs/yd	10.19	18.37
	Field w/ out Slag	7.57	11.23

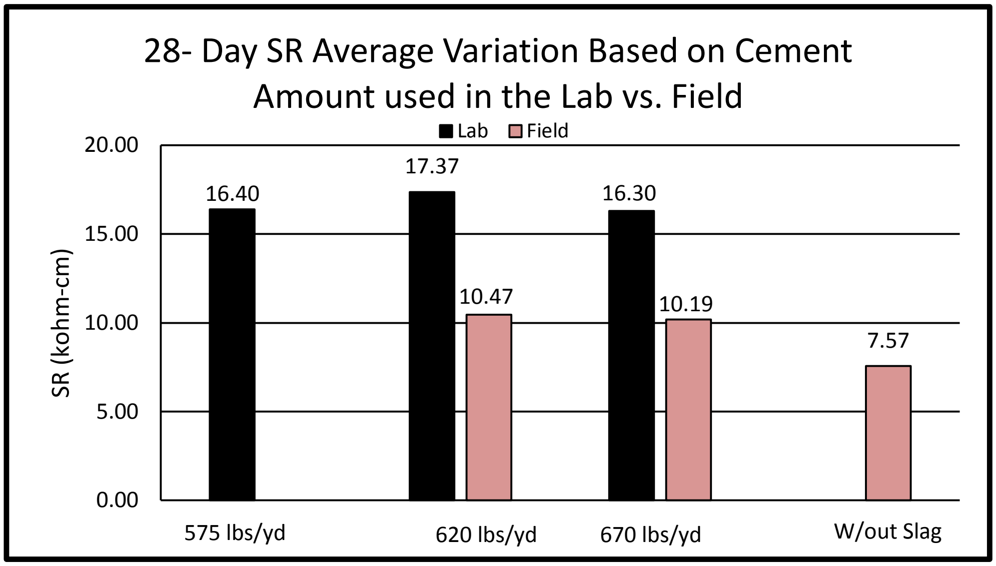

Figure 3: 28-Day SR Result Variation Based on Cement amount for Lab and Field Mixes

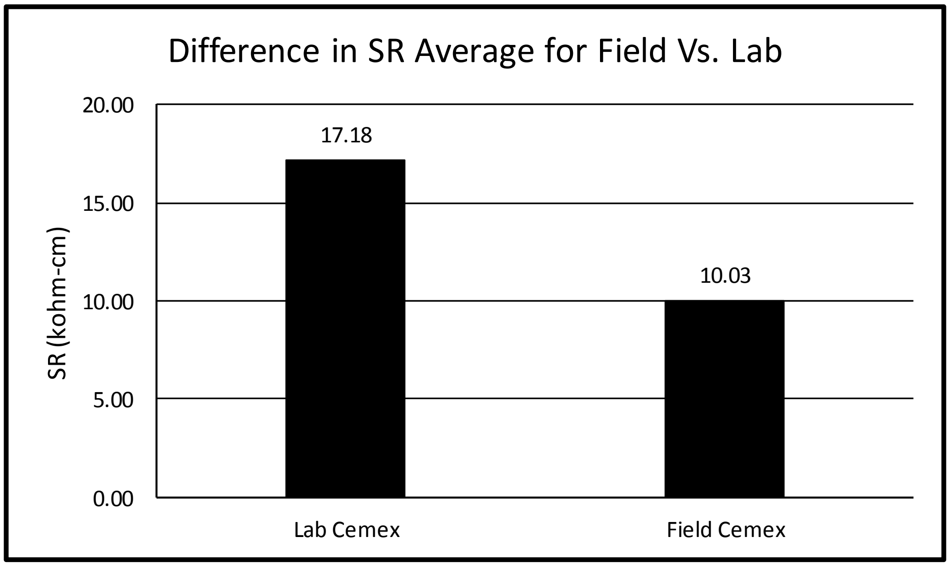

Figure 4: 28 Day SR result Averages by Mix Location.

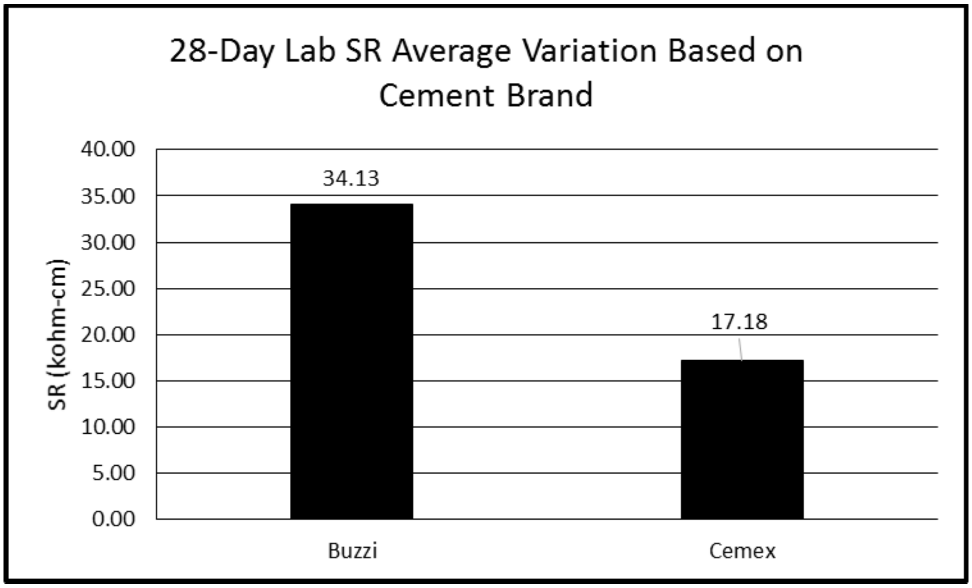

Figure 5: 28 Day SR Result Averages by Cement Brand (Lab)

3.4 Shrinkage Tests

Nine sets of shrinkage prisms were cast and measurements taken. The results of the tests, along with the definitions of the different sets of tests, are shown in the following figures. The graphs show very little difference in shrinkage between specimens with different cement contents, although the specimens with the least amount of cement had the least shrinkage. As with all other test results, the lab mixes outperformed the field mix, although not by much. Again consistent with other test results, the largest difference in shrinkage was between specimens made with Buzzi cement versus those made with Cemex cement.

Nine sets of shrinkage prisms were cast and measurements taken. These samples include the variables described below.

- Set 1 – 2 specimens Buzzi Cement 620 (50-30-20) 8/12/2014
- Set 2 – 3 specimens Cemex Cement 620 (50-30-20) 8/21/2014
- Set 3 – 3 specimens Cemex Cement 670 (60-20-20 Field Mix) 9/3/2014
- Set 4 – 3 specimens Cemex Cement 575 (50-30-20) 10/2/2014
- Set 5 – 3 specimens Cemex Cement 670 (60-20-20) 10/30/2014
- Set 6 - 3 specimens Cemex Cement 620 (50-30-20) 1/07/2015 with dry aggregate. Water was added until slump reaches an acceptable amount
- Set 7 - 3 specimens Cemex Cement 620 (50-30-20) 1/14/2015 with properly soaked aggregate
- Set 8 -3 specimens Cemex Cement 620 (50-30-20) 1/21/2015 with poorly soaked aggregate
- Set 9 - 3 specimens Cemex Cement 620 (50-30-20) 4/09/2015 with dry aggregate. Water reducer was added to raise the slump to an acceptable amount

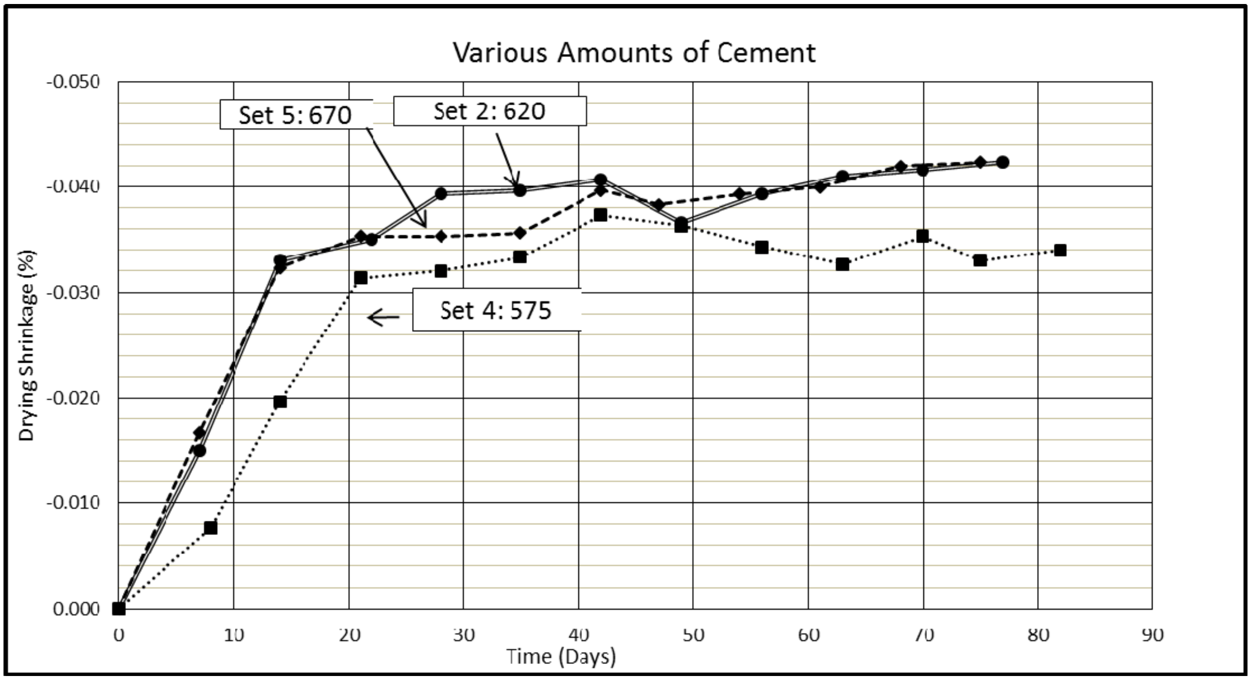

Figure 6: The Variation in Shrinkage due to Changes in Cement Amount (lbs/yd)

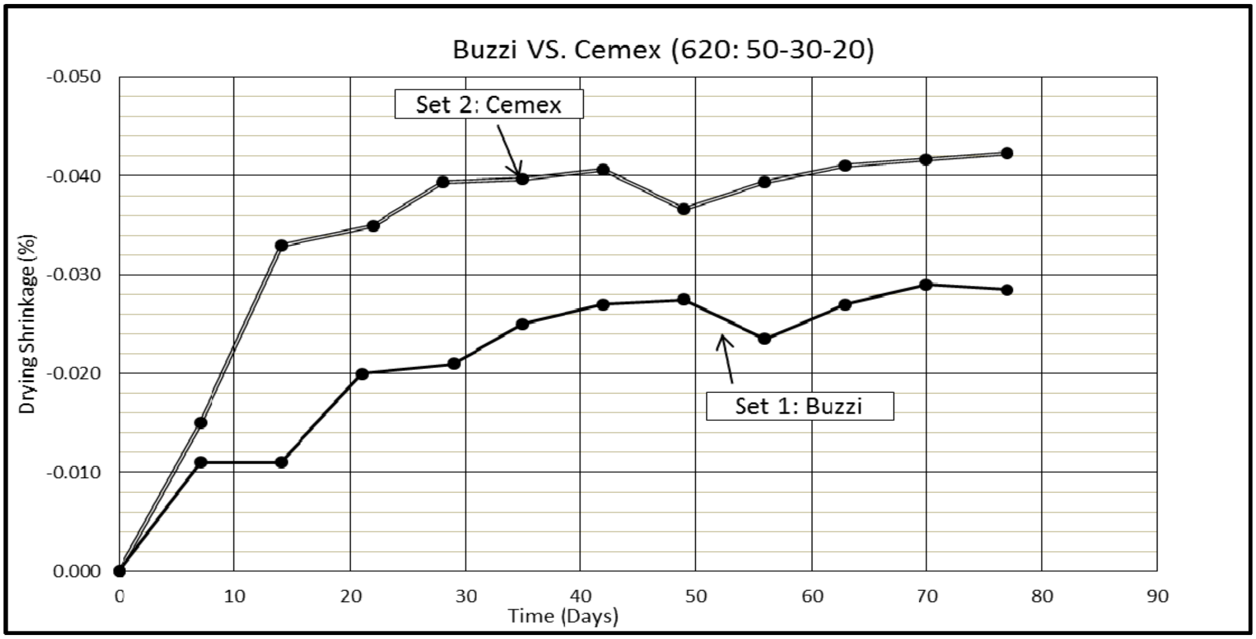

Figure 7: Figure 8: The Variation in Shrinkage due to Changes in Cement Brand

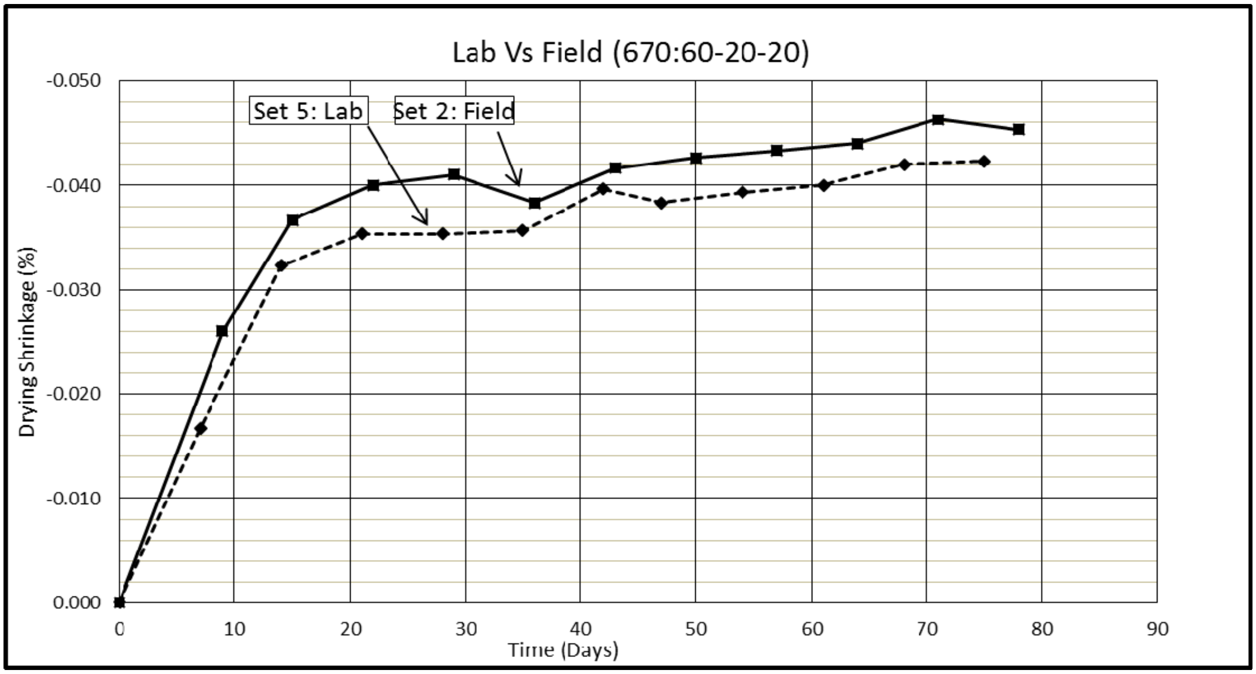

Figure 9: The Variation in Shrinkage due to Changes in Mix Location

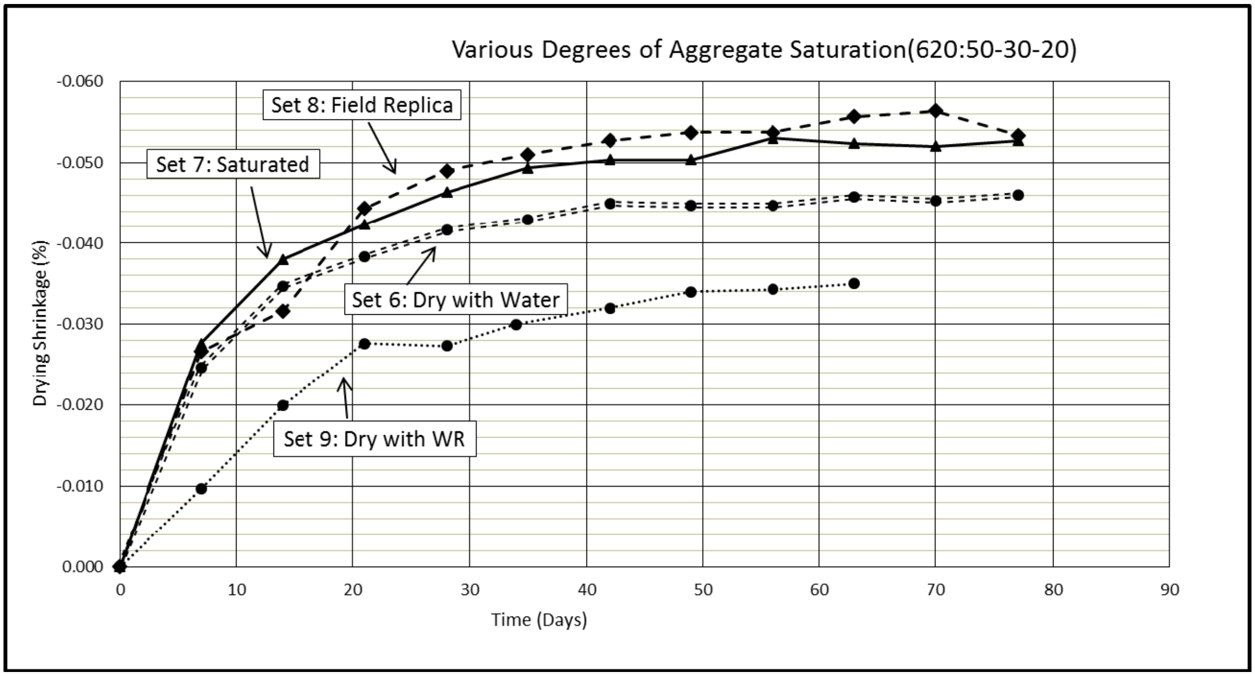

Figure 10: The Variation in Shrinkage due to Changes in Aggregate Saturation

3.5 Cold Weather Concreting

At the request of Jeff Walker with Ray Bell, contractors for the bridge deck, some experiments were conducted to investigate the effects of placing the concrete in relatively cold weather. The results of those tests and conclusions drawn from these results are presented in a paper included here as Attachment 2. Briefly summarized, the laboratory results did not explain or in any way justify getting low SR readings from specimens cured in the way that Ray Bell was curing them.

3.6 Inspection of Existing Lightweight Concrete Bridge Decks

In June and early July of 2015, a cursory inspection of five LWC decks was conducted. The first of these was the SR 56 Hurricane Bridge in DeKalb County. An earlier inspection of this deck was made in the summer of 2013, before this project officially began on August 1, 2013, while the deck was under construction. The appearance of the deck had changed dramatically in two years, although there was no deterioration of particular significance. While there was some cracking, there was nothing to suggest a cracking problem that would jeopardize the integrity of the deck. But at least 85% of the deck had been ground to meet profile requirements. Also, the deck had been grooved for improved traction. Both of these made crack identification more difficult than would have been the case two years ago. At least partly because lightweight aggregate tends to float closer to the surface of the deck than normal weight concrete, the grinding process ground the aggregates smooth, exposing the pores in the expanded slate. While expanded slate has less pore connectivity than either expanded shale or expanded clay, there is still some connectivity of pores. Thus, water and deicing salts can permeate into the slab. Whether this leads to a durability problem is, at this time, an unanswered question.

The other four decks were State Route 40 (SR 40) over Brush Creek, SR 30, north and south bound bridges, over the Hiwassee River and SR 34 over the south Holston river/lake (Truss Bridge). Overall each deck exhibited similar concerns. They all had “spider web” cracking across the surface and had significant portions of the deck ground and grooved for ridability. There was minimal longitudinal cracking and nothing noted larger than hairline in size. On the last bridge inspected, the Truss bridge on SR 34 over the Holston in Sullivan County, there was a trend of cracks forming where truss nodes connected to the deck. Every truss node at deck level had a crack that crossed the width of the deck for each member that framed into the node. The crack also propagated through the concrete bridge rails. None of these bridges raised serious concerns. The SR 34 Bridge had the most overall visible cracking. However the SR 30 Bridge had the most cracking that had been filled with tar.

4.0 Conclusions

The objectives of this research project, as stated in the original proposal, are reiterated in Section 1 of this Final Report. In regard to those stated broad objectives and based on the research results reported herein, the following conclusions are drawn.

(1) There is nothing inherent in the make-up of lightweight concrete to suggest that the use of it in either replacement decks or newly built decks is in any way inappropriate. Based on available literature, the choice of expanded slate as the lightweight coarse aggregate, rather than expanded shale or clay, is a sound one. There are, however, some special considerations that affect the use of lightweight concrete and have some influence on acceptance criteria for lightweight concrete.

(2) In general, LWC requires a higher degree of quality control than normal weight concrete does. For example, accounting for aggregate saturation and the moisture content of the aggregates is at once more difficult and more important than in normal weight concrete. In fact, based both on research reported in available literature and experience on this project, one can argue that proper aggregate saturation is the primary quality control concern for LWC. The positive effect of internal curing only occurs with properly saturated aggregate. Poorly saturated aggregate leads to difficulty in pumping; the pressure in the pumping process forces water into the partially open voids in the aggregate, thus reducing the amount of water available to enhance the lubricating effect of the cementitious paste. Providing and accounting for proper aggregate saturation also affects the amount of water required in the mix and thus affects the w/cm ratio.

(3) One motivating objective of this project was to identify a reasonable minimum SR value to specify for mix designs to achieve an adequate resistance to chloride ion penetration. Work to accomplish this objective evolved into a study of the effects a number of variables have

on Surface Resistivity, the results of which are reported herein. However, the surprising discovery of the large effect that cement brand had on the test results, along with the difference in results between lab and field, made the specification of a lower bound SR value essentially impossible. A lower bound of 18 would not be unreasonable for Buzzi mixes; based on the tests performed on this project, that lower bound would be almost unreachable for Cemex mixes.

(4) The results of tests conducted because of the moist room debacle led to one important conclusion. In any specification which involves measuring SR, the specification should be clear that (a) for any SR reading, the specimen must have been cured in either a lime bath or in a properly calibrated moist room with a relative humidity of 100% and that (b) SR readings should be taken according to AASHTO Specifications and should be done immediately after removal from the curing environment.

(5) Shrinkage of properly saturated lightweight concrete is not appreciably different from that of normal weight concrete. At 28-days the shrinkage of lightweight concrete may actually be a bit lower than that of comparable normal weight concrete; however, the final shrinkage would be expected to be somewhat larger than that of normal weight.

(6) The inspection of five bridge decks indicated only minor cracking but raised potential concerns because of one difference between lightweight and normal weight aggregates. Lightweight aggregate tends to float closer to the top than normal weight aggregate, a phenomenon which is particularly exacerbated by improper aggregate saturation. Although contactors have reported that it is often cheaper to finish a deck and later grind it smooth rather than meet profile requirements, the grinding exposes the lightweight aggregate near the surface which is then ground smooth. This aggregate exposure is a potential issue for porous aggregate as the pore connectivity potentially allows some chloride ion penetration into the deck.

Table 4: Summary of Initial Data Gathered

SUMMARY OF RESULTS			
Casting Date	f'$_c$ (psi)	SR (kohm-cm)	
	28-day	28-day (MR-84)	56-day (MR-84)
10/31/2013	4420	7.7	-
10/31/2013	3050	8.2	-
11/12/2013	5779	61.9	105.2
11/19/2013	5043	54.8	83.8
11/21/2013	5083	61.6	97.2
12/12/2013	3753	65.9	111.4
12/19/2013	-	8.2	30.4
12/19/2013	-	9.2	34.1
1/9/2014	-	16.0	-
1/9/2014	-	15.1	-
1/16/2014	1,845	20.8	-
1/21/2014	4,997	45.8	95.4
2/11/2014	-	-	78.4
2/20/2014	5,102	55.9	100.9
2/26/2014	-	8.6	-
2/26/2014	-	9.6	-
2/27/2014	6,225	20.4	49
3/6/2014	6,000	23.7	57.8
3/13/2014	5,582	21.7	-
4/1/2014	6,002	29.9	-
4/10/2014	5,160	43.9	59.6

Table 5: Summary of data gathered to compare the effects of curing methods

SUMMARY OF RESULTS									
Casting Date	**f'$_c$ (psi)**	**SR (kohm-cm)**				**RCP (Coulombs)**			
	28-day	**28-day (LB)**	**28-day (MR-84)**	**56-day (LB)**	**56-day (MR-84)**	**28-day (LB)**	**28-day (MR-84)**	**56-day (LB)**	**56-day (MR-84)**
4/17/2014	4765	40.8	78.9	-	-	-	-	-	-
(1) 5/14/2014	-	10.2	16.9	14.5	34.7	6299	5031	3777	2582
(1) 5/14/2014	-	5.7	-	-	-	-	-	-	-
6/5/2014	6820	53.6	56.3	72.2	95.5	664	633	474	390
6/19/2014	5209	16.9	60.6	32.7	120.6	2507	2060	1282	1179
6/24/2014	6713	9.3	23.4	17.7	50.6	4150	2121	2154	1094
6/26/2014	4557	25.6	61.9	40.4	101.5	2392	1427	816	1647
(2) 7/7/2014	5641	6	11.4	8.9	19.5	6608	6729	4094	3440
7/10/2014	3898	10.7	44.9	19.7	75.9	3939	3126	1811	4386
7/10/2014	7402	18.5	23.9	29.5	43	2018	1517	821	1159
7/15/2014	6099	29.3	76.5	48.9	121.3	1165	1275	700	1271
7/17/2014	4985	9.7	29.7	16.8	63	4994	3142	2637	1649
7/24/2014	4871	13.5	50.6	24.3	83.3	3072	4001	1707	MR
(3) 7/29/2014	6498	29.3	64.8	47.9	MR	999	1292	703	MR
(4) 7/31/2014	6330	28.6	61.1	44.4	MR	1425	3388	806.00	MR
8/5/2014	4372	8.1	24	15.2	MR	5699	2580	2002	MR

Table 5: Continued

SUMMARY OF RESULTS									
Casting Date	f'c (psi)	SR (kohm-cm)				RCP (Coulombs)			
	28-day	28-day (LB)	28-day (MR-84)	56-day (LB)	56-day (MR-84)	28-day (LB)	28-day (MR-84)	56-day (LB)	56-day (MR-84)
(5) 8/12/2014	5290	31.7	29.3	49.7	46.4	1811	1144	672	777
8/21/2014	5610	14.5	MR	26.6	MR	2387	MR	1310	MR
8/26/2014	5344	10.2	MR	18.2	MR	4325	MR	1689	MR
9/11/2014	6564	15.6	MR	31.3	MR	2209	MR	1148	MR
9/16/2014	6616	17.7	MR	32.2	MR	2041	MR	1066	MR
10/2/2014	6784	16.4	MR	27.5	MR	2254	MR	1239	MR
(4) 10/21/2014	7349	15.5	MR	19.3	MR	NW	MR	NW	MR
10/22/2014	6343	10.8	MR	22	MR	4147	MR	1828	MR
10/30/2014	6550	16.3	MR	22.9	MR	1943	MR	1244	MR

Table 5: Continued

SUMMARY OF RESULTS									
Casting Date	**f'_c (psi)**	**SR (kohm-cm)**				**RCP (Coulombs)**			
	28-day	**28-day (LB)**	**28-day (MR-84)**	**56-day (LB)**	**56-day (MR-84)**	**28-day (LB)**	**28-day (MR-84)**	**56-day (LB)**	**56-day (MR-84)**
1/7/2015	6821	21.6	MR	36.7	MR	SR. vs RCP correlation has been confirmed and RCP Testing Stopped			
1/14/2015	6499	21.7	MR	36.5	MR				
1/21/2015	6615	17.9	MR	32.7	MR				
(2) 1/21/2015 (TDOT)	4143	8.2	MR	13.1	MR				
(2) 3/18/2015	4336	7.2	MR						
(2) 3/20/2015	5494	7.3	7.3						
4/9/2015	3788	7.7	7.8						
4/9/2015	5114	23.1	MR						

(1) All specimens came from a test pour at the Dandridge concrete plant. The first set of results are specimens cured in the UT lab and the second are from specimens cured at Ready Mix USA lab.
(2) Specimens are mixes without slag
(3) 7/29/2014 casting cylinders were exposed to a delayed entrance of 3 days (3DD) and 7 days (7DD) to the lime bath
(4) 7/31/2014 and 10/31/2014 are normal weight mixes
(5) 8/12/2014 cylinders listed under moist room are actually cured in a water bath
LB- Lime Bath
MR-84: Moist Room (inadequate humidity)

ATTACHMENT 1

A Study and Comparison of the Effects of Curing on Results obtained from both Surface Resistivity and Chloride Ion Penetration Tests of Lightweight Concrete

by

Andrew Wagner, Edwin Burdette, and Marvin Martinez

A Study and Comparison of the Effects of Curing on Results obtained from both Surface Resistivity and Chloride Ion Penetration Tests of Lightweight Concrete

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Introduction

As the infrastructure in the United States continues to deteriorate and be replaced, increasing the life expectancy of new construction and repairs has become an increasingly higher priority. Structures must be made more durable in order in increase their useful life, where durability is defined as the ability to withstand repeated use over a long period of time without significant deterioration that could hinder performance. A major factor in improving the durability of concrete structures is protecting the steel reinforcement from corrosion. This corrosion is primarily caused by the penetration of chloride ions. As these ions penetrate through the concrete to the steel and corrosion occurs, the concrete will begin to crack and spall.

Background

In August 2013, a previous study at The University of Tennessee (UT) assessing the durability of normal weight concrete in Tennessee bridge decks was concluded. That study evaluated concrete durability as a function of its ability to resistance the penetration of chloride ions that cause corrosion of the reinforcing steel. When the steel corrodes, the deck will begin to deteriorate at a faster rate. The project confirmed the presence of a strong correlation between the Rapid Chloride Ion Penetration (RCP) test and the Surface Resistivity (SR) test. Upon confirming the correlation and evaluating several hundred cylinders from deck placements across the state of Tennessee, a specification was proposed but not implemented requiring a minimum resistance to chloride ion penetration based on SR test results.

Research on the previous normal weight concrete (NWC) project has since been refocused on developing a specification for lightweight concrete (LWC). The overall purpose of the current project, funded by the Tennessee Department of Transportation (TDOT), is to assess the durability and performance characteristics of LWC as measured by electrical resistance as indicated by SR test results. In order to perform a comprehensive evaluation and address other potential concerns with LWC, compression tests, shrinkage tests and resilience to freezing and thawing cycles are also being conducted.

Curing: Hydration and Internal Curing

The type and adequacy of curing affects essentially every aspect of hardened concrete. Proper curing will increase durability, strength, water tightness, abrasion resistance, volume stability, resistance to freezing and thawing, and the effect of deicers (Kosmatka, Kerhoff, & Panarese, 2003)., The effect of moist room versus lime bath (LB) curing on the hydration process is reasonably well understood. Similarly, the SR test is affected by the curing method used before testing. AASHTO TP 95-11 recognizes this effect and specifies a 1.10 multiplier on SR results for specimens cured in the LB. The multiplier on LB samples, as suggested by AASHTO, indicates that the lime solution decreases the electrical resistance by 10% compared to SR values measured on cylinders cured in a moist room. This reasoning is open to question as noted later herein.

The chemical reactions that occurs between water and Portland cement, known as hydration, are of particular interest in SR and RCP testing. Cement hydration is a continuous process by which the cement minerals are replaced by new hydration products, with the pore solution acting as a necessary transition zone between the two solid states. Figure 1 shows a graph of rate of cement hydration over time broken into 4 phases (Thomas & Jennings, 2008). Phases 1 and 2 happen in such a short period of time that by the time any concrete specimens are stored in the appropriate curing condition, the hydration process has already reached phase 3.

Therefore, phase 3 and 4 are arguably the more important phases during hydration when considering curing effects.

The rate of hydration is controlled by the rate at which the hydration products form and grow (Thomas & Jennings, 2008). As the hydration products grow, they occupy the space that was once taken up by the water. At the end of phase 3, typically around 30% of the original cement has been hydrated (Thomas & Jennings, 2008). In order for further hydration to take place, water molecules must find their way to unreacted cement particles. As the cement particles become thicker during hydration, the process becomes slower (Thomas & Jennings, 2008). The slowing of hydration can be seen in phase 3 of Figure 1. Two factors determine the cement's maximum attainable degree of hydration: the availability of space for hydration products and the availability of water for the cement hydration (Lopez, 2011).

The process of providing moisture for hydration from within the concrete is known as internal curing, a process that LWC benefits from but NWC does not. Internal curing has been proven to enhance hydration and provide important benefits (Lopez, 2011). Water from soaked lightweight aggregate (LWA) is absorbed by the surrounding cement. The internal curing water needs to be described in three main ways: 1) the volume of water available for internal curing, 2) the ability of the water to leave the saturated LWA when needed for internal curing, and 3) the distribution of the saturated LWA so that it is well-dispersed and water can travel to all of the sections in the paste where cement remains not fully hydrated (Schlitter, Henkensiefken, Castro, Raoufi, & Weiss, 2010).

The ability of the water to leave the saturated LWA is due to the suction that develops in the pore moisture within the hydrating cement paste (Schlitter, Henkensiefken, Castro, Raoufi, & Weiss, 2010). As previously mentioned, the pores in the cement particles decrease as hydration continues. This decrease in pore size increases the pressure due to suction pulling as much available water as possible from the LWA (Schlitter, Henkensiefken, Castro, Raoufi, & Weiss, 2010). When LWA is well distributed and properly saturated before mixing, a more complete hydration process will occur, creating a denser cement matrix. Having a denser matrix will decrease the average pore size and thus increase the impedance of LWC.

At the start of the current project, The Civil and Environmental Engineering department had just moved into the new John D. Tickle Building (JDT) with state of the art labs. For the previous UT projects that had confirmed the SR to RCP correlation, all samples had been cured in a LB. Due to delays in opening the building, the LB had not been moved or set up in the new lab at the start of the project. However, the controlled moist room, referred to herein as MR-84, was operational and was therefore used exclusively until the LB was set up.

ASTM C511 states that, except during those times when specimens are being placed into or removed from storage, the atmosphere in the moist room must be maintained at a temperature of 23.0 ± 2.0°C (69.8 - 77°F) and a relative humidity of not less than 95% . AASHTO specifies the same temperature but 100% relative humidity. Atmospheric conditions within the moist room must be maintained such that the specimens in storage are saturated with moisture to the degree needed to ensure that the exposed surfaces of all specimens in storage both look and feel moist.

Testing methods (RCP vs SR)

As previously mentioned, the primary methods for determining the penetrability of concrete samples are the SR and RCP tests. Both tests measure permeability indirectly through an electrical indication based on resistance or conductance respectively. The SR test is an easy to perform, non-destructive test which is also lower cost than any other test currently available

(Kessler P. P., 2008). The RCP test is a time consuming and laborious test. However, a strong correlation between the two tests does exist.

The Florida Department of Transportation (FDOT) started a research program in 2002 to evaluate all available electrical indicators of concrete impedance to chloride ions. The first research project correlated results from both RCP and SR tests. The two tests showed a strong correlation with an R^2 value of 0.95 at 28 days. The strong correlation between RCP and SR values allowed for FDOT to eliminate the RCP test from its specification and replace it with the SR test in 2007 (Kessler P. P., 2008). The previous UT research project yielded an R^2 value of 0.88 for SR vs. RCP for combined 28 and 56 day data (Ankabrandt, 2014). The strong correlation between RCP and SR values in the FDOT research and the strong correlation found in the previous UT research project provided justification for only performing SR tests in the beginning of the current UT research project on LWC.

All SR tests were performed in accordance with AASHTO TP 95-11. The SR meter has four probes, a current is applied to the two outer probes, and the potential difference is measured between the two inner probes as seen in Figure 2. The current is carried by ions in the pore moisture of the sample. The calculated resistivity depends on the spacing of the probes (Proceq, 2011). In the lab an SR meter with 1.5” probe spacing was used which conforms to the specification in AASHTO TP 95-11. A high SR result, indicating high impedance, is desirable.

All RCP tests were conducted in accordance with ASTM C1202. The test consists of a conditioning phase and a testing phase. During the conditioning phase, which takes at least 24 hours, the concrete samples are prepared so that any electrically conductive materials that are present in the concrete samples are driven out. During the testing phase, a constant voltage is applied across a concrete specimen, and the amount of charge that passes through the specimen in a 6 hour period is measured (Ankabrandt, 2014). The test measures the electrical conductance of concrete, a quantity taken to be an appropriate measure of chloride ion penetration (ASTM C1201). A low RCP test result, indicating the sample has high impedance, is good.

Both the SR and RCP tests are indirect electrical indications of permeability. The two tests are, theoretically, inversely related to each other based on the following equation:

$$\sigma = \frac{1}{\rho}$$

where σ represents conductivity (RCP measurement) and ρ represents resistance (SR measurement) (Ankabrandt, 2014). Thus, if everything is perfect-- the samples are cured perfectly, the tests are performed perfectly, and the equipment is operating perfectly and calibrated perfectly—the R^2 value should be 1.0; all the points should lie on the “best fit” line. However, in an imperfect world where variables, both recognized and unidentified, abound, the probability of obtaining an R^2 of 1.0 is infinitesimal. The RCP test in particular is rife with possible sources of error. The samples must be prepared for testing “just right”, and for high values of RCP, the heat generated by the test itself can cause an erroneously high reading. The SR test, on the other hand, was deemed to be essentially foolproof.

At the beginning of this research project, the plan was to perform only SR tests. Because of the absence of a sound lime bath, the moist room in the brand new Tickle Building was used, a situation already described. Some unexpected results led the research team, admittedly a bit late, to question the accuracy of SR test results on specimens cured in the new moist room and to significant further investigation. The investigation and its results are described in the following paragraphs.

One potential weakness, common to both the SR and RCP tests relates to the effects of supplementary cementitious materials (SCMs) such as fly ash, blast furnace slag, and silica fume. The addition of these materials to a concrete mixture has been shown repeatedly to increase the measure of the impedance of chloride ions into concrete. For example, add silica fume to a mix and the RCP values are drastically reduced, while the SR values go up markedly. But does the actual resistance of the concrete to the penetration of chloride ions increase correspondingly, or do these SCMs simply increase the values measured by the two test methods? The ponding test is as close to a “gold standard” as currently exists to assess concrete permeability. A correlation between ponding tests and RCP tests has been shown to exist for mixtures without SCMs. Until extensive testing is done to examine a similar correlation between the two methods and the ponding tests for samples with SCMs, the question raised above remains unanswered.

Moist Room 84 (MR-84)

As previously mentioned, the research team made the move to a new building at the start of the project. The new building had a moist room that was assumed operable, but a lime bath had yet been established. As testing progressed SR results were predicting higher impedance than initially expected; thus, the decision was made to begin RCP testing. During this time the LB was properly set up and checked to ensure that ASTM requirements were met for lime concentration. SR to RCP testing continued with samples being cured in both the lime bath and moist room. The initial idea was to develop a LWC multiplier similar to the 1.10 suggested by AASTHO as well as confirm the correlation between SR and RCP results.

After testing several samples, data points were graphed and the resulting plots and correlations can be seen in Figures 3 through 5. Figure 4 particularly shows that the SR to RCP correlation was atrocious for samples cured in the moist room. As the lime bath was determined to have the correct concentration of lime, attention turned to the moist room. The moist room, being brand new, was assumed to be working properly. It was set up by a private contractor, and the outside gage was reading around 100% humidity. A researcher then noted when retrieving cylinders that it was more “like a hot and humid day in Memphis” in the moist room than the same feeling that he experienced at the TDOT Region 1 moist room.

The moist room was then checked for adequacy. The built in humidity sensor was checked using a psychrometer and an at home weather station. Although both confirmed that the proper temperature was being maintained, both also indicated that the relative humidity was 84%, below the required minimum. ASTM requires that a moist room maintains at least 95% humidity, but AASTHO TP 95-11 specifies 100% relative humidity for SR testing. Clearly, the humidity in the new JDT moist room was grossly out of spec. Henceforth in this paper the term MR-84 is used to indicate samples cured in the dryer than specified environment in the JDT. Further investigation revealed the large effect that proper moist room curing had, particularly on SR results, and raised questions about the effects of different curing methods on SR and RCP test results.

Results

Over the course of this project, several LWC samples were cast in the lab as well as collected from the field. Table 1 shows a comprehensive list of test results from tests completed at the time of this report. Tables 2 and 3 are provided to help identify differences in MR-84 and LB results respectively. Table 1 has several notes listed at the end that are used to identify mix variations that were investigated to identify causes in the variability of SR results. The project has shown that SR values vary more than RCP results due to inconsistencies in the sample condition at time of testing. The RCP test, at least to a large degree, avoids this inconsistency by specifying a detailed sample conditioning process. Both SR and RCP results fluctuated with cement brand, curing method, location of casting, and the delayed exposure to the curing process.

Effects of Curing Environment

Figure 3 shows the results for the overall project with MR-84 and LB samples identified. Figures 4 and 5 separate MR-84 and LB samples respectively. A trend line plotted, using a power curve, indicates the RCP to SR correlation. The overall R^2 for the project at that time is 0.38, indicating that there was a very weak correlation between SR and RCP results for LWC samples. However, when the data is separated out by curing method, as shown in Figures 4 and 5, the correlation is very strong. For samples cured in the LB an R^2 of 0.91 was found. Samples cured in MR-84 had an abysmal correlation with an R^2 of 0.179. The actual magnitudes of SR values are much more variable than values from RCP tests for cylinders cured in the inadequate moist room. The difference is RCP and SR ranges is an indication that the SR test is more sensitive to sample condition and curing than is the RCP test. Samples used for RCP testing have an extensive conditioning phase during which samples are vacuumed dry and then re-saturated with de-aired water before testing. This sample preparation phase attempts to remove any variability in sample conditions before testing. Samples used for SR testing are removed from their curing environment and tested, only ensuring that the surface is damp. This simple process makes SR testing much faster to complete but ignores the possible effects of internal moisture or lack of it.

The RCP test is an electrolysis reaction that is dependent on the diffusion rate through the concrete samples. Samples are saturated at the start of testing from the conditioning phase completing the channel that will attempt to pass the electrical current. By using the specified set up, chloride ions constitute the primary diver in the conductance of electricity through the sample. The SR test, on the other hand, does not have this conditioning phase to ensure that samples are saturated. When SR tests are conducted, if the sample is not properly saturated, the test will indicate a high impedance potential due to the lack of pore moisture that allows the current to pass, while the actual impedance of the concrete may not be that high. When using the AASHTO specification, SR results from samples cured in the LB should be multiplied by 1.10 to account for a decrease in resistance that the specification suggests is caused by lime water curing. The idea that SR results are artificially high when cured in a MR due to the lack of internal moisture might suggest that it would be more appropriate to have a reduction in SR for specimens cured in a moist room rather than increasing SR results for LB cured samples.

To determine if the lime solution or the degree of sample saturation played a primary role in the difference between LB and MR-84 results, samples from a casting completed in the lab were placed in the LB, MR-84, and a plain water bath. The water for the bath was tap water and not de-aired or de-ionized water. The results from this specific set of tests are shown in Figure 6. Due to the use of MR-84 samples being used for 28 day breaks after testing, the 56 day SR results for MR-84 samples are not available. Figure 6 does show that samples cured in the water bath and those in the LB exhibited very similar SR results, with LB results slightly higher. As a result, the SR test is believed to be affected more by the degree of saturation of the sample than the lime solution in the internal pores. Due to the conditioning phase, RCP results are not as affected by curing conditions. This theory that the difference between moist room and LB samples is further supported by testing discussed in “Timely Performance of SR Testing” below.

Field vs. Lab Castings

Throughout the entire project there has been a large difference in SR results for samples cast in the lab and those cast in the field during the placement of bridge decks. When a specification is executed to evaluate placed concrete, samples will be collected from the field; thus, finding the cause for the drastic change in SR values is important. Figures 7 through 9 show the SR result differences between using different cement brands and field mixes. The cause of SR value fluctuation due to different cement brands was not identifiable because all samples collected from field castings used the same brand of cement. The idea of SR values being effected by different cements brands is considered valid as a correlation does exist between the SR and RCP for each brand, as shown by figures 10 and 11.

When samples are cast in the field, a few days may pass before reaching the lab. Field samples are cast in accordance with ASTM standards and then left on the job site for at least 24 hours, often longer, before being transported to the TDOT region 1 office just outside of Knoxville. The samples collected consist of 13 cylinder that are placed and transported in a large cooler. The cooler helps to maintain a humid environment. Upon reaching TDOT's region 1 office, the research team is notified and retrieves the cylinders for curing and testing at UT. In all, when compared to casting completed in the lab, field samples reach proper curing between 2 and 6 days later. Although mix quality control and proper aggregate saturation before mixing are concerns this delayed curing is of primary importance.

Mix quality control and aggregate saturation are important but if an SR specification is passed, the quality control will come as ready mix providers strive to meet the new standards. For this reason the effects of the delayed curing should be understood in order to make a fair comparison between samples that are able to reach the lab in a timelier manner and those that take more time. To evaluate the delayed curing effects a set of cylinders were cast in the lab but placed into proper curing at different times. Samples were placed in the LB initially, at a 3 day and 7 day delay. Figure 12 shows the effects delayed curing exposure had on SR results. As the amount of delay increased, the 28day SR value increased. This effect is important to note when comparing samples that reach the testing lab at different times after casting occurs.

Timely Performance of SR Testing

The research discussed above has shown that the specimen's degree of saturation and delayed curing of specimens takes an effect on the SR results. Based on those results, another source of variation that should be considered when specifying a minimum SR value is the time between removing the sample from the curing environment and SR testing. AASHTO TP 95-11 accounts for this by requiring that testing occur in the first 5 minutes after being removed from the curing environment (AASHTO, 2011).

The research was able to confirm this effect by testing a sample set out of the LB at 28 days, allowing the sample set to sit out for 24 hours before testing again. Finally the sample set was placed back in the LB and tested again at 30 days. As Figure 13 shows, the SR value after 24 hours of drying and then dampening just the surface to test, has the highest SR value. The 28 day has the lowest SR value, followed by the 30 day SR value. The 29 day SR on a dry cylinder was the highest. The fact that the 30 day SR result was higher than the 28 day SR value is consistent with other tests showing the continued increase of SR values through 56 day test. This very limited set of tests highlights the importance of meeting the 5 minute testing requirement between removal of a cylinder from its curing environment and testing specified by AASHTO, and also shows the effect on SR results resulting from a sample being no longer saturated. Interestingly and perhaps coincidentally, the ratio of 29 day result (8.5 kohm-cm) on a dry sample to the 30 day (7.7 kohm-cm) test on the same sample that was saturated is 1.10, identical to the multiplier suggested by AASTHO for samples cured in the LB.

Conclusions

The SR test is a valid test and is a useful and practical option for testing when specifying that concrete meet a minimum impedance requirement. However, when conducting SR testing and writing a specification that is reliant on it, several precautions should be taken. SR results from improperly cured concrete can be highly variable, giving a false indication of the ability of the concrete to impede the penetration of chloride ions.

The 1.10 multiplier specified in the AASHTO SR Specifications has not been verified by this research, nor has any support for the reasoning given for that multiplier been determined from the testing. However, based on the results of the tests of cylinders cured in an improperly moist environment, a simple explanation for SR values obtained on cylinders cured in a lime bath being lower than values obtained on cylinders cured in a moist room may be as follows. No matter how moist a moist room is, full 100% relative humidity, it is virtually impossible for a cylinder cured in that moist room to be quite as saturated as an identical cylinder cured in a lime bath. Simply the hydrostatic pressure of the water in the bath will logically lead to a more nearly complete saturation of the cylinder, thus lowering the resistivity by some amount. Why ten percent? Only an extensive testing program can establish that. Why increase the SR value from a lime bath rather than decrease the RCP value from a moist room? Perhaps one can call that a “fielder’s choice” as the only difference it makes is in the determination of appropriate SR values to delineate between, for example, “good” SR values and “very good” SR values.

The RCP test measures the penetrability of chloride ions into concrete; the SR test measures the resistivity of concrete to the penetration of chloride ions. Thus, a low value of the former is desirable; a high value of the latter is desirable. In order to relate the two in any discussion of relative merits or of strengths and weaknesses of the two methods, a common term will be useful. So, for discussion and comparison purposes, both methods may be said to measure the capacity of concrete to withstand exposure to chloride ions—or to “impede” the penetration of chloride ions into the concrete. The fact that one method’s low readings are “good” while the other’s high readings are “good” are removed from the discussion by saying that a high value of impedance, however measured, is desirable or “good.”

One conclusion drawn from the tests performed on this research project relates to the effects of improper curing on results obtained from SR and/or RCP tests. In brief summary all results point toward the following conclusion. Both methods are affected by improper curing conditions. Improperly cured concrete will lead to a falsely higher measure of impedance to chloride ion penetration as measured by the SR test, while the same improper curing will lead to falsely lower impedance as measured by the RCP test. Thus, it may be said that the SR test is an “upper bound” method; the true impedance is no larger than that measured but may be smaller. The RCP test, on the other hand, may be termed a “lower bound” method; the true impedance is as least as large as that measured by the RCP test. From this conclusion one can further conclude that, if results of SR tests are to be used in a specification, the assurance of proper curing and sample preparation should be included in the specification.

Appendix

Table 1: Summary of data recorded to compare the effects of curing methods

SUMMARY OF RESULTS									
Casting Date	**f'_c (psi)**	**SR (kohm-cm)**				**RCP (Coulombs)**			
	28-day	**28-day (LB)**	**28-day (MR)**	**56-day (LB)**	**56-day (MR)**	**28-day (LB)**	**28-day (MR)**	**56-day (LB)**	**56-day (MR)**
4/17/2014	4765	40.8	78.9	-	-	-	-	-	-
(1) 5/14/2014	-	10.2	16.9	14.5	34.7	6299	5031	3777	2582
(1) 5/14/2014	-	5.7	-	-	-	-	-	-	-
6/5/2014	6820	53.6	56.3	72.2	95.5	664	633	474	390
6/19/2014	5209	16.9	60.6	32.7	120.6	2507	2060	1282	1179
6/24/2014	6713	9.3	23.4	17.7	50.6	4150	2121	2154	1094
6/26/2014	4557	25.6	61.9	40.4	101.5	2392	1427	816	1647
(2) 7/7/2014	5641	6	11.4	8.9	19.5	6608	6729	4094	3440
7/10/2014	3898	10.7	44.9	19.7	75.9	3939	3126	1811	4386
7/10/2014	7402	18.5	23.9	29.5	43	2018	1517	821	1159
7/15/2014	6099	29.3	76.5	48.9	121.3	1165	1275	700	1271
7/17/2014	4985	9.7	29.7	16.8	63	4994	3142	2637	1649
7/24/2014	4871	13.5	50.6	24.3	83.3	3072	4001	1707	MR
(3) 7/29/2014	6498	29.3	64.8	47.9	MR	999	1292	703	MR

(3) 3DD 7/29/2014	6498	36.4	MR	-	MR	-	-	-	-
(3) 7DD 7/29/2014	6498	38.2	MR	-	MR	-	-	-	-
(4) 7/31/2014	6330	28.6	61.1	44.4	MR	1425	3388	806.00	MR
8/5/2014	4372	8.1	24	15.2	MR	5699	2580	2002	MR
(5) 8/12/2014	5290	31.7	29.3	49.7	46.4	1811	1144	672	777
8/21/2014	5610	14.5	MR	26.6	MR	2387	MR	1310	MR
8/26/2014	5344	10.2	MR	18.2	MR	4325	MR	1689	MR
9/11/2014	6564	15.6	MR	31.3	MR	2209	MR	1148	MR
9/16/2014	6616	17.7	MR	32.2	MR	2041	MR	1066	MR
10/2/2014	6784	16.4	MR	27.5	MR	2254	MR	1239	MR
(4) 10/21/2014	7349	15.5	MR	19.3	MR	NW	MR	NW	MR
10/22/2014	6343	10.8	MR	22	MR	4147	MR	1828	MR
10/30/2014	6550	16.3	MR	22.9	MR	1943	MR	1244	MR

(1) All specimens came from a test pour at the Dandridge concrete plant. The first set of results are specimens cured in the UT lab and the second are from specimens cured at Ready Mix USA lab.
(2) 7/7/2014 specimens came from a pour that Ready Mix USA provided for an interior slab for a local high school (NO SLAG)
(3) 7/29/2014 casting cylinders were exposed to a delayed entrance of 3 days (3DD) and 7 days (7DD) to the lime bath
(4) 7/31/2014 and 10/31/2014 are normal weight mixes
(5) 8/12/2014 cylinders listed under moist room are actually cured in a water bath
LB- Lime Bath
MR- Moist Room (inadequate humidity)

Table 2: Summary “Moist Room” samples only

SUMMARY OF RESULTS FOR "MOIST ROOM" SAMPLES							
Casting Date	**Mix Site**	**Cement Brand**	**Mix Design (Cement, Slag, FA)**	**f'$_c$ (psi)**		**SR (kohm-cm)**	
				7-day	**28-day**	**28-day**	**56-day**
10/31/2013	Field	Cemex	50-30-20 (575)	2210	4420	7.7	-
10/31/2013	Field	Cemex	50-30-20 (620)	1510	3050	8.2	-
11/12/2013	UTK Lab	Buzzi	50-30-20 (620)	3311	5779	61.9	105.2
11/19/2013	UTK Lab	Buzzi	50-30-20 (620)	2816	5043	54.8	83.8
11/21/2013	UTK Lab	Buzzi	50-30-20 (620)	3025	5083	61.6	97.2
12/12/2013	UTK Lab	Buzzi	50-30-20 (620)	2384	3753	65.9	111.4
12/19/2013	Field	Cemex	50-30-20 (620)	-	-	8.2	30.4
12/19/2013	Field	Cemex	50-30-20 (620)	-	-	9.2	34.1
1/9/2014	Field	Cemex	50-30-20 (620)	-	-	16.0	-
1/9/2014	Field	Cemex	50-30-20 (620)	-	-	15.1	-
1/16/2014	UTK Lab	Cemex	50-30-20 (620)	1,082	1,845	20.8	-
1/21/2014	UTK Lab	Cemex	50-30-20 (620)	2,965	4,997	45.8	95.4
2/11/2014	UTK Lab	Cemex	50-30-20 (620)	2,415	-	-	78.4
2/20/2014	UTK Lab	Cemex	50-30-20 (620)	3,267	5,102	55.9	100.9
2/26/2014	Field	Cemex	50-30-20 (620)	-	-	8.6	-
2/26/2014	Field	Cemex	50-30-20 (620)	-	-	9.6	-

2/27/2014	UTK Lab	Cemex	50-30-20 (575)	3,412	6,225	20.4	49
3/6/2014	UTK Lab	Cemex	50-30-20 (620)	3,165	6,000	23.7	57.8
3/13/2014	UTK Lab	Cemex	50-30-20 (620)	2,127	5,582	21.7	-
4/1/2014	UTK Lab	Cemex	60-20-20 (620)	2,742	6,002	29.9	-
4/3/2014	UTK Lab	Cemex	60-20-20 (620)	1,141	-	-	-
4/10/2014	UTK Lab	Buzzi	50-30-20 (620)	2,899	5,160	43.9	59.6
4/17/2014	UTK Lab	Buzzi	50-30-20 (620)	-	4765	78.9	-
5/14/2014	Field	Cemex	50-30-20 (620)	-	-	16.9	34.7
5/14/2014	Field	Cemex	50-30-20 (620)	-	-	-	-
6/5/2014	UTK Lab	Buzzi	50-30-20 (620)	-	6820	56.3	95.5
6/19/2014	Field	Cemex	50-30-20 (620)	-	5209	60.6	120.6
6/24/2014	Field	Cemex	60-20-20 (670)	-	6713	23.4	50.6
6/26/2014	UTK Lab	Buzzi	50-30-20 (620)	-	4557	61.9	101.5
7/7/2014	Field	Cemex	85-15 (670)	-	5641	11.4	19.5
7/10/2014	UTK Lab	Cemex	50-30-20 (620)	-	3898	44.9	75.9
7/10/2014	Field	Cemex	60-20-20 (670)	-	7402	23.9	43
7/15/2014	UTK Lab	Buzzi	50-30-20 (620)	-	6099	76.5	121.3
7/17/2014	Field	Cemex	60-20-20 (670)	-	4985	29.7	63
7/24/2014	UTK Lab	Cemex	50-30-20 (620)	-	4871	50.6	83.3
(1) 7/29/2014	UTK Lab	Buzzi	50-30-20 (620)	-	6498	64.8	MR
(2) 7/31/2014	UTK Lab	Buzzi	50-30-20 (620)	-	6330	61.1	MR
8/5/2014	Field	Cemex	60-20-20(670)	-	4372	24	MR

Table 3: Summary of Lime Bath samples only

SUMMARY OF RESULTS FOR LIME BATH SAMPLES						
Casting Date	**Mix Site**	**Cement Brand**	**Mix Design (Cement, Slag, FA)**	**f'_c (psi)**	**SR (kohm-cm)**	
				28-day	**28-day (LB)**	**56-day (LB)**
4/17/2014	UTK Lab	Buzzi	50-30-20 (620)	4765	40.8	-
5/14/2014	Field	Cemex	50-30-20 (620)	-	10.2	14.5
5/14/2014	Field	Cemex	50-30-20 (620)	-	5.7	-
6/5/2014	UTK Lab	Buzzi	50-30-20 (620)	6820	53.6	72.2
6/19/2014	Field	Cemex	50-30-20 (620)	5209	16.9	32.7
6/24/2014	Field	Cemex	60-20-20 (670)	6713	9.3	17.7
6/26/2014	UTK Lab	Buzzi	50-30-20 (620)	4557	25.6	40.4
7/7/2014	Field	Cemex	85-15 (670)	5641	6	8.9
7/10/2014	UTK Lab	Cemex	50-30-20 (620)	3898	10.7	19.7
7/10/2014	Field	Cemex	60-20-20 (670)	7402	18.5	29.5
7/15/2014	UTK Lab	Buzzi	50-30-20 (620)	6099	29.3	48.9
7/17/2014	Field	Cemex	60-20-20 (670)	4985	9.7	16.8
7/24/2014	UTK Lab	Cemex	50-30-20 (620)	4871	13.5	24.3
(1) 7/29/2014	UTK Lab	Buzzi	50-30-20 (620)	6498	29.3	47.9
(2) 7/31/2014	UTK Lab	Buzzi	50-30-20 (620)	6330	28.6	44.4
8/5/2014	Field	Cemex	60-20-20(670)	4372	8.1	15.2
8/12/2014	UTK Lab	Buzzi	50-30-20 (620)	5290	31.7	49.7

8/21/2014	UTK Lab	Cemex	50-30-20 (620)	5610	14.5	26.6
8/26/2014	Field	Cemex	60-20-20(670)	5344	10.2	18.2
9/11/2014	UTK Lab	Cemex	50-30-20 (620)	6564	15.6	31.3
9/16/2014	UTK Lab	Cemex	50-20-30 (620)	6616	17.7	32.2
10/2/2014	UTK Lab	Cemex	50-20-30 (575)	6784	16.4	27.5
(4) 10/21/2014	Field	Cemex	60-20-20 (670)	7349	15.5	19.3
10/22/2014	Field	Cemex	60-20-20(670)	6343	10.8	22
10/30/2014	UTK Lab	Cemex	60-20-20(670)	6550	16.3	22.9

Table 4: Chloride Ion Penetration Classification, SR vs. RCP Test (Kessler P. P., 2008)

Chloride Ion Penetration	**ASTM C1202 RCP test Charge Passed (coulombs)**	**28 Day Surface Resistivity Test**		
		4" x 8" Cylinder (kOhm – cm) (a = 1.5")	**6" x 12" Cylinder (kOhm – cm) (a = 1.5")**	**Semi-Infinite Slab**
High	> 4,000	< 12	< 9.5	< 6.7
Moderate	2,000 – 4,000	12 - 21	9.5 – 16.5	6.7 – 11.7
Low	1,000 – 2,000	21 - 37	16.5 – 29	11.7 – 20.6
Very Low	100 – 1,000	37 - 254	29 – 199	20.6 – 141.1
Negligible	< 100	> 254	> 199	> 141.1

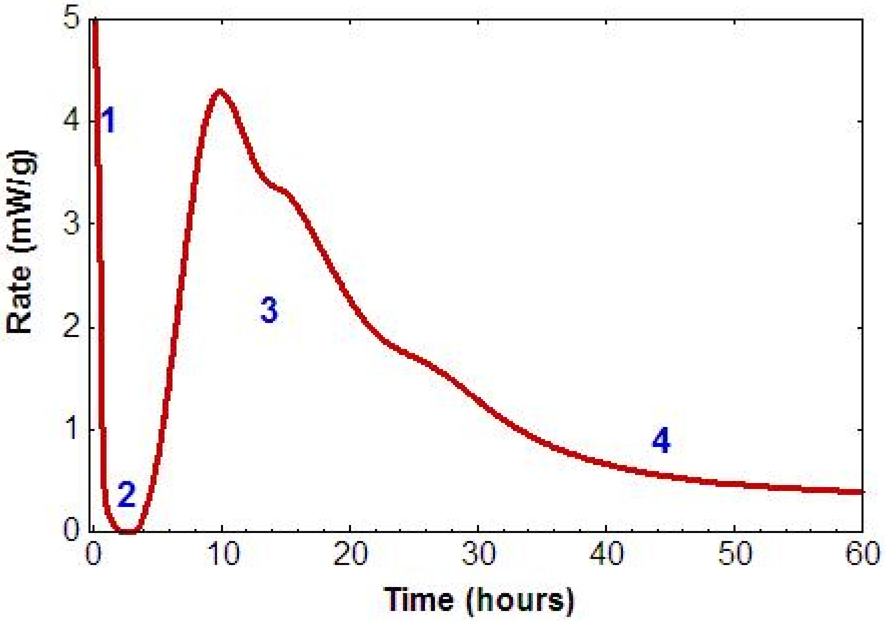

Figure 1: Rate of cement hydration versus time (Thomas & Jennings, 2008)

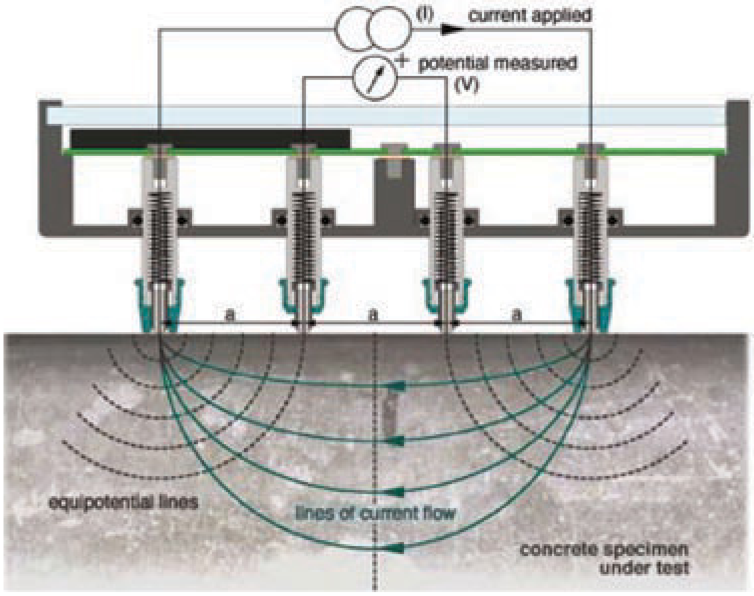

Figure 2: SR meter

Source: Resipod Sales Flyer

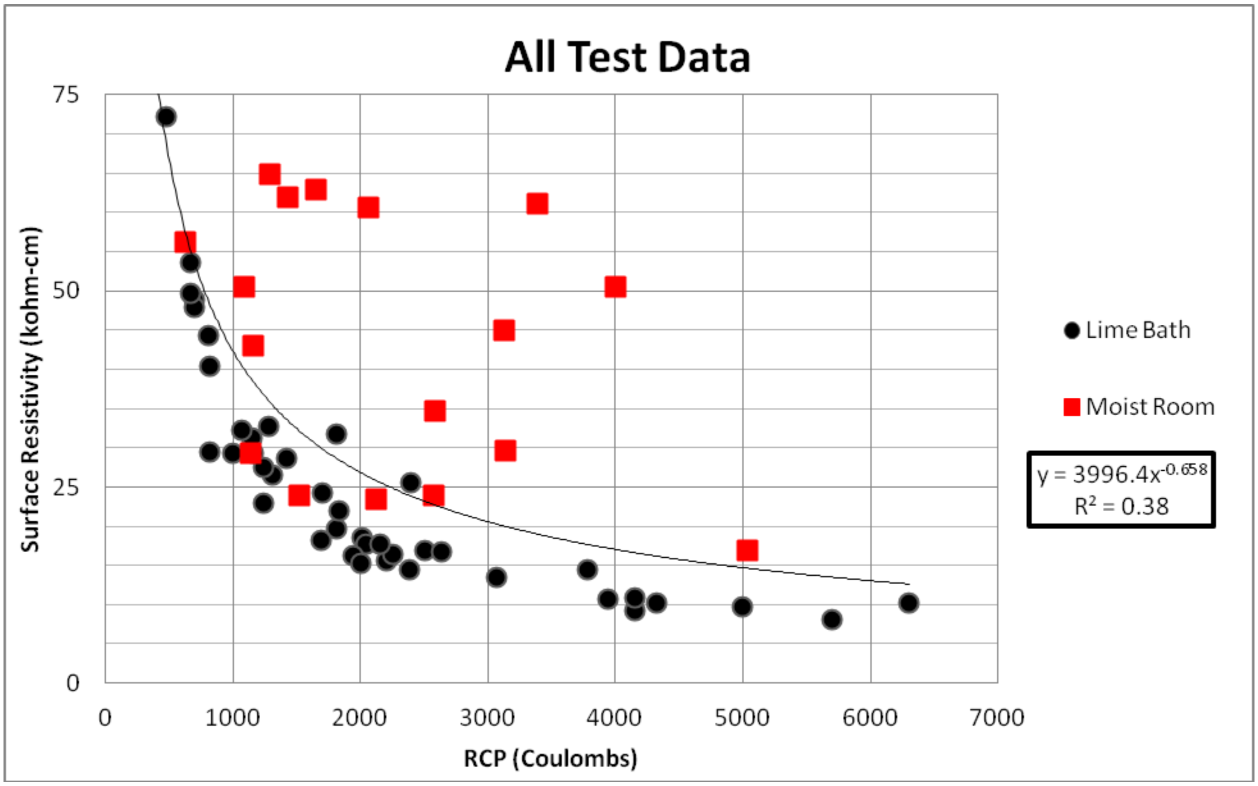

Figure 3: RCP to SR correlation for all Test Data ($R^2 = 0.38$)

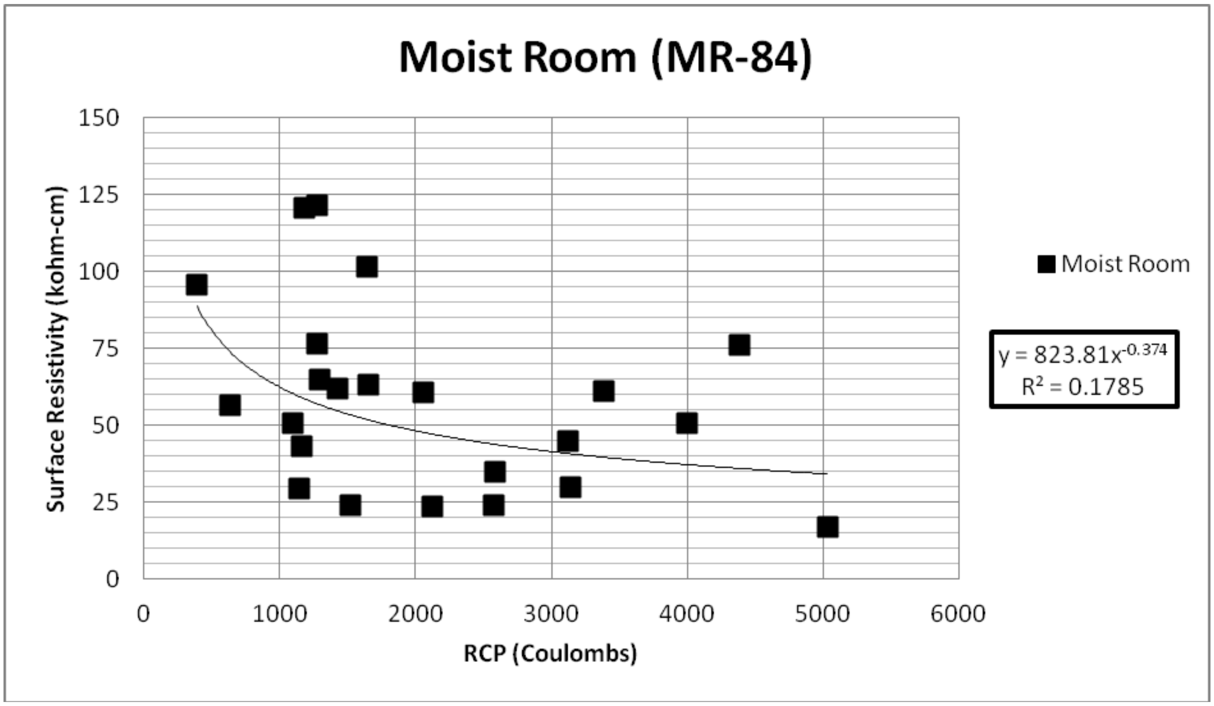

Figure 4: Moist Room correlation (R^2 = 0.1785)

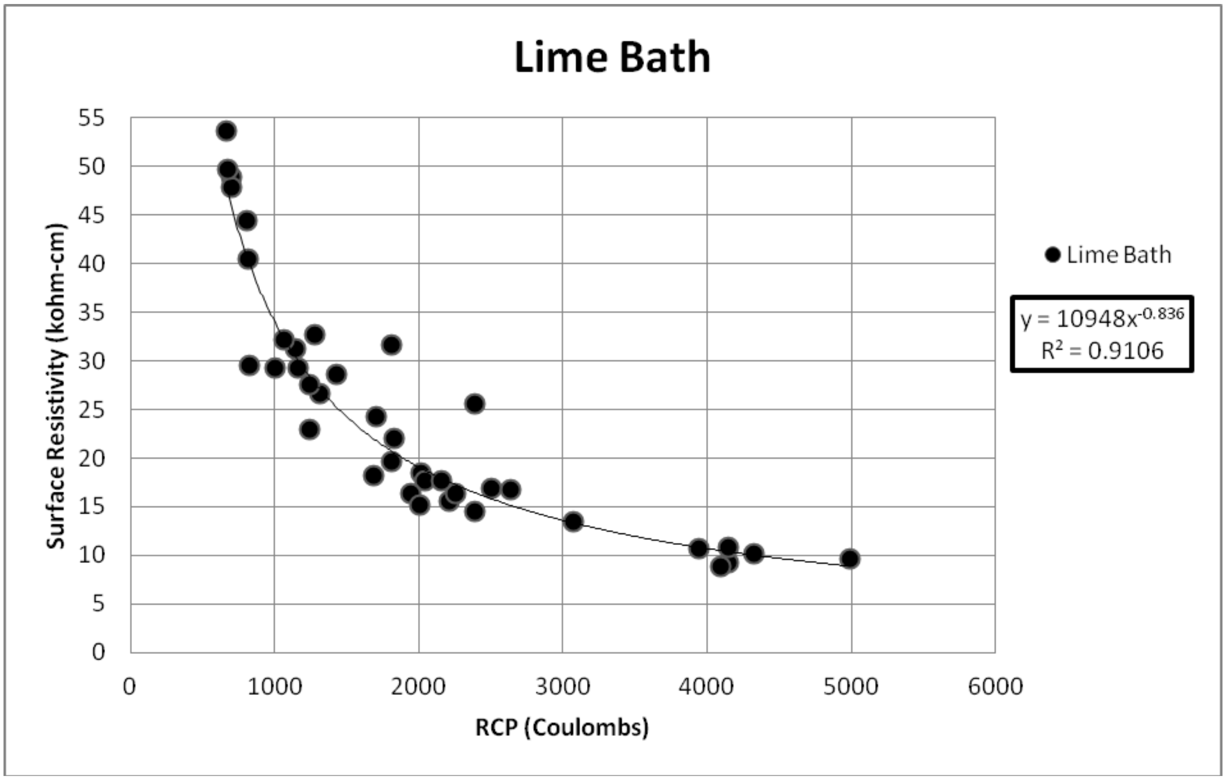

Figure 5: RCP to SR correlation for Lime Bath Samples (R^2 = 0.9106,)

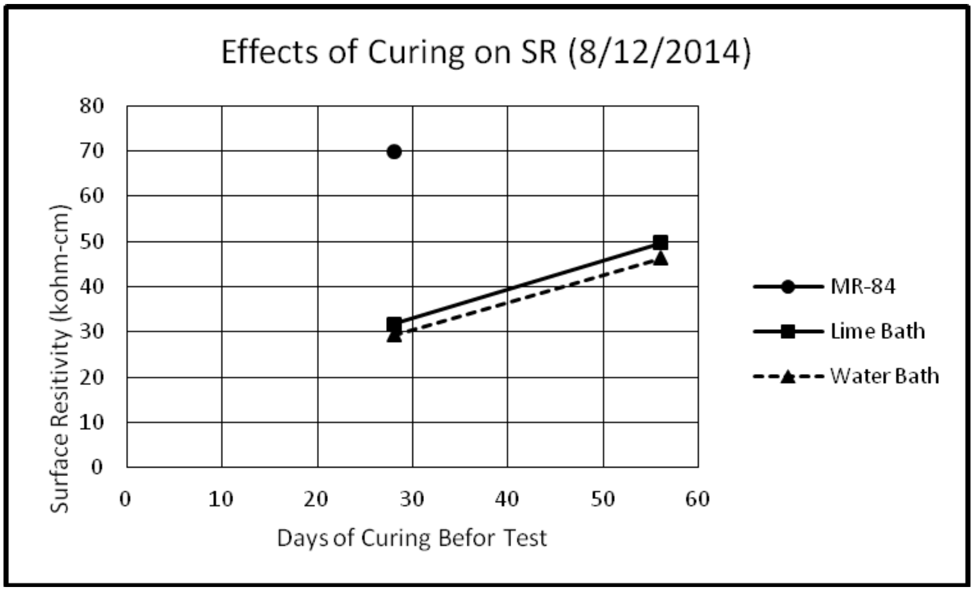

Figure 6: Water Bath curing compared to LB and MR-84

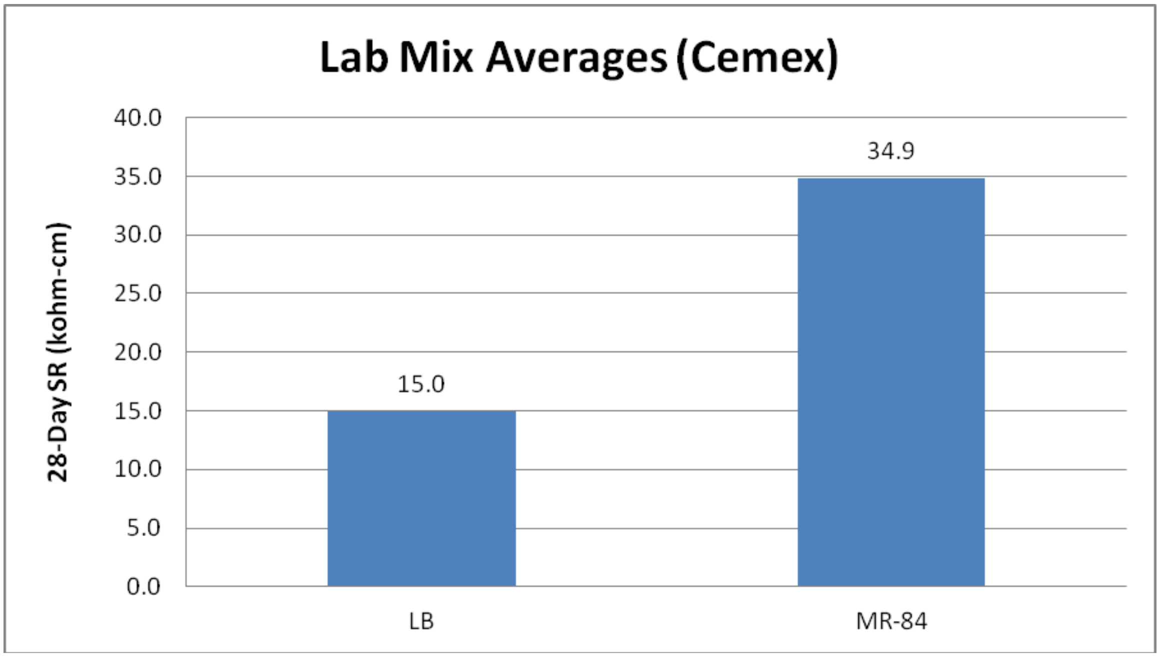

Figure 7: 28 Day Average SR Values (Lab Mixes, Cemex cement)

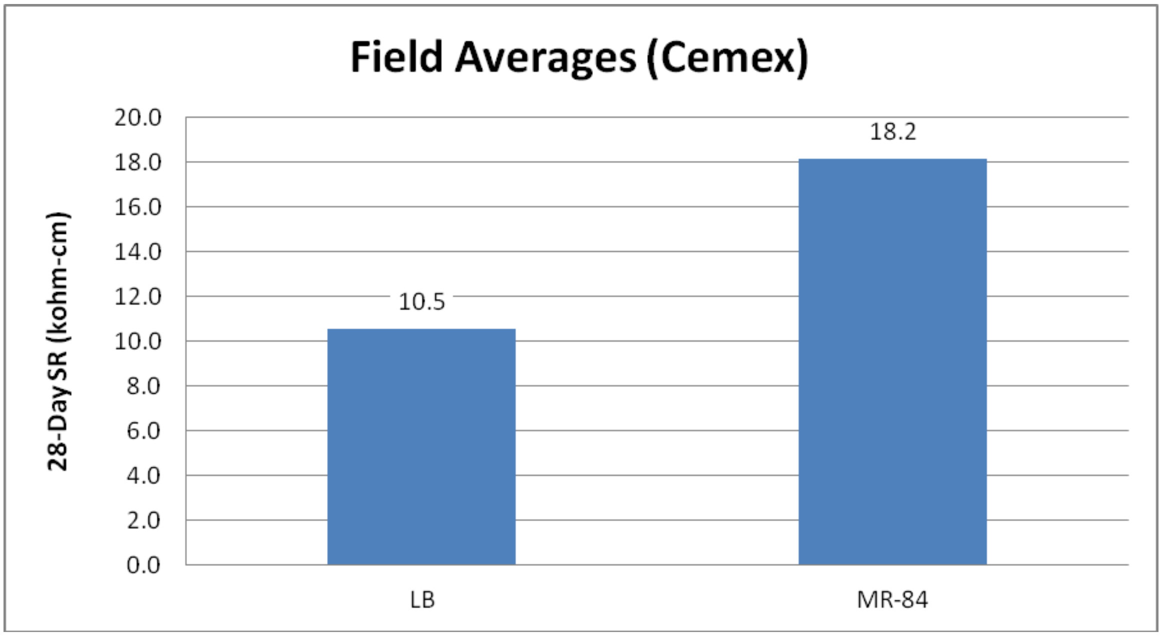

Figure 8: 28 Day Average SR Values (Field Mixes, Cemex cement)

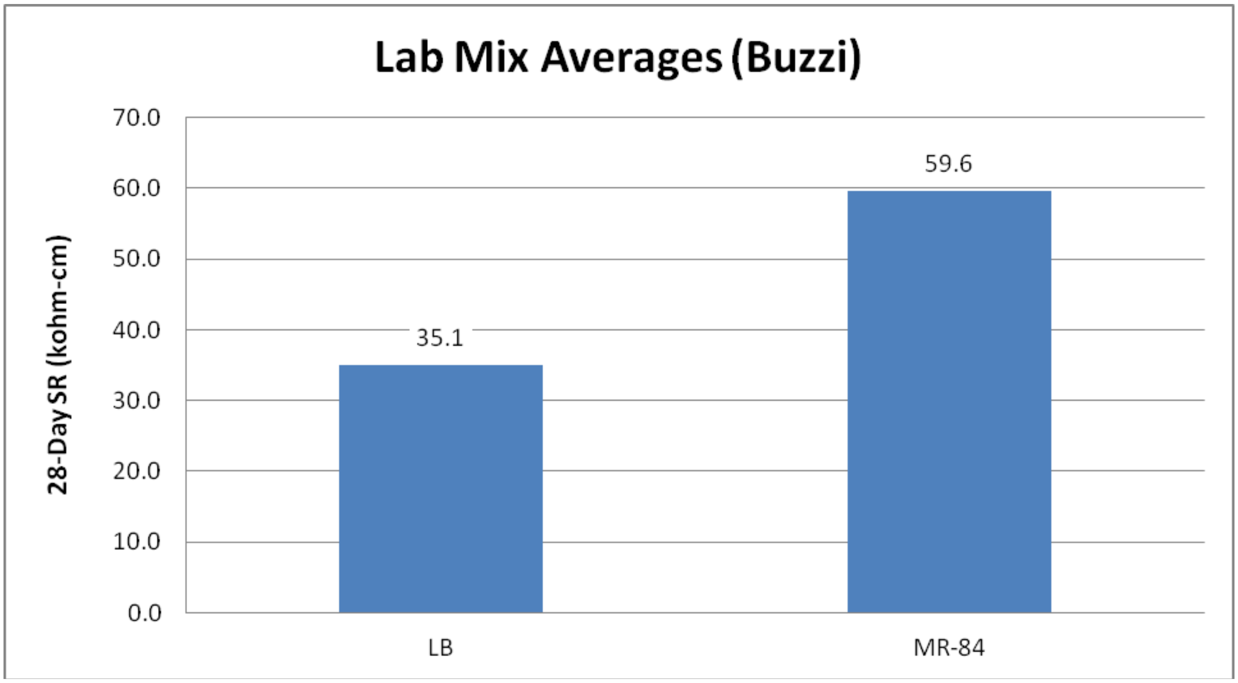

Figure 9: 28 Day Average SR Values (Lab Mixes, Buzzi cement)

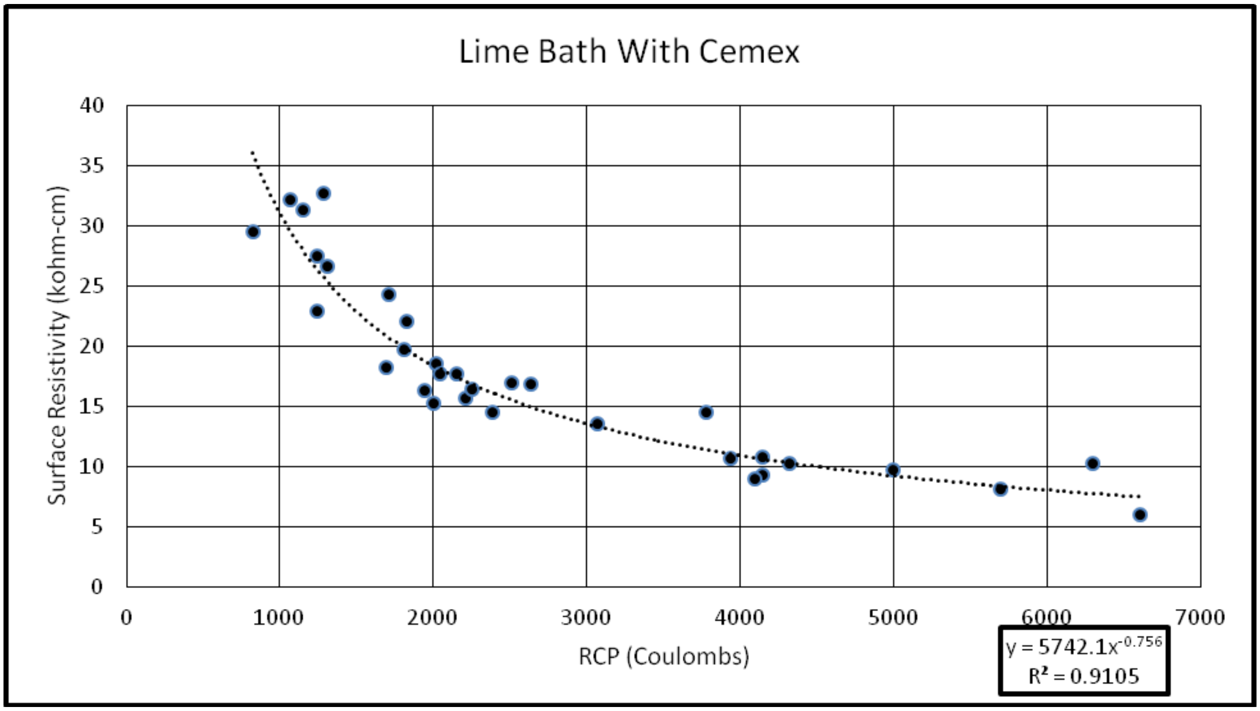

Figure 10: SR vs RCP for Lab mixes using Cemex and LB cured.

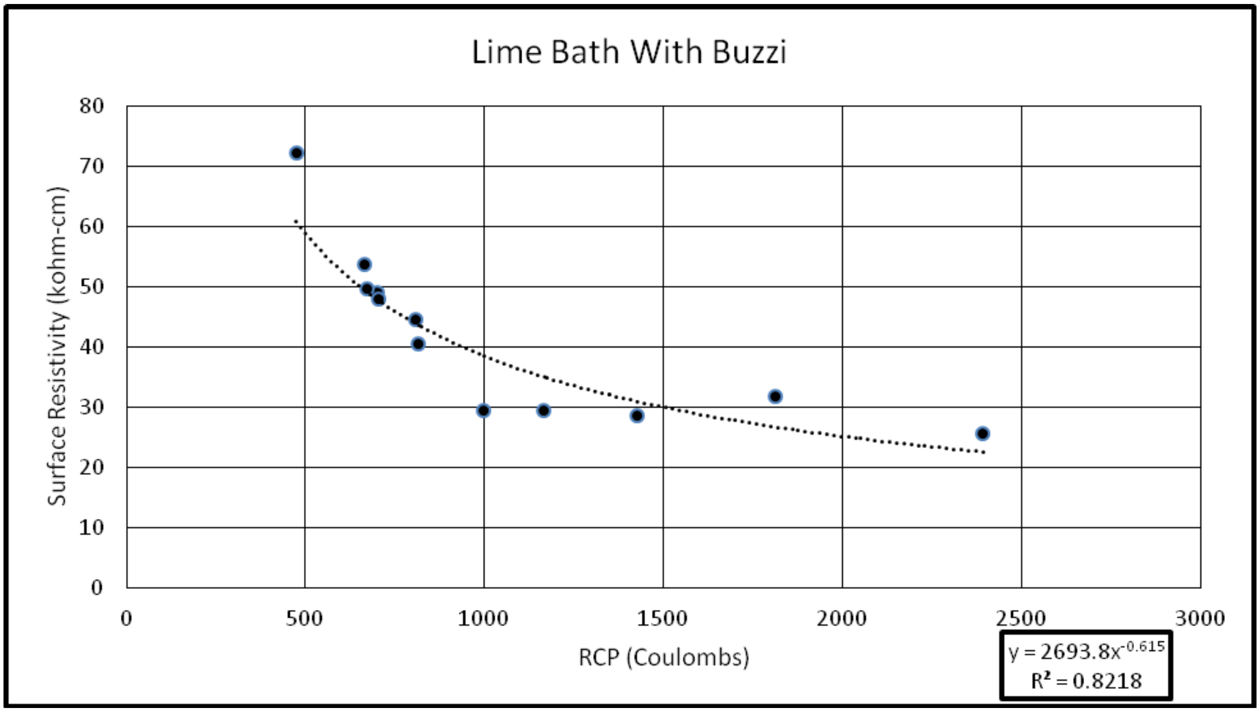

Figure 11: SR vs RCP for Lab mixes using Buzzi and LB cured.

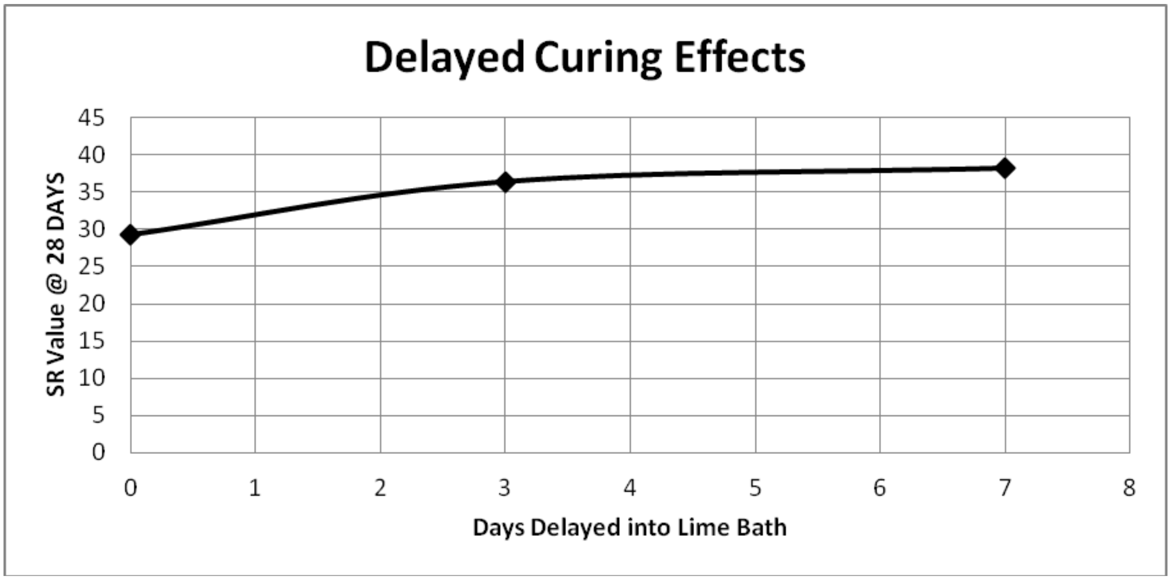

Figure 12: Effects of delayed curing on SR values

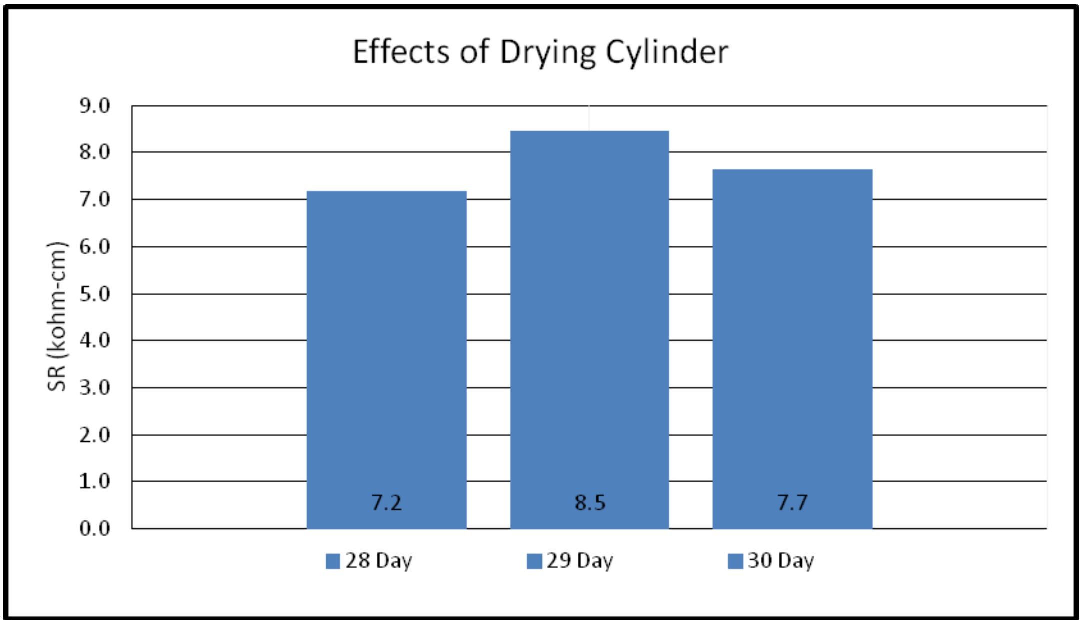

Figure 13: The effects of the cylinder drying before testing.

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ATTACHMENT 2

Cold Weather Mixing and Curing Testing for Strength and SR Results

Lightweight Concrete for Tennessee Bridge Decks

Cold Weather Mixing and Curing Testing for Strength and SR Results

To: The Tennessee Department of Transportation
Research Development and Technology Program

Report Period:

February 1, 2015 to March 13, 2015

Project #: RES 2013-18
EG 1438333

Agreement Period
From: August 1, 2013 To: July 31, 2018

Disclaimer

This report is disseminated for review purposes only and as such is regarded as proprietary. The information contained in this document will be shared at the discretion of TDOT management.

1.0 Background

At the start of February 2015, the research group was approached with concerns over cold weather effects, primarily on strength, for concrete being placed in Morristown Tennessee. The concern stems from a 7 day break for a cylinder that was cast on November 24, 2014. That cylinder fell below expectations and broke at 2042 psi. When projected to 28 days, this specimen would not meet a 4,000 psi specification requirement. The cause was first speculated to be the cold weather. In order to identify the cause of this low break, an identical mix was conducted in the lab at UT.

The understanding of the research group is that when cylinders are cast in the field some are cured overnight while others are cured for up to 21 days in the field before being exposed to proper laboratory curing conditions. The specimens that are field cured overnight are then taken to TDOT and cured in a moist room until testing. The specimens that are field cured for up to 21 days are then transported to a ready mix testing facility and are cured in a lime bath until testing.

The field curing box used in each case is comprised of a plywood box lined with insulating foam to protect the specimens from direct exposure to the environment. However, these boxes are not temperature or humidity controlled and are not sealed.

1.1 Mix Used

To best replicate this specific cylinder, the mix used in the lab was the exact mix identified in the mix report. A mix with 670lbs per yard of cementitious material was used and proportioned to 60/20/20 (Cement/Fly Ash/ Slag). Table 1 below shows the mix used by the lab, and the mix report from casting in the field can be found at the end of this report. Both the lab and the filed mixes use Cemex cement. There is a difference in chemical admixtures used for air entrainment and water reduction, but this difference should not impact strength or surface resistivity results.

Table 1: Lightweight Mix Design

Lightweight Ternary 60/20/20 Mix		
W/C Ratio		0.4
Total Cementitious Material Content (lb/yd^3)		670
Cement (lb/yd^3)		402
Fly Ash (lb/yd^3)		134
Slag (lb/yd^3)		134
Water (lb/yd^3)		268
Aggregates (lb/yd^3)	#57 LW	930
	Natural Sand	1297

1.2 Mixing and Casting

To directly compare the cold weather casting and curing effects, the specimens were divided into 3 groups, depending on curing method. Each group, A, B and C, is detailed at the end of this section. In order to eliminate effects created by small mixing differences, all 36 specimens where batched and cast at one time.

Simulated cold weather mixing and casting was conducted on February 12, 2014. The mixing laboratory was sealed off from the rest of the building by closing all doors and vents. The garage door was then left open and the heat to the space was turned off. The temperature outside was 28°F. After three hours, the ambient room temperature stabilized and was recorded at 52°F. The room was able to maintain this temperature during mixing and casting. Mixing was then conducted per ASTM standards with mixture temperature, air and slump measurements recorded.

The concrete mixing went smoothly with no issues to report. The concrete temperature at the time of casting was 56^{o}F, and the mix had a slump of 9.25 inches. The air content was measured using the rolameter at 3.50%, lower than that of the field mix. The lower air content should have minimal affects on the results of these tests. It is possible that specimens undergoing field curing could be exposed to freezing temperatures, and as a result, damage due to the lack of air voids could occur. The results should help to indicate if this damage has occurred.

The most difficult variable to eliminate and control for this experiment was the weather. Figure 1 shows the average temperature for the first 21 days after the cylinders were cast for the actual casting and the replica mix conducted in the lab. From this figure it is clear that the laboratory replica mix was exposed to much colder curing temperatures. Figures 2 and 3 have also been included to show the temperature trends, low, medium and high temperature for each 21 day period after casting. A second difference is the amount of precipitation that the filed curing sites received. The actual casting saw 12 days of precipitation during the first 21 days while the lab replica received precipitation on 16 of the 21 days. However, as figure 4 shows, the 21 days after the actual casting had generally higher humidity levels than that of the replica mix. All of these data seem to indicate that the actual field casting was exposed to more favorable conditions and should have had better results than those obtained from the replica mix cast in the lab if cold weather was the cause of the poor strength test results.

<u>Group A</u>: Group A is used as an experimental control for the other groups of cylinders being evaluated. Group A includes 12 cylinders which were cured overnight in cylinder molds stored in the moist room. After 24 hours the molds were removed, and 9 cylinders were placed in the

lime bath while 3 cylinders were placed in the moist room. Surface resistivity (SR) testing was conducted on cylinders stored in each environment, while breaks are done on those in the lime bath as that is considered the typical laboratory curing method for this project.

Group B: Group B was used in this set of experiments to simulate overnight field curing effects. Group B also consisted of 12 cylinders that were cured overnight in cylinder molds but left in a field curing box. After 24 hours the molds were removed and 3 cylinders were placed in the lime bath while 6 cylinders were placed in the moist room. Surface resistivity (SR) testing was conducted on cylinders stored in each environment, while breaks were done on those in the moist room as that is considered the typical curing method used by TDOT.

Group C: Group C was used in this set of experiments to simulate extended field curing (21 Days) effects. Group C also consisted of 12 cylinders which were placed in the field curing box for 21 days. After 21 days, 3 cylinders were placed in the moist room, while 6 were placed in the lime bath, with 3 cylinders having been used for 7 day breaks. Surface resistivity testing was conducted on cylinders cured in each environment while cylinders for breaks are cured in the lime bath.

2.0 Results

2.1 Strength

Based on the tests conducted in the lab, reaching a strength of 4,000 psi at 28 days was not an issue. All strength values are reported in table 2 below. For each test, three cylinders were loaded and then the results averaged. The only set that showed any concern were the 7 day results on specimens from group C, that were still in the field curing box at that time. These specimen failed at significantly lower stresses than those placed in the lime bath or moist room at 24 hours from groups A and B. The cylinders from group C also reached a 28 day strength lower than that of cylinders of the other groups. However, all three performed well and met the 4,000 psi strength requirement at 28 days. Final 56 day load testing on these specimen will be concluded on April 9th, 2015. By reaching higher strengths, the possibility of damage due to freezing of the concrete with lower air entrainment can be eliminated.

Table 2: Compressive Strength Results

	Lab Curing (LB)	Overnight Field Curing (MR)	21 Day Field Curing (Box/LB)
7 Day f'c Average (psi)	5686	5069	2537
28 Day f'c Average (psi)	7338	7494	6163

2.2 Surface Resistivity (SR)

This testing regimen revealed a great deal of information about the effects curing, especially field curing, has on SR results and the rate of resistance gain. In order to capture initial gain, SR readings were taken 24 hours after casting had occurred as the cylinders where removed from the molds. Also, for this experiment on curing effects, SR readings were taken every 7 days from all three groups and from each location in which that group was being cured; moist room, lime bath, or field box. So far, although all SR results were disappointingly low, the cylinders that are in group A, cured according to laboratory procedures, have consistently shown the highest surface resistivity. A summary of all SR values are presented in table 3.

Figures 5, as well as figures 6(lime bath) and 7 (moist room) compare the SR results for each group. The figures show the best resistance in group A with group C showing the least amount of resistance gain. It is important to note the specimens in group C, in figures 5, 6 and

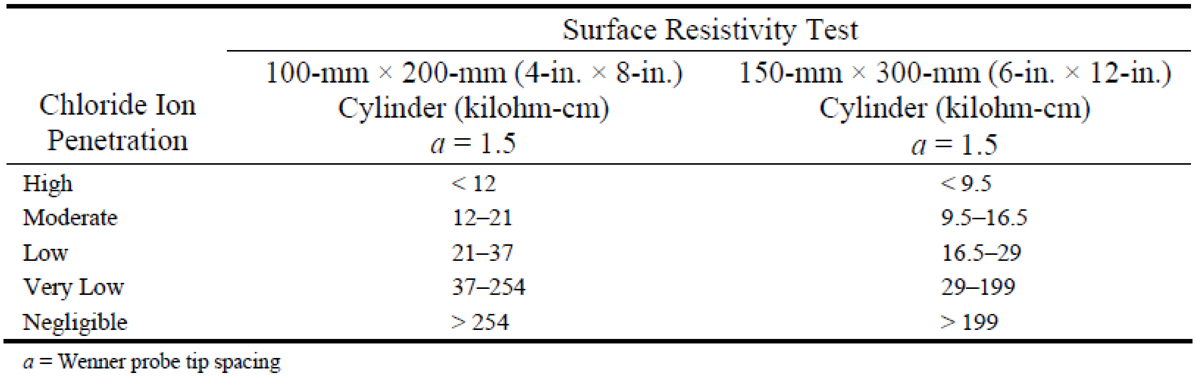
7, experienced a much higher increase in resistance after day 21 when they were exposed to proper curing methods and hydration source. However, most results still fall in very high permeability range. Only group A and the moist room sample from group B fall above the High Chloride Ion Penetration range.

Figures 8, 9 and 10 present the SR results for each group A, B and C respectively. Each figure has two lines representing the cylinders being placed in the moist room or the lime bath after initial curing. In figures 8 and 9, the initial results show higher resistance for specimen in the lime bath. However, the moist room results would surpass the lime bath results between 7 and 14 days for group B and between 14 and 21 days for group A. Based on trend lines, samples being cured in the moist room will continue to grow faster than those in the lime bath. The moist room resistance increase has been linear while the lime bath results have started to curve as the trend line indicates Figure 9 does not have any trend lines plotted at 28 days. The graph does indicate that the SR values did not increase beyond the 4.2 that was seen at 7 days until the specimens are exposed to proper curing environments. When exposed to proper curing method, the added moisture assist with the hydration process of the cement paste. The specimen cured in the moist room for, group C did show the greater improvement than lime bath samples, but the small difference could be considered negligible.

Table 3: Summary of SR Results. (MR: Moist Room, LB: Lime Bath, FB: Field Box)

Day of Test	Group A		Group B		21 Day Field Curing	
0	0		0		0	
1	2.3 (MR)		1.7 (FB)		1.7 (FB)	
7	4.7 (MR)	5.8 (LB)	4.0 (MR)	4.4 (LB)	4.2 (FB)	
14	7.8 (MR)	8.4 (LB)	6.8 (MR)	6.6 (LB)	4.0 (FB)	
21	10.9 (MR)	10.5 (LB)	9.8 (MR)	8.2 (LB)	3.9 (FB)	
28	13.8 (MR)	13 (LB)	12.6 (MR)	10.2 (LB)	6.5 (MR)	6.2 (LB)
35	16.9 (MR)	16.5 (LB)	15.5 (MR)	13.2 (LB)	10.0 (MR)	9.8 (LB)
42	19.1 (MR)	18.7 (LB)	18 (MR)	14.6 (LB)	13 (MR)	12.4 (LB)
49	22.3 (MR)	21.1 (LB)	20.3 (MR)	16.5 (LB)	16.3 (MR)	15.2 (LB)
56	25.0 (MR)	23.6 (LB)	22.7 (MR)	18.4 (LB)	19.4 (MR)	17.6 (LB)

Table 4: Ranges for SR results



Chloride Ion Penetration	Surface Resistivity Test	
	100-mm × 200-mm (4-in. × 8-in.) Cylinder (kilohm-cm) $a = 1.5$	150-mm × 300-mm (6-in. × 12-in.) Cylinder (kilohm-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

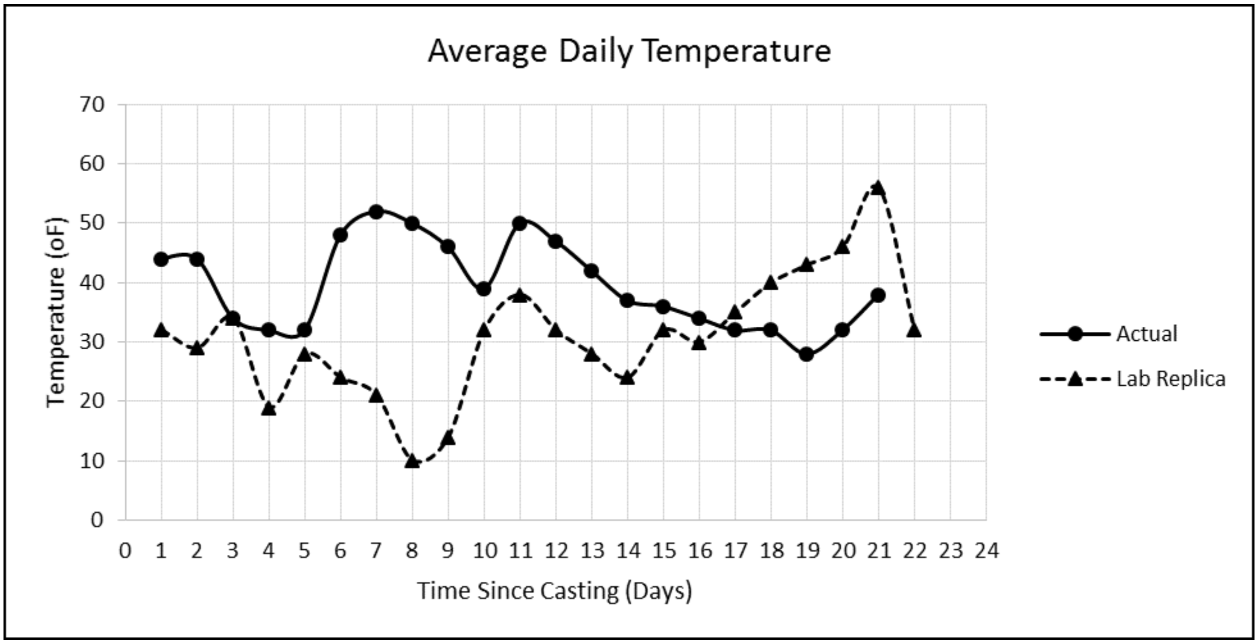


Figure 1: Average Daily Temperatures

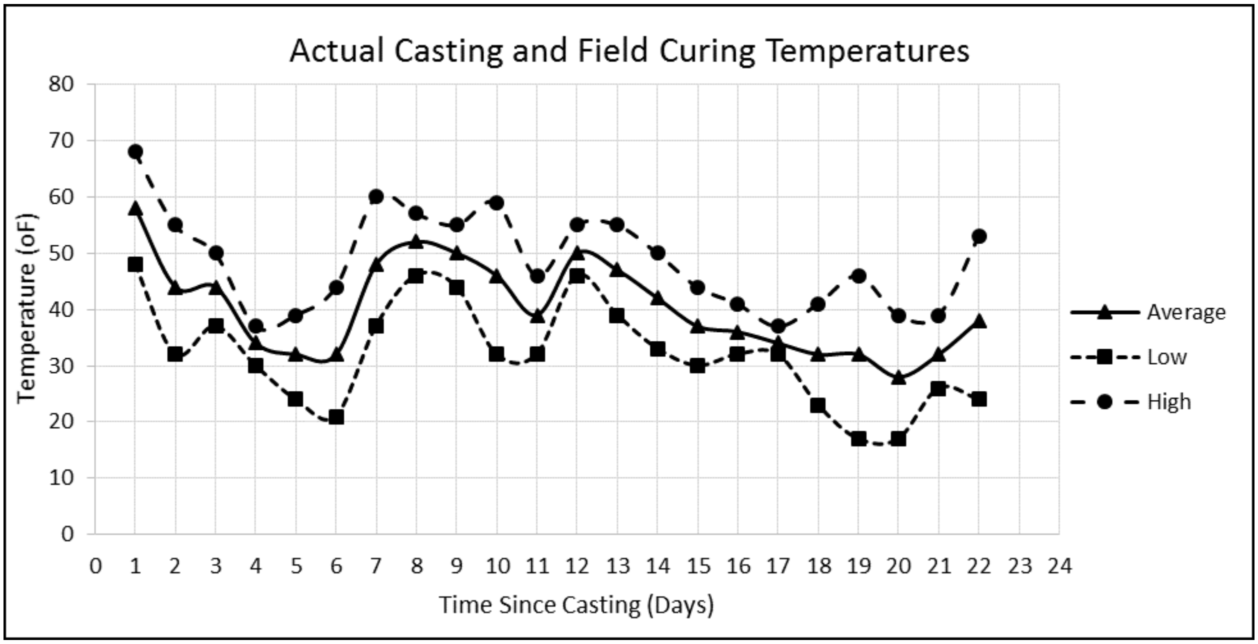


Figure 2: Daily Temperature changes during actual casting

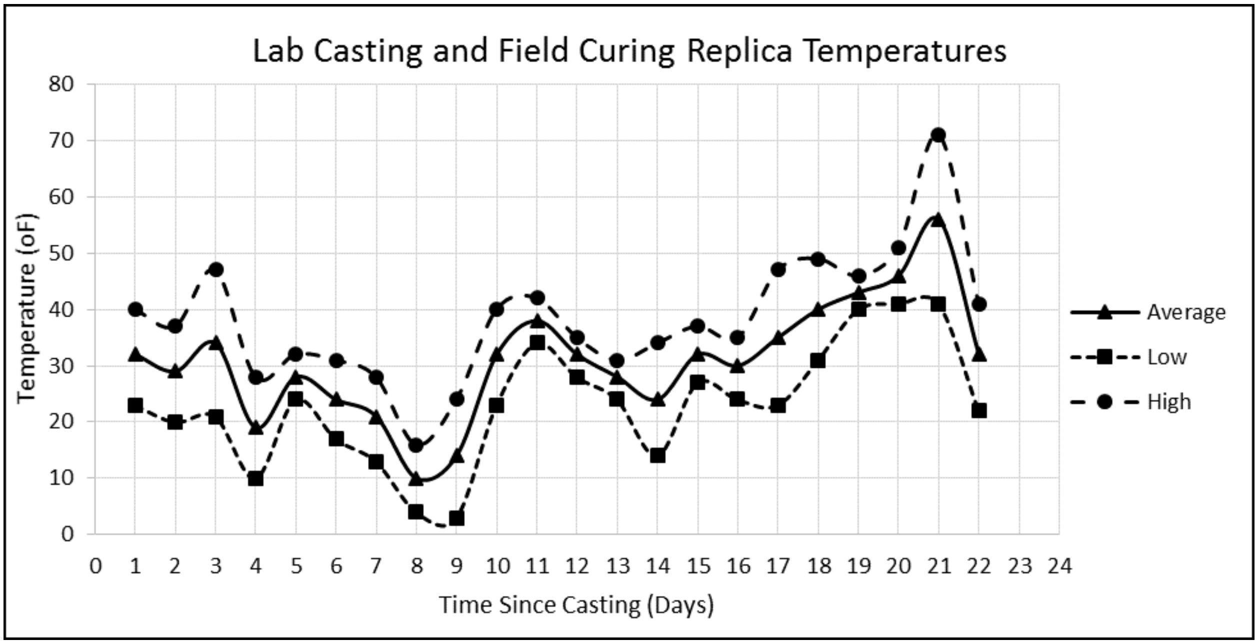


Figure 3: Daily Temperature Change during replica mix

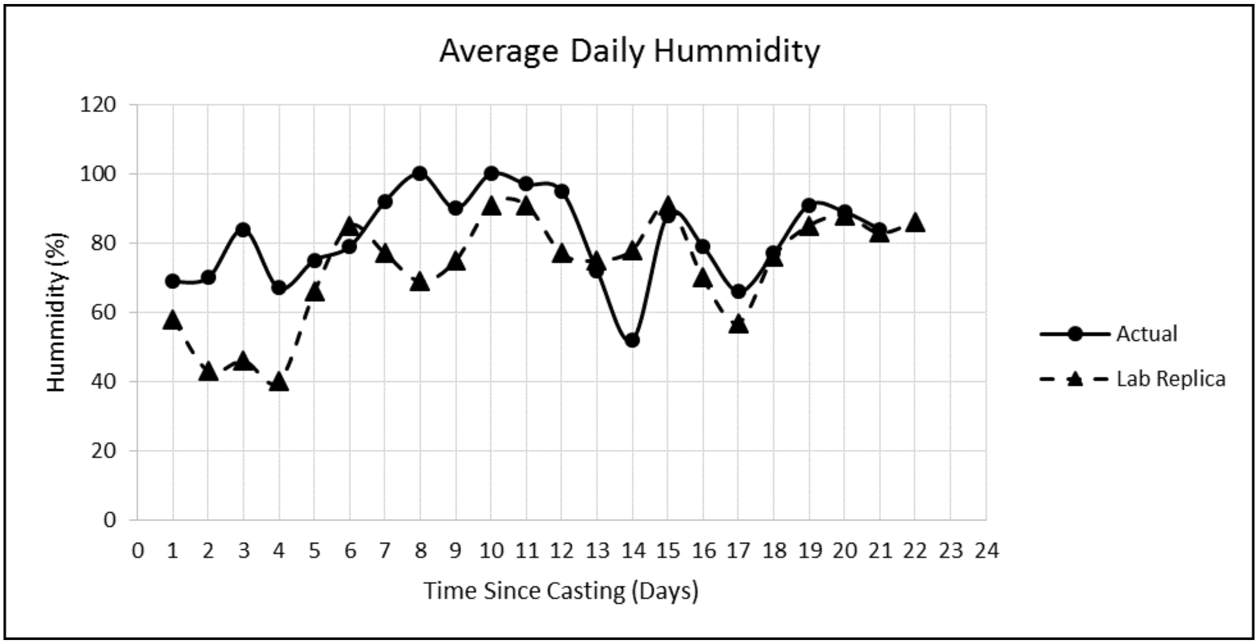


Figure 4: Average Daily Humidity.

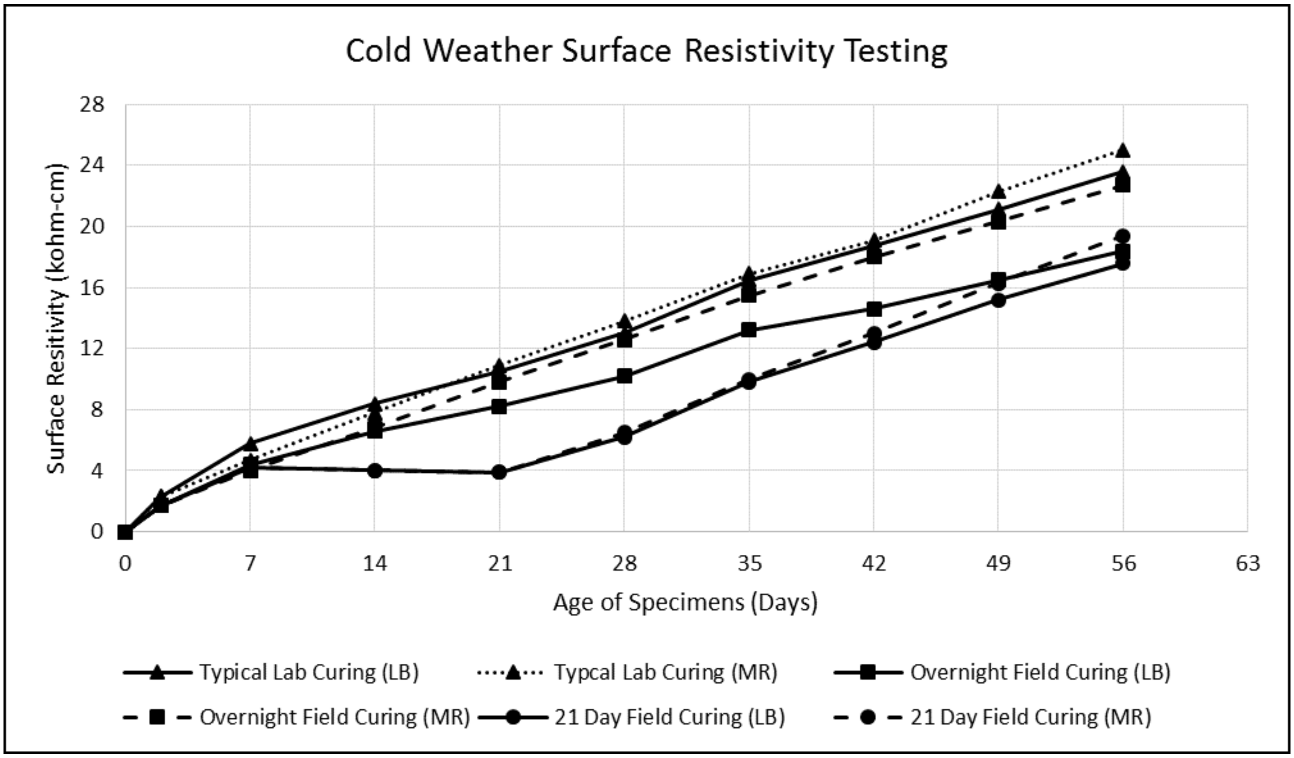


Figure 5: Comparison of all Surface Resistivity Results

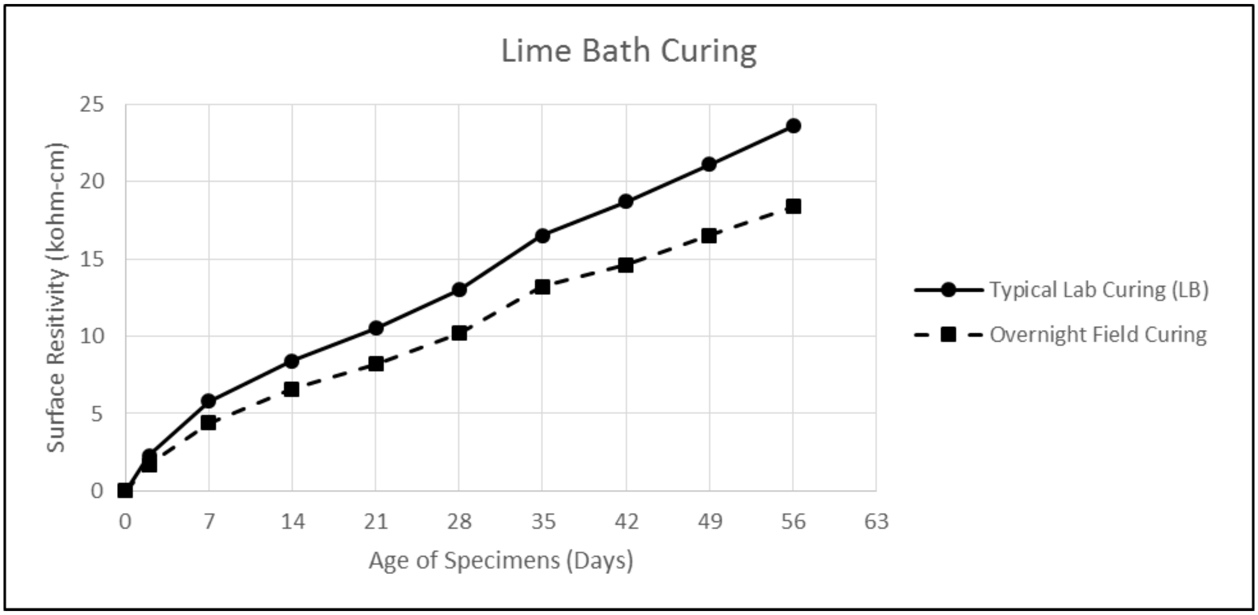


Figure 6: Lime Bath Results

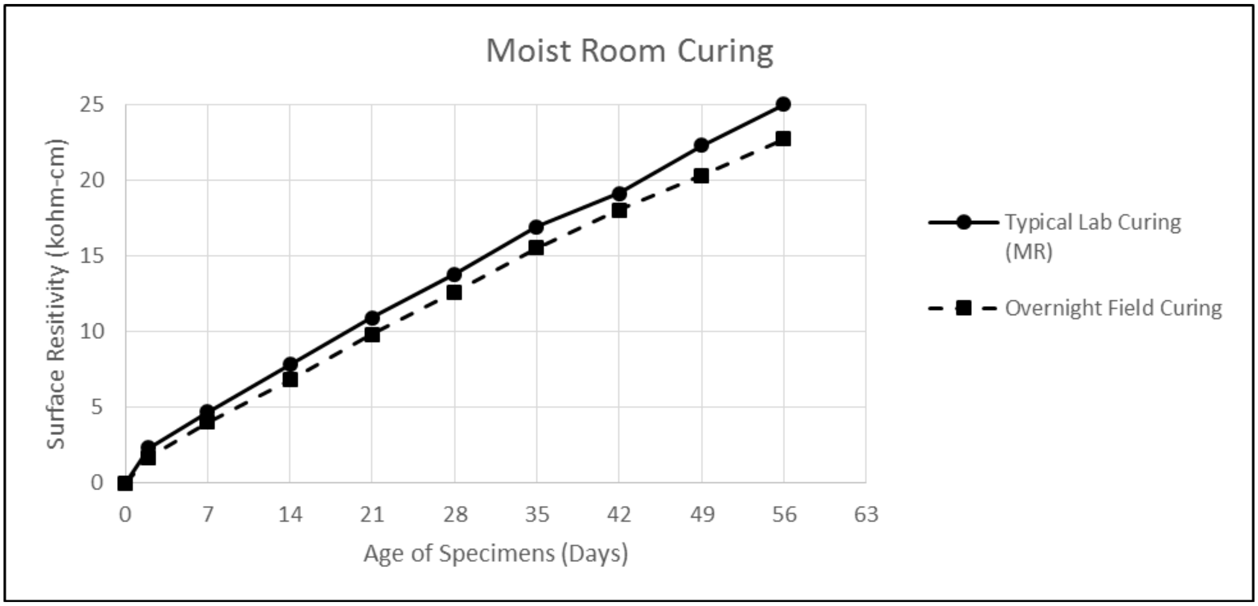


Figure 7: Moist Room Results

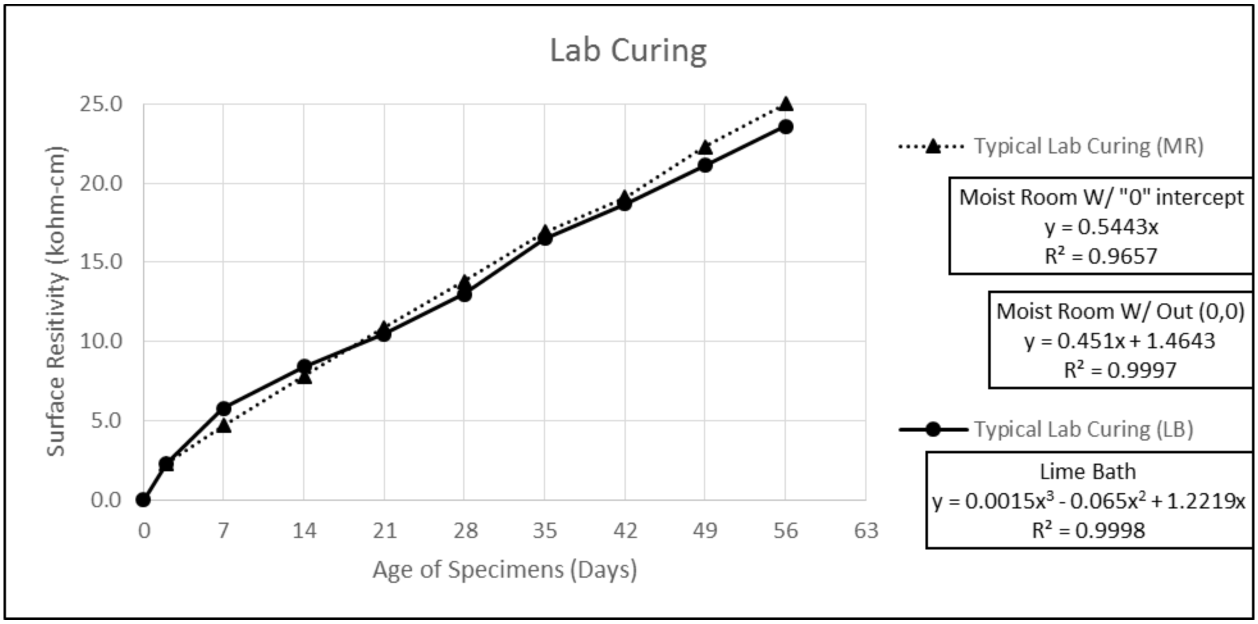


Figure 8: Group A; Typical Laboratory Curing

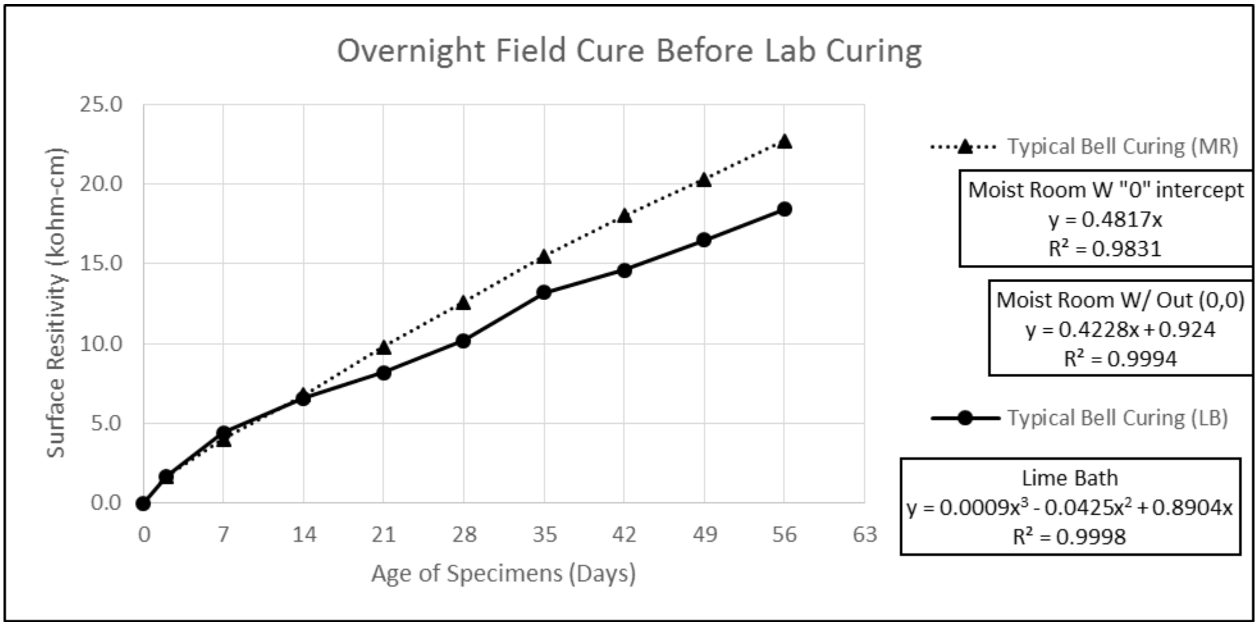


Figure 9: Group B; Overnight Field Curing

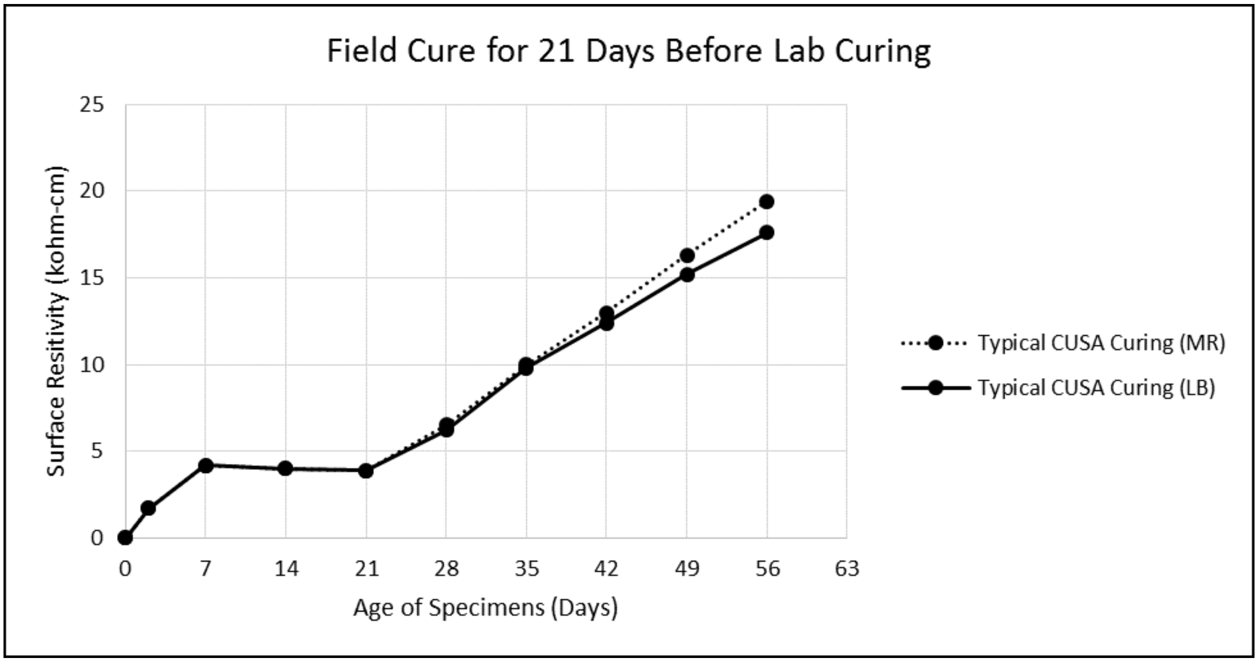
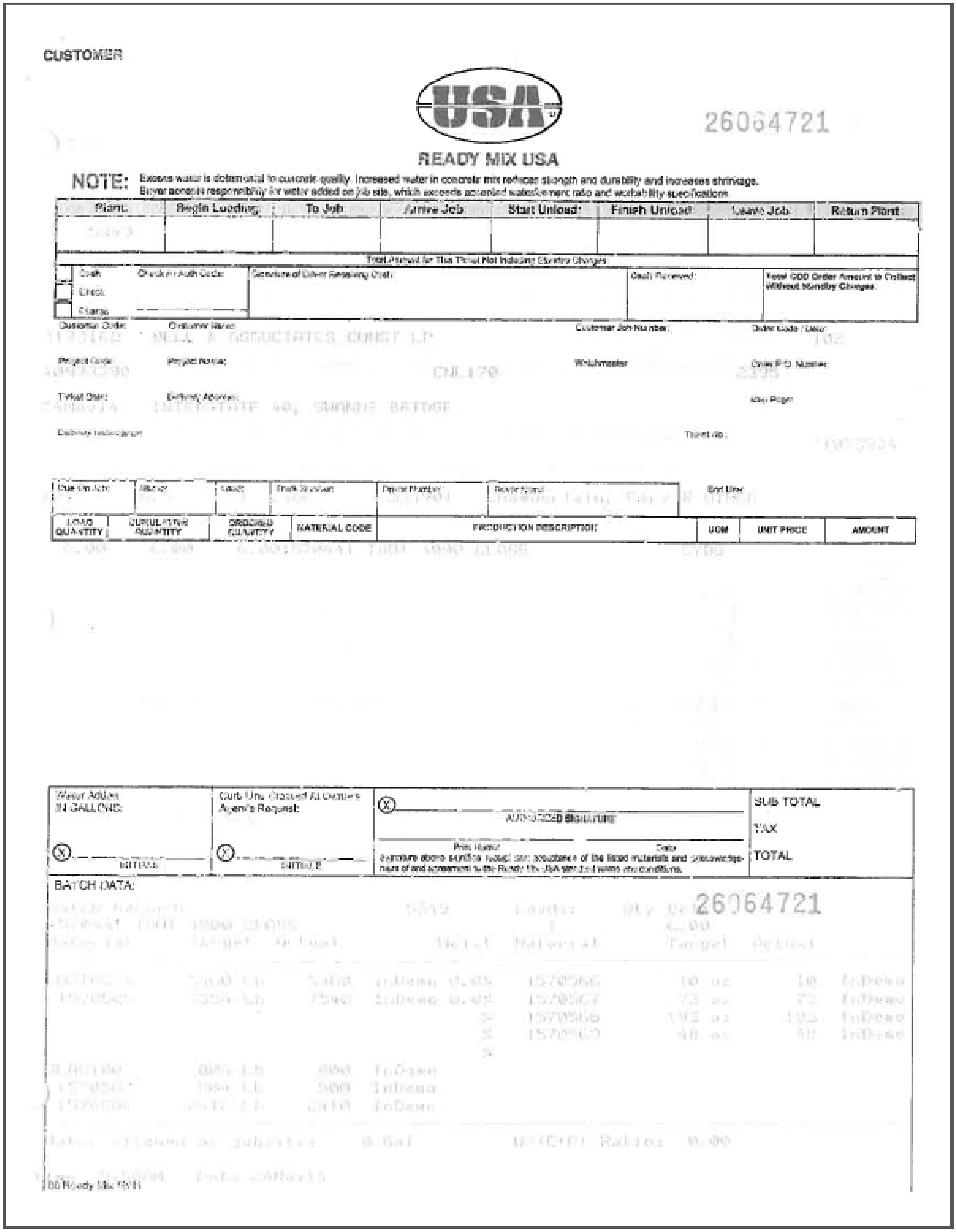


Figure 10: Group C; 21 Day Field Curing



CUSTOMER

26064721

READY MIX USA

NOTE: Excess water is detrimental to concrete quality. Increased water in concrete mix reduces strength and durability and increases shrinkage. Buyer accepts responsibility for water added on job site, which exceeds accepted water/cement ratio and workability specifications.

Plant:	Begin Loading:	To Job:	Arrive Job:	Start Unload:	Finish Unload:	Leave Job:	Return Plant:
5519							

Total Amount for This Ticket Not Including Standby Charges

☐ Cash
☐ Check
☐ Charge

Check # or Auth Code:

Signature of Driver Receiving Cash:

Cash Received:

Total COD Order Amount to Collect Without Standby Charges:

Customer Code: 133162
Customer Name: BELL & ASSOCIATES CONST LP
Customer Job Number:
Order Code / Date: 102

Project Code: 40973290
Project Name: CNL170
Weighmaster:
Order P.O. Number: 2395

Ticket Date: 24Nov14
Delivery Address: INTERSTATE 40, SWORDS BRIDGE
Map Page:

Delivery Instructions:
Ticket No.: 1972934

Due On Job:	Slump:	Load:	Truck Number:	Driver Number:	Driver Name:	End User
[illegible]	[illegible]	1	2106	5217901	[illegible]	

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	MATERIAL CODE	PRODUCTION DESCRIPTION	UOM	UNIT PRICE	AMOUNT
6.00	6.00	6.00	1570441	1000 4000 CLASS	CYDS		

Water Added IN GALLONS: Ⓧ INITIALS	Curb Line Crossed At Owner's Agent's Request: Ⓧ INITIALS	Ⓧ AUTHORIZED SIGNATURE Print Name / Date Signature above signifies receipt and acceptance of the listed materials and acknowledgement of and agreement to the Ready Mix USA standard terms and conditions.	SUB TOTAL TAX TOTAL

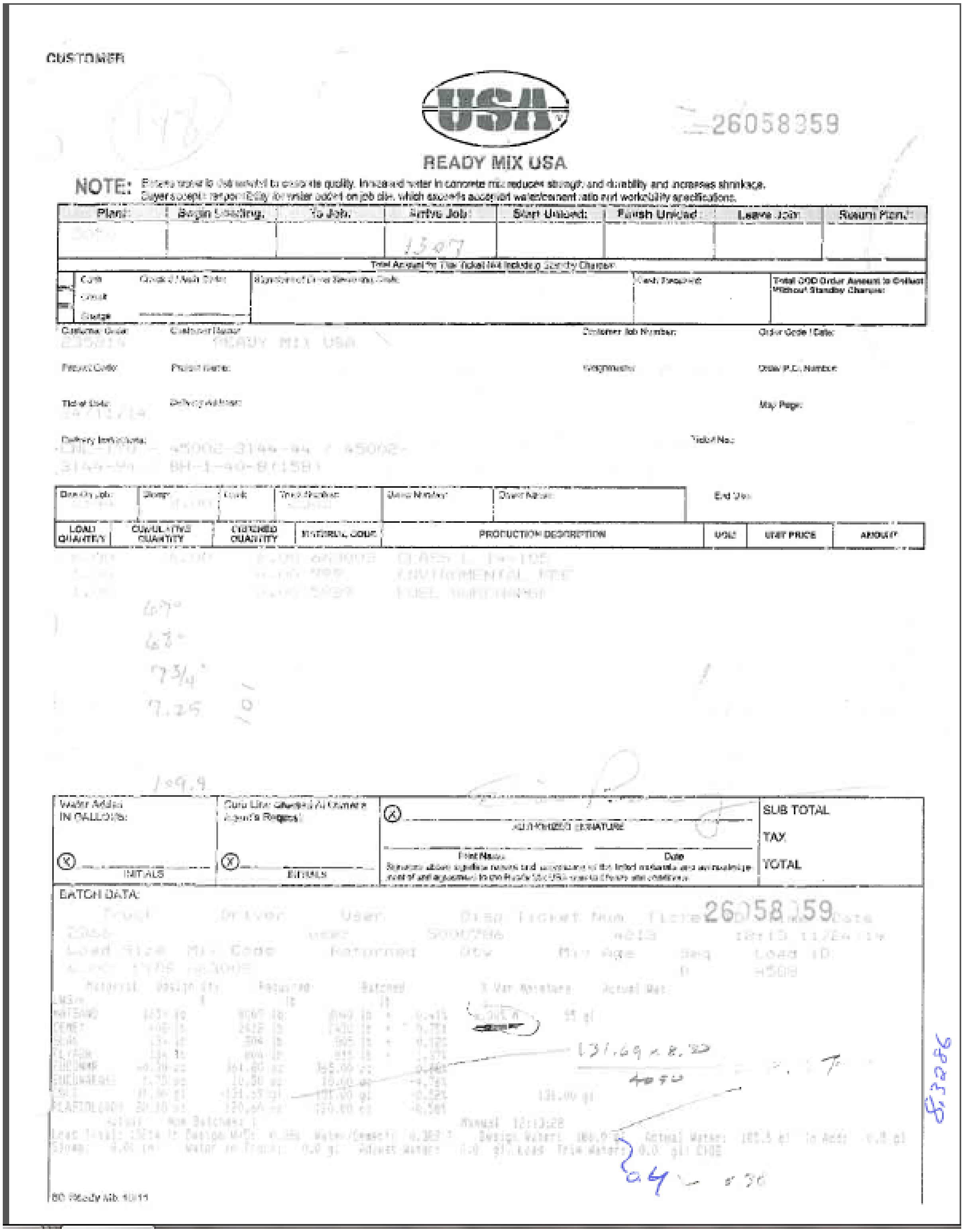
BATCH DATA:

```
Batch Record:                   5519     Loads:      Qty Del: 26064721
1570441  1000 4000 CLASS                   1          6.00
Material     Target  Actual        Moist  Material       Target  Actual
[illegible]  5400 Lb  5400 InDemo  0.0%   1570566        10 oz    10  InDemo
1520585      7554 Lb  7540 InDemo  0.0%   1570567        72 oz    72  InDemo
                                   %      1570566       192 oz   192  InDemo
                                   %      1570563        48 oz    48  InDemo
                                   %
8.00100       000 Lb   000 InDemo
1570507       000 Lb   000 InDemo
1570508      2610 Lb  2610 InDemo

Water allowed on jobsite:   0 Gal        W/(C+P) Ratio:  0.00

Time: 7:50AM   Date: 24Nov14
```

BB Ready Mix 10/11



CUSTOMER

READY MIX USA

26058359

NOTE: Excess water is detrimental to concrete quality. Increased water in concrete mix reduces strength and durability and increases shrinkage. Buyer accepts responsibility for water added on job site, which exceeds accepted water/cement ratio and workability specifications.

Plant:	Begin Loading:	To Job:	Arrive Job:	Start Unload:	Finish Unload:	Leave Job:	Return Plant:
			13:07				

Total Amount for This Ticket Including Standby Charges:

Cash / Check / Charge | Signature of Driver Receiving Cash: | Cash Received: | Total COD Order Amount to Collect Without Standby Charges:

Customer Order: 235214 | Customer Name: READY MIX USA | Customer Job Number: | Order Code / Date:

Project Code: | Project Name: | Weighmaster: | Order P.O. Number:

Ticket Date: 11/24/14 | Delivery Address: | Map Page:

Delivery Instructions:
CNE-170 - 45002-3144-94 / 45002-
3144-94 BH-1-40-B(15B)

Ticket No:

Due On Job: | Slump: | Truck: | Truck Number: | Driver Number: | Driver Name: | End Use:

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	MATERIAL CODE	PRODUCTION DESCRIPTION	UOM	UNIT PRICE	AMOUNT
8.00	8.00	8.00	663005	CLASS 1 14-105			
1.00		1.00	999	ENVIRONMENTAL FEE			
1.00		1.00	5997	FUEL SURCHARGE			

67°
68°
73¼°
7.25
109.9

Water Added IN GALLONS: ⓧ INITIALS

Curb Line Crossed At Owner's Agent's Request: ⓧ INITIALS

ⓧ AUTHORIZED SIGNATURE

Print Name | Date

SUB TOTAL
TAX
TOTAL

BATCH DATA:

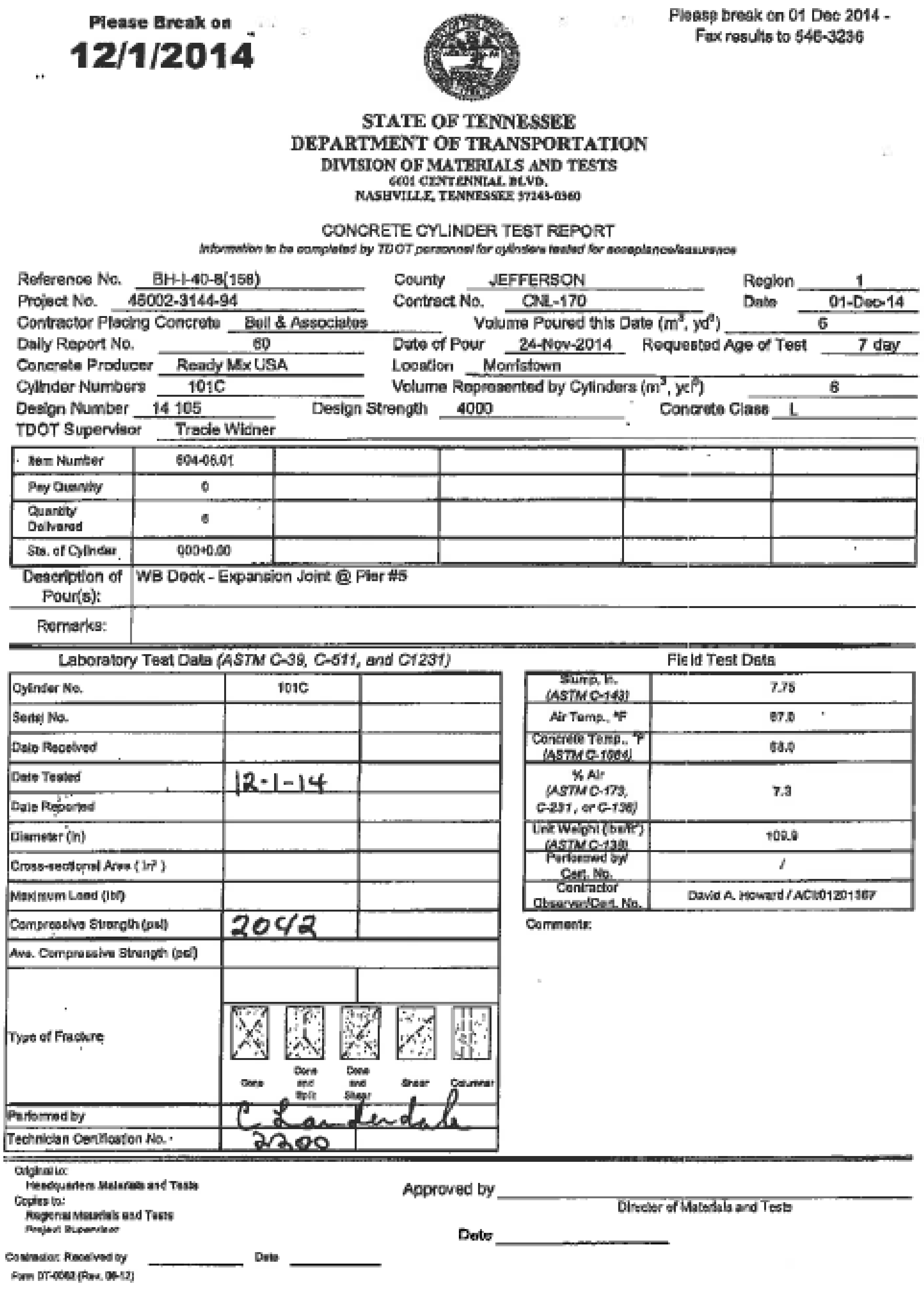
26058359

131.69 × 8.32
4050

.24 – .50

83286

80 Ready Mix 10/11



Please Break on
12/1/2014

Please break on 01 Dec 2014 -
Fax results to 546-3236

STATE OF TENNESSEE
DEPARTMENT OF TRANSPORTATION
DIVISION OF MATERIALS AND TESTS
6601 CENTENNIAL BLVD.
NASHVILLE, TENNESSEE 37243-0360

CONCRETE CYLINDER TEST REPORT
Information to be completed by TDOT personnel for cylinders tested for acceptance/assurance

Reference No. BH-I-40-8(158)
County JEFFERSON
Region 1
Project No. 45002-3144-94
Contract No. CNL-170
Date 01-Dec-14
Contractor Placing Concrete Bell & Associates
Volume Poured this Date (m^3, yd^3) 6
Daily Report No. 60
Date of Pour 24-Nov-2014
Requested Age of Test 7 day
Concrete Producer Ready Mix USA
Location Morristown
Cylinder Numbers 101C
Volume Represented by Cylinders (m^3, yd^3) 6
Design Number 14 105
Design Strength 4000
Concrete Class L
TDOT Supervisor Tracie Widner

Item Number	604-05.01				
Pay Quantity	0				
Quantity Delivered	6				
Sta. of Cylinder	000+0.00				

Description of Pour(s): WB Deck - Expansion Joint @ Pier #5

Remarks:

Laboratory Test Data *(ASTM C-39, C-511, and C1231)*

Cylinder No.	101C	
Serial No.		
Date Received		
Date Tested	12-1-14	
Date Reported		
Diameter (in)		
Cross-sectional Area (in^2)		
Maximum Load (lbf)		
Compressive Strength (psi)	2042	
Ave. Compressive Strength (psi)		
Type of Fracture	Cone / Cone and Split / Cone and Shear / Shear / Columnar	
Performed by	C. Lauderdale	
Technician Certification No.	2200	

Field Test Data

Slump, in. *(ASTM C-143)*	7.75
Air Temp., °F	87.8
Concrete Temp., °F *(ASTM C-1064)*	88.0
% Air *(ASTM C-173, C-231, or C-138)*	7.3
Unit Weight (lb/ft³) *(ASTM C-138)*	109.9
Performed by/ Cert. No.	/
Contractor Observer/Cert. No.	David A. Howard / ACI01201187

Comments:

Original to:
Headquarters Materials and Tests
Copies to:
Regional Materials and Tests
Project Supervisor

Approved by ____________________
Director of Materials and Tests

Date ____________________

Contractor Received by __________ Date __________
Form DT-0062 (Rev. 06-12)