

1-1-2011

Accelerated test methods for evaluating alkali-silica reactivity of recycled concrete aggregates

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ACCELERATED TEST METHODS FOR EVALUATING ALKALI-SILICA REACTIVITY
OF RECYCLED CONCRETE AGGREGATES

BY

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Ryerson University
2009

A Thesis Presented To Ryerson University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Applied Science
In The Program of
Civil Engineering

Toronto, Ontario, Canada, 2011

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ACCELERATED TEST METHODS FOR EVALUATING ALKALI-SILICA REACTIVITY
OF RECYCLED CONCRETE AGGREGATES

Master of Applied Science, 2011

Robert C. Johnson

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This thesis reports the findings of a study carried out to determine the effectiveness of Accelerated Tests in evaluating the Alkali-Silica Reactivity of Recycled Concrete Aggregates. The study evaluated the variability of the Accelerated Mortar Bar Test due to test variables as well as the single and multi-laboratory variation. The variability of the Concrete Microbar Test due to test variables and the correlation to results from Accelerated Mortar Bar and Concrete Prism Test results were also evaluated. The tests were corroborated by comparing the porosity, permeability and alkali binding capacity of samples tested by the accelerated tests. It was found that the Accelerated Mortar Bar Test provides acceptable results when the test variables, such as crushing method and absorption values, are carried out and evaluated properly. The Concrete Microbar Test was found to underestimate the expansion of reactive aggregates. However, the same test was found to provide good correlation to the expansion results of Concrete Prisms incorporating Supplementary Cementing Materials when the test duration was increased.

Acknowledgements

I owe all of this work to the mentorship of Dr. Medhat Shehata of Ryerson University. From my second year of undergraduate studies, where I was introduced to the Materials branch of Civil Engineering, he has encouraged me to meet the potential he saw in my work and his guidance has helped me reach where I am today. His knowledge and experience in researching Alkali-Silica Reaction in concrete and his commitment to sustainable developments in the concrete industry were a constant encouragement to my work.

The same gratitude is extended to my family who has supported me through all of the trials inherent to Graduate Studies. Without their support I would not have been able to devote my time to this research program and would never have reached my goals.

I must thank my friends and compatriots at Ryerson for their support and assistance during my time. Special thanks are owed to Anto Sucic and Brad Maguire for their work in the lab on my behalf. Their efforts made it possible to complete some of the most time and labour intensive portions of the research.

Table of Contents

| | |
|--|----------|
| Declaration of Authorship | ii |
| Abstract | iii |
| Acknowledgements | iv |
| List of Tables | xi |
| List of Figures | xiv |
| List of Appendices | xviii |
| | |
| 1 – Introduction and Objectives | 1 |
| 1.1 – Introduction..... | 1 |
| 1.2 – Research Significance..... | 3 |
| 1.3 – Research Objectives..... | 3 |
| 1.4 – Outline of Thesis..... | 4 |
| | |
| 2 – Literature Review | 7 |
| 2.1 – Alkali Silica Reaction in Concrete..... | 7 |
| 2.1.1 – Overview of Alkali Silica Reaction..... | 7 |
| 2.1.2 – Mechanism and Effect on Concrete..... | 8 |
| 2.1.3 – Testing of Aggregate for alkali Silica Reaction..... | 10 |
| 2.1.3.1 – Petrographic Analysis..... | 11 |
| 2.1.3.2 – Concrete Prism Test..... | 11 |
| 2.1.3.3 – Accelerated Mortar Bar Test..... | 12 |
| 2.1.3.4 – Concrete Microbar Test..... | 13 |
| 2.1.4 – Amelioration of Alkali Silica Reaction..... | 15 |
| 2.1.4.1 – Aggregate and Cement Selection..... | 15 |
| 2.1.4.2 – Use of Supplementary Cementing Materials..... | 15 |
| 2.1.4.3 – Use of Chemical Admixtures..... | 17 |
| 2.2 – Recycled Concrete Aggregate..... | 17 |
| 2.2.1 – Sources of Recycled Concrete Aggregate..... | 18 |
| 2.2.2 – Physical Characteristics of Recycled Concrete Aggregate..... | 18 |

| | |
|--|-----------|
| 2.2.3 – Strength of Concrete made with Recycled Concrete Aggregate..... | 19 |
| 2.2.4 – Durability of Concrete made with Recycled Concrete Aggregate..... | 20 |
| 2.3 – Alkali Silica Reaction in Recycled Concrete Aggregate..... | 21 |
| 2.3.1 – Considerations for the Mechanism and Effect of ASR in RCA..... | 21 |
| 2.3.2 – Considerations for the Testing of ASR in RCA..... | 22 |
| 2.3.2.1 – Considerations for the Concrete Prism Test..... | 23 |
| 2.3.2.2 – Considerations for the Accelerated Mortar Bar Test..... | 23 |
| 2.3.2.3 – Considerations for the Concrete Microbar Test..... | 24 |
| 2.3.3 – Amelioration of Alkali Silica Reaction in Recycled Concrete Aggregate..... | 24 |
| 2.3.3.1 – Use of Supplementary Cementing Materials with RCA..... | 25 |
| 2.3.3.2 – Use of Chemical Admixtures with RCA..... | 25 |
| 3 – Experimental Details and Materials..... | 27 |
| 3.1 – Accelerated Mortar Bar Interlaboratory Study Procedures..... | 27 |
| 3.1.1 – Objectives..... | 27 |
| 3.1.2 – Preliminary Preparation of RCA Samples..... | 28 |
| 3.1.3 – Preparation of Samples for Mixing..... | 29 |
| 3.1.4 – Mixing Procedure..... | 30 |
| 3.1.5 – Mortar Bar Moulding and Preparation Procedure..... | 31 |
| 3.1.6 – NaOH Test Solution Preparation..... | 32 |
| 3.1.7 – AMBT Testing Procedure..... | 32 |
| 3.2 – Accelerated Mortar Bar Variable Testing Procedures..... | 34 |
| 3.2.1 – Objectives..... | 34 |
| 3.2.2 – Preliminary Preparation of RCA Samples..... | 34 |
| 3.2.3 – Preparation of Samples for Mixing..... | 36 |
| 3.2.4 – AMBT Mixing, Moulding & Preparation, and Testing Procedures..... | 37 |
| 3.3 – Concrete Microbar Testing Procedures..... | 38 |
| 3.3.1 – Objectives..... | 38 |
| 3.3.2 – Preparation of Virgin Spratt Specimens..... | 39 |
| 3.3.3 – Preparation of RCA Specimens..... | 39 |
| 3.3.4 – Preparation of Samples for Mixing..... | 39 |

| | |
|--|----|
| 3.3.5 – Mixing Procedure..... | 40 |
| 3.3.6 – Micro-Bar Moulding and Preparation Procedure..... | 41 |
| 3.3.7 – CMBT Testing Procedure..... | 42 |
| 3.4 – Porosity and Permeability Test Procedures..... | 43 |
| 3.4.1 – Objectives..... | 43 |
| 3.4.2 – Aggregate Preparation of Porosity and Permeability AMBT Specimens..... | 43 |
| 3.4.3 – Sample Preparation for AMBT Specimens..... | 43 |
| 3.4.4 – Mixing Procedure for AMBT Specimens..... | 44 |
| 3.4.5 – Cylinder Moulding for AMBT Specimens..... | 45 |
| 3.4.6 – Curing Procedure for AMBT Specimens..... | 46 |
| 3.4.7 – Aggregate Preparation of Porosity and Permeability CMBT Specimens..... | 47 |
| 3.4.8 – Sample Preparation for CMBT Specimens..... | 47 |
| 3.4.9 – Mixing Procedure for CMBT Specimens..... | 47 |
| 3.4.10 – Cylinder Moulding for CMBT Specimens..... | 47 |
| 3.4.11 – Curing Procedure for CMBT Specimens..... | 48 |
| 3.4.12 – Aggregate Preparation of Porosity and Permeability CPT Specimens..... | 48 |
| 3.4.13 – Sample Preparation for CPT Specimens..... | 48 |
| 3.4.14 – Mixing Procedure for CPT Specimens..... | 49 |
| 3.4.15 – Cylinder Moulding for CPT Specimens..... | 49 |
| 3.4.16 – Curing Procedure for CPT Specimens..... | 49 |
| 3.4.17 – Porosity and Permeability Test Procedures..... | 50 |
| 3.5 – Alkali Leaching Test Procedures..... | 52 |
| 3.5.1 – Objectives..... | 52 |
| 3.5.2 – Preparation of RCA Specimens..... | 52 |
| 3.5.3 – Preparation and Mixing of Paste Specimens..... | 52 |
| 3.5.4 – Moulding and Curing of Paste Specimens..... | 53 |
| 3.5.5 – Crushing and Grading of Paste Specimens..... | 54 |
| 3.5.6 – Testing for Evaporable Water in Paste Specimens..... | 55 |
| 3.5.7 – Testing for Non-Evaporable Water in Paste Specimens..... | 55 |
| 3.5.8 – Preparation of Alkali Leaching Solution..... | 56 |
| 3.5.9 – Preparation of Alkali Leaching Specimens..... | 56 |

| | |
|---|-----------|
| 3.5.10 – Preparation of Alkali Leaching Flame Photometer Specimens..... | 57 |
| 3.5.11 – Testing of Alkali Leaching Flame Photometer Specimens..... | 57 |
| 3.6 – Chemical Analysis..... | 59 |
| 4 – Results and Discussion..... | 61 |
| 4.1 – Accelerated Mortar Bar Testing Results and Analysis..... | 61 |
| 4.1.1 – Scope of Accelerated Mortar Bar Testing..... | 61 |
| 4.1.2 – Interlab Crusher’s Fines Accelerated Mortar Bar Testing..... | 62 |
| 4.1.2.1 – Interlab Alberta Crusher’s Fines AMBT Results..... | 62 |
| 4.1.2.2 – Interlab Bernier Crusher’s Fines AMBT Results..... | 64 |
| 4.1.2.3 – Interlab Potsdam Crusher’s Fines AMBT Results..... | 65 |
| 4.1.2.4 – Interlab Springhill Crusher’s Fines AMBT Results..... | 67 |
| 4.1.3 – Interlab Coarse Accelerated Mortar Bar Testing..... | 69 |
| 4.1.3.1 – Interlab Alberta Coarse AMBT Results..... | 69 |
| 4.1.3.2 – Interlab Bernier Coarse AMBT Results..... | 70 |
| 4.1.3.3 – Interlab Potsdam Coarse AMBT Results..... | 72 |
| 4.1.3.4 – Interlab Springhill Coarse AMBT Results..... | 73 |
| 4.1.4 – Variance of RCA Test Size on Accelerated Mortar Bar Test..... | 75 |
| 4.1.4.1 – Interlab Alberta AMBT Results..... | 75 |
| 4.1.4.2 – Interlab Bernier AMBT Results..... | 76 |
| 4.1.4.3 – Interlab Potsdam AMBT Results..... | 78 |
| 4.1.4.4 – Interlab Springhill AMBT Results..... | 80 |
| 4.1.5 – Interlab Variance of Accelerated Mortar Bar Test..... | 82 |
| 4.1.5.1 – Interlab Variance of Alberta AMBT Results..... | 82 |
| 4.1.5.2 – Interlab Variance of Bernier AMBT Results..... | 85 |
| 4.1.5.3 – Interlab Variance of Potsdam AMBT Results..... | 88 |
| 4.1.5.4 – Interlab Variance of Springhill AMBT Results..... | 91 |
| 4.1.6 – Variation in Expansion of Laval RCA due to Modified Testing Conditions..... | 95 |
| 4.1.6.1 – Variation in Expansion of Laval RCA due to W/C Ratio Fluctuations..... | 95 |
| 4.1.6.2 – Variation in Expansion of Laval RCA due to Method of Crushing..... | 96 |
| 4.1.6.3 – Variation in Expansion of Laval RCA due to Washing of RCA..... | 98 |

| | |
|--|------------|
| 4.1.7 – Discussion of AMBT Test Results..... | 100 |
| 4.2. – Concrete Microbar Testing..... | 103 |
| 4.2.1 – Scope of Concrete Microbar Testing..... | 103 |
| 4.2.2 – Virgin Aggregate Concrete Microbar Test Results..... | 104 |
| 4.2.2.1 –Virgin Spratt Concrete Microbar Test Results..... | 104 |
| 4.2.2.2 –Variation due to Alkali content in Concrete Microbar Test Results..... | 107 |
| 4.2.2.3 –Expansion of Virgin Spratt with SCM Concrete Microbar Test Results..... | 112 |
| 4.2.2.4 – Comparison of Concrete Microbar Test Results to CPT Results..... | 114 |
| 4.2.3 – Recycled Concrete Aggregate Concrete Microbar Test Results..... | 117 |
| 4.2.3.1 – CMBT Results of RCA from Ottawa Test Blocks..... | 117 |
| 4.2.3.2 – Variation due to Gradation of RCA from Ottawa Test Blocks CMBT Results..... | 119 |
| 4.2.3.3 – Variation between CMBT and AMBT Results of RCA from Ottawa Test Blocks..... | 122 |
| 4.2.3.4 – 100% Spratt RCA CMBT Results..... | 125 |
| 4.2.3.5 – Variation of 100% Spratt RCA CMBT and CPT Results..... | 127 |
| 4.2.3.6 – 70% Spratt RCA CMBT Results..... | 131 |
| 4.2.3.7 – Variation of 70% Spratt RCA CMBT and CPT Results..... | 132 |
| 4.2.3.8 – Variation of CMBT, AMBT and CPT Results..... | 136 |
| 4.2.4 – Discussion of CMBT Test Results..... | 140 |
| 4.3 – Results and Analysis of the Analytical Supporting Tests..... | 143 |
| 4.3.1 – Scope of Analytical Supporting Tests..... | 143 |
| 4.3.2 – Porosity and RCPT Results..... | 143 |
| 4.3.3 – Alkali Leaching Test Results..... | 145 |
| 4.3.4 – Discussion of Analytical Support Testing Results..... | 149 |
| 5 – Summary of Results, Conclusions and Recommendations for Future Research..... | 151 |
| 5.1 – Accelerated Mortar Bar Testing..... | 151 |
| 5.1.1 – Conclusions for AMBT using RCA..... | 151 |
| 5.2 – Concrete Microbar Testing..... | 152 |
| 5.2.1 – Conclusions for CMBT with Virgin Spratt Aggregate..... | 152 |

| | |
|--|------------|
| 5.2.2 – Conclusions for CMBT using RCA..... | 153 |
| 5.3 – Analytical Support Testing..... | 153 |
| 5.3.1 – Conclusions for Analytical Support Testing..... | 153 |
| 5.4 – Conclusions for Accelerated Test Methods for RCA..... | 154 |
| 5.5 – Recommendations for Future Research..... | 155 |
| | |
| Appendices..... | 157 |
| Appendix A – Test Mix Designs..... | 157 |
| Appendix B – AMBT Test Program Results..... | 160 |
| Appendix C – CMBT Test Program Results..... | 166 |
| Appendix D – Porosity and RCPT Results..... | 174 |
| Appendix E – Alkali Leaching Test Results..... | 177 |
| Appendix F – Alkali Leaching Test Calculation Procedure..... | 184 |
| | |
| References..... | 185 |
| Reference Methods..... | 185 |
| Reference Documents..... | 185 |

List of Tables

| | |
|--|-----|
| Table 2.1 – CPT, AMBT and CMBT mix proportions..... | 14 |
| Table 3.1 – List of RCA samples provided by CANMET..... | 27 |
| Table 3.2 – Aggregate and cement mix proportions for AMBT testing..... | 30 |
| Table 3.3 – Standard batch for CMBT..... | 40 |
| Table 3.4 – AMBT aggregate gradation for porosity and permeability specimens..... | 44 |
| Table 3.5 – CMBT standard mix design for porosity and permeability specimens..... | 47 |
| Table 3.6 – CPT standard mix design for porosity and permeability specimens..... | 48 |
| Table 3.7 – Cementitious materials blends for alkali leaching testing..... | 53 |
| Table 3.8 – Major oxide composition of cementitious materials..... | 59 |
| Table 4.1 – Virgin Aggregate Information for RCA Interlab Study..... | 61 |
| Table 4.2 – Expansion and COV of Alberta Crusher’s Fines RCA AMBT..... | 63 |
| Table 4.3 – Expansion and COV of Bernier Crusher’s Fines RCA AMBT..... | 64 |
| Table 4.4 – Expansion and COV of Potsdam Crusher’s Fines RCA AMBT..... | 66 |
| Table 4.5 – Expansion and COV of Springhill Crusher’s Fines RCA AMBT..... | 67 |
| Table 4.6 – Expansion and COV of Alberta Coarse RCA AMBT..... | 69 |
| Table 4.7 – Expansion and COV of Bernier Coarse RCA AMBT..... | 71 |
| Table 4.8 – Expansion and COV of Potsdam Coarse RCA AMBT..... | 72 |
| Table 4.9 – Expansion and COV of Springhill Coarse RCA AMBT..... | 74 |
| Table 4.10 – Mean and allowable range of expansion for Alberta RCA specimens..... | 83 |
| Table 4.11 – Mean and allowable range of expansion for Bernier RCA specimens..... | 86 |
| Table 4.12 – Mean and allowable range of expansion for Potsdam RCA specimens..... | 89 |
| Table 4.13 – Mean and allowable range of expansion for Springhill RCA specimens..... | 92 |
| Table 4.14 – Expansion and COV of Laval RCA with varied water corrections..... | 96 |
| Table 4.15 – Expansion and COV of Laval RCA with varied crushing method..... | 97 |
| Table 4.16 – Expansion and COV of Laval RCA for washed specimens..... | 98 |
| Table 4.17 – Expansion of virgin Spratt aggregate..... | 105 |
| Table 4.18 – Expansion of virgin Spratt with SCM..... | 113 |
| Table 4.19 – Expansion of RCA from Ottawa Test Blocks in CMBT..... | 117 |
| Table 4.20 – Expansion of 100% Spratt RCA with SCM in CMBT..... | 126 |

| | |
|---|-----|
| Table 4.21 – Expansion of 100% Spratt RCA with SCM in CMBT..... | 128 |
| Table 4.22 – Expansion of 70% Spratt RCA with SCM in CMBT..... | 132 |
| Table 4.23 – Expansion of 70% Spratt RCA with SCM in CMBT and CPT..... | 134 |
| Table 4.24 – Expansion of Spratt RCA with SCM in CMBT, AMBT and CPT..... | 137 |
| Table 4.25 – Curing details of CMBT, CPT and AMBT test specimens..... | 144 |
| Table 4.26 – Porosity and permeability of CMBT, CPT and AMBT test specimens..... | 145 |
| Table A.1 – Interlab RCA crushed coarse AMBT mix designs..... | 157 |
| Table A.2 – Interlab RCA crusher’s fines AMBT mix designs..... | 157 |
| Table A.3 – Virgin Spratt CMBT mix designs..... | 158 |
| Table A.4 – Virgin Spratt with modified SCM CMBT mix designs..... | 158 |
| Table A.5 – Interlab RCA CMBT mix designs..... | 158 |
| Table A.6 – Spratt RCA with SCM CMBT mix designs..... | 159 |
| Table A.7 – Spratt RCA with SCM AMBT mix designs..... | 159 |
| Table A.8 – Porosity/RCPT representing AMBT mix designs..... | 159 |
| Table A.9 – Porosity/RCPT representing CMBT mix designs..... | 159 |
| Table A.10 – Porosity/RCPT representing CPT mix designs..... | 159 |
| Table B.1 – Sample of data worksheet for recording AMBT expansion results..... | 160 |
| Table B.2 – Interlab RCA crushed coarse average expansion results..... | 161 |
| Table B.3 – Interlab RCA crusher’s fines average expansion results..... | 163 |
| Table B.4 – Laval RCA average expansion results..... | 165 |
| Table C.1 – Sample of data worksheet for recording CMBT expansion results..... | 166 |
| Table C.2 – Virgin Spratt aggregate with normal alkali average expansion results..... | 167 |
| Table C.3 – Virgin Spratt aggregate with raised alkali average expansion results..... | 168 |
| Table C.4 – Virgin Spratt aggregate with modified SCM average expansion results..... | 169 |
| Table C.5 – 100% Spratt RCA with SCM average expansion results..... | 170 |
| Table C.6 – 70% Spratt RCA with SCM average expansion results..... | 171 |
| Table C.7 – Interlab RCA average expansion results..... | 172 |
| Table C.8 – Spratt RCA AMBT Comparison average expansion results..... | 173 |
| Table D.1 – Porosity and Permeability test results for CPT test specimens..... | 174 |
| Table D.2 – Porosity and Permeability test results for AMBT test specimens..... | 174 |
| Table D.3 – Porosity and Permeability test results for CMBT test specimens..... | 175 |

| | |
|---|-----|
| Table E.1 – Specimen batch sizes for SCM paste specimens..... | 176 |
| Table E.2 – Specimen batch sizes for SCM paste with RCA specimens..... | 176 |
| Table E.3 – Specimen batch sizes for SCM paste with 70% RCA specimens..... | 176 |
| Table E.4 – Specimen batch sizes for PC paste and RCA control specimens..... | 176 |
| Table E.5 – Evaporable water content of paste specimens..... | 177 |
| Table E.6 – Non-evaporable water content of paste specimens..... | 177 |
| Table E.7 – Estimated loss on ignition for solids in paste specimens..... | 177 |
| Table E.8 – Alkali concentration of solution in SCM paste specimens..... | 178 |
| Table E.9 – Alkali concentration of solution in SCM paste with RCA specimens..... | 178 |
| Table E.10 – Alkali concentration of solution in SCM paste with RCA specimens..... | 179 |
| Table E.11 – Alkali concentration of solution in PC paste and RCA control specimens..... | 179 |
| Table E.12 – Alkali binding capacity of SCM paste specimens..... | 180 |
| Table E.13 – Alkali binding capacity of SCM paste with RCA specimens..... | 181 |
| Table E.14 – Alkali binding capacity of SCM paste with 70% RCA specimens..... | 182 |
| Table E.15 – Alkali binding capacity of PC paste and RCA control specimens..... | 183 |
| Table F.1 – Outline of correction procedures for calculating results of the alkali leaching test | 184 |

List of Figures

| | |
|---|----|
| Figure 2.1 – ASR Cracking..... | 7 |
| Figure 2.2 – Simplified ASR chemical model..... | 9 |
| Figure 2.3 – Alkali silica gel reaction with calcium..... | 9 |
| Figure 4.1 – Expansion of Alberta Crusher’s Fines RCA AMBT..... | 63 |
| Figure 4.2 – Expansion of Bernier Crusher’s Fines RCA AMBT..... | 65 |
| Figure 4.3 – Expansion of Potsdam Crusher’s Fines RCA AMBT..... | 65 |
| Figure 4.4 – Expansion of Springhill Crusher’s Fines RCA AMBT..... | 68 |
| Figure 4.5 – Expansion of Alberta Coarse RCA AMBT..... | 70 |
| Figure 4.6 – Expansion of Bernier Coarse RCA AMBT..... | 71 |
| Figure 4.7 – Expansion of Potsdam Coarse RCA AMBT..... | 73 |
| Figure 4.8 – Expansion of Springhill Coarse RCA AMBT..... | 74 |
| Figure 4.9 Expansion of 100% and 50% Alberta RCA AMBT..... | 75 |
| Figure 4.10 Expansion of 25% Alberta RCA AMBT..... | 76 |
| Figure 4.11 – Expansion of 100% and 25% Bernier RCA AMBT..... | 77 |
| Figure 4.12 – Expansion of 50% Bernier RCA AMBT..... | 78 |
| Figure 4.13 – Expansion of Potsdam RCA AMBT..... | 79 |
| Figure 4.14 – Expansion of Potsdam RCA for AMBT and Virgin Potsdam for CPT..... | 79 |
| Figure 4.15 – Expansion of 100% Springhill RCA AMBT..... | 80 |
| Figure 4.16 – Expansion of 50% and 25% Springhill RCA AMBT..... | 81 |
| Figure 4.17 – Mean expansion of Ryerson and overall interlab 100% Alberta RCA specimens..... | 83 |
| Figure 4.18 – Mean expansion of Ryerson and overall interlab 50% Alberta RCA specimens..... | 84 |
| Figure 4.19 – Mean expansion of Ryerson and overall interlab 25% Alberta RCA specimens..... | 84 |
| Figure 4.20 – Mean expansion of Ryerson and overall interlab 100% Bernier RCA specimens..... | 86 |
| Figure 4.21 – Mean expansion of Ryerson and overall interlab 50% Bernier RCA specimens..... | 87 |

| | |
|--|-----|
| Figure 4.22 – Mean expansion of Ryerson and overall interlab 25% Bernier RCA specimens..... | 87 |
| Figure 4.23 – Mean expansion of Ryerson and overall interlab 100% Potsdam RCA specimens..... | 89 |
| Figure 4.24 – Mean expansion of Ryerson and overall interlab 50% Potsdam RCA specimens..... | 90 |
| Figure 4.25 – Mean expansion of Ryerson and overall interlab 25% Potsdam RCA specimens..... | 90 |
| Figure 4.26 – Mean expansion of Ryerson and overall interlab 100% Springhill Coarse RCA specimens..... | 92 |
| Figure 4.27 – Mean expansion of Ryerson and overall interlab 100% Springhill crusher’s fines RCA specimens..... | 93 |
| Figure 4.28 – Mean expansion of Ryerson and overall interlab 50% Springhill RCA specimens..... | 93 |
| Figure 4.29 – Mean expansion of Ryerson and overall interlab 25% Springhill RCA specimens..... | 94 |
| Figure 4.30 – Expansion of Laval RCA with varied water corrections..... | 96 |
| Figure 4.31 – Expansion of Laval RCA with varied crushing method..... | 97 |
| Figure 4.32 – Expansion of Laval RCA for washed specimens..... | 99 |
| Figure 4.33 – Expansion of high replacement virgin Spratt aggregate with normal alkali PC..... | 105 |
| Figure 4.34 – Expansion of low replacement virgin Spratt aggregate with normal alkali PC..... | 106 |
| Figure 4.35 – Expansion of high replacement virgin Spratt aggregate with raised alkali PC..... | 106 |
| Figure 4.36 – Expansion of low replacement virgin Spratt aggregate with raised alkali PC..... | 107 |
| Figure 4.37 – Expansion of 100% virgin Spratt aggregate..... | 109 |
| Figure 4.38 – Expansion of 70% virgin Spratt aggregate..... | 110 |
| Figure 4.39 – Expansion of 50% virgin Spratt aggregate..... | 110 |
| Figure 4.40 – Expansion of 30% virgin Spratt aggregate..... | 111 |
| Figure 4.41 – Expansion of 10% virgin Spratt aggregate..... | 111 |

| | |
|--|-----|
| Figure 4.42 – Expansion of Non-Reactive aggregate..... | 112 |
| Figure 4.43 – Variation in expansion due to modified replacement SCM for HCFA and Slag..... | 113 |
| Figure 4.44 – Variation in expansion due to modified replacement SCM for LCFA..... | 114 |
| Figure 4.45 – Expansion of 100% virgin Spratt aggregate in CPT and CMBT..... | 115 |
| Figure 4.46 – Expansion of 70% virgin Spratt aggregate in CPT and CMBT..... | 116 |
| Figure 4.47 – Expansion of 50% virgin Spratt aggregate in CPT and CMBT..... | 116 |
| Figure 4.48 – Expansion of fine graded RCA from Ottawa Test Blocks in CMBT..... | 118 |
| Figure 4.49 – Expansion of coarse graded ILS RCA in CMBT..... | 118 |
| Figure 4.50 – Expansion of fine and coarse graded Alberta RCA in CMBT..... | 120 |
| Figure 4.51 – Expansion of fine and coarse graded Bernier RCA in CMBT..... | 121 |
| Figure 4.52 – Expansion of fine and coarse graded Potsdam RCA in CMBT..... | 121 |
| Figure 4.53 – Expansion of fine and coarse graded Springhill RCA in CMBT..... | 122 |
| Figure 4.54 – Variation in expansion for Alberta RCA CMBT and AMBT..... | 123 |
| Figure 4.55 – Variation in expansion for Bernier RCA CMBT and AMBT..... | 124 |
| Figure 4.56 – Variation in expansion for Potsdam RCA CMBT and AMBT..... | 124 |
| Figure 4.57 – Variation in expansion for Springhill RCA CMBT and AMBT..... | 125 |
| Figure 4.58 – Expansion of 100% Spratt RCA with SCM in CMBT..... | 126 |
| Figure 4.59 – Expansion of 100% Spratt RCA with SCM in CMBT..... | 127 |
| Figure 4.60 – Expansion of 100% Spratt RCA with 20% LCFA & 30% Slag in CMBT and CPT..... | 129 |
| Figure 4.61 – Expansion of 100% Spratt RCA with 5% SF & 45% Slag in CMBT and CPT..... | 129 |
| Figure 4.62 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in CMBT and CPT..... | 130 |
| Figure 4.63 – Expansion of 100% Spratt RCA with 5% SF & 20% LCFA in CMBT and CPT..... | 130 |
| Figure 4.64 – Expansion of 100% Spratt RCA with 5% SF & 25% Slag in CMBT and CPT..... | 131 |
| Figure 4.65 – Expansion of 70% Spratt RCA with SCM in CMBT..... | 132 |
| Figure 4.66 – Expansion of 70% Spratt RCA in CMBT and CPT..... | 134 |

| | |
|--|-----|
| Figure 4.67 – Expansion of 70% Spratt RCA with 25% LCFA in CMBT and CPT..... | 135 |
| Figure 4.68 – Expansion of 70% Spratt RCA with 50% Slag in CMBT and CPT..... | 135 |
| Figure 4.69 – Expansion of 70% Spratt RCA with 25% LCFA in AMBT, CMBT and CPT..... | 138 |
| Figure 4.70 – Expansion of 70% Spratt RCA with 25% LCFA in AMBT, CMBT and CPT..... | 138 |
| Figure 4.71 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in AMBT, CMBT and CPT..... | 139 |
| Figure 4.72 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in AMBT, CMBT and CPT..... | 139 |
| Figure 4.73 – Alkali concentration of plain cement paste and RCA specimens..... | 147 |
| Figure 4.74 – Alkali concentration of SCM paste specimens..... | 147 |
| Figure 4.75 – Alkali concentration of SCM paste and RCA specimens..... | 148 |
| Figure 4.76 – Alkali concentration of SCM paste and 70% RCA specimens..... | 148 |

List of Appendices

| | |
|--|-----|
| Appendix A – Test Mix Designs..... | 157 |
| Appendix B – AMBT Test Program Results..... | 160 |
| Appendix C – CMBT Test Program Results..... | 166 |
| Appendix D – Porosity and RCPT Results | 174 |
| Appendix E – Alkali Leaching Test Results..... | 176 |
| Appendix F – Alkali Leaching Test Calculation Procedure..... | 184 |

1 – Introduction and Objectives

1.1 – Introduction

Alkali silica reaction is form of deleterious expansion in concrete that occurs when reactive silica in aggregate reacts with alkali provided by cement in concrete structures. The gel produced by this reaction absorbs water and expands which leads to eventual cracking. Severe reactions will lead to a loss of serviceability and require the afflicted structure be abandoned. The abandoned structures are demolished and sent to landfill where space is already limited. The culture of sustainable development has created interest in the diversion of waste concrete from landfill for use in new concrete.

This recycled concrete aggregate is finding use in new construction slowly as research is developed providing strong support for its use. (Oikonomou 2005) However, this introduces the risk of unintentionally introducing a reactive aggregate to the concrete mix. The higher alkali content of modern cement means that aggregates that were innocuous when used with older cement may cause deleterious expansion when used. Therefore the detection and assessment potential alkali silica reaction of recycled concrete aggregate is very important to its acceptance for use.

The concrete prism test is shown to be the most comparable to field conditions but requires 1 year to provide results. (Gratten-Bellew et. al. 2004) If the goal is to assess the mitigation of alkali silica reaction this time extends to 2 years. This long term testing is acceptable for assessing natural aggregate from a potential quarry site where production may run for decades. However, for assessing the reactivity of recycle concrete from a single demolition site which may be active for a matter of weeks this is far too long. The cost of transporting and then storing a volume of recycled concrete until results are available is prohibitive. Testing has shown that the concrete prism test is effective in assessing the alkali silica reactivity of recycled concrete.

The accelerated mortar bar test provides a potential alternative since it is able to provide results within 14 days. However, the prevailing industry requirement is that the test only be used to exclude an aggregate and confirmation is required by the concrete prism test to approve of the aggregate. (Thomas et. al. 2006) Testing has shown that the accelerated mortar bar tests will provide acceptable results when used to assess recycled concrete aggregate. (Shehata et. al. 2010) However, the multi-laboratory variation and the effect of certain recycled concrete variables are not well understood. The gradation of the test aggregate is particularly concerning because it is well known that the paste fraction is generally more prevalent in fine gradations of recycled concrete aggregate. The paste fraction is less likely to contain reactive constituents and therefore likely to underestimate the expansion. Until a significant body of research shows that the accelerated mortar bar test is effective in assessing alkali silica reactivity of recycled concrete it will not be accepted by the industry and the concrete prism test must be used.

The concrete microbar test is a new form of accelerated test being developed to address the limitations of the concrete prism and accelerated mortar bar tests. The concrete microbar test accelerates the alkali silica reaction to provide results at a proposed 28 day limit. (Gratten-Bellew et. al. 2003) It also uses a coarse gradation of aggregate which limits the problems inherent with fine RCA. The problem is that a standard is not yet available for virgin aggregates let alone recycle concrete. The development of this test shows promise but requires still a significant body of research to develop the method. Once that is accomplished the results using recycled concrete can be compared and assessed.

This research program seeks to provide research to support the use of accelerated test methods in assessing alkali silica reaction. Different recycled concrete samples were tested and compared with results developed by collaborating researchers using the accelerated mortar bar test. The effect of material selection as well as the material properties was compared to determine the result on the expansion of the bars. The test program was standardized for this particular program to address the physical properties inherent to RCA and evaluate the effects on test results. Further testing was completed to assess the importance of thorough specimen evaluation and correct processing procedures when preparing test specimens.

The research program also investigates the effectiveness of the concrete microbar test as well. Testing included assessment of test variables on virgin aggregate to determine the effect on expansion. The effectiveness of evaluating the mitigating effects of supplementary cementing materials was also investigated. The concrete microbar test was then used to evaluate the alkali silica reactivity of recycle concrete aggregates. These results were compared to the results of the accelerated mortar bar test specimens and evaluated. Testing was also conducted to evaluate the mitigating effect of supplementary cementing materials in comparison to the concrete prism test results from previous research programs.

1.2 – Research Significance

This is the first research conducted in North America evaluating the effectiveness of accelerated testing for alkali silica reaction in recycled concrete aggregate using the accelerated mortar bar test and the concrete microbar test. The focus of the accelerated mortar bar testing phase is to develop a modified procedure that will provide consistent and repeatable results with minimal variation. The focus of the concrete microbar test phase is to prove that the test is a viable accelerated testing option for recycled concrete aggregate. It is hoped that this thesis will provide further impetus for the acceptance of accelerated tests to screen for alkali silica.

1.3 – Research Objectives

The first phase of research was designed as part of an interlaboratory study that assessed the multi-laboratory precision of the accelerated mortar bar test when used to evaluate Recycled Concrete Aggregate (RCA). Four different RCA's were produced from outdoor exposure test blocks and pre-processed by a single lab for distribution to the four labs selected for the program. The effect of the using coarse or fine RCA, the level of replacement with non-reactive aggregate and the single-laboratory precision were assessed for each individual test. Due to the increased absorption of RCA the test was also used to evaluate a proposed method of preparation that accounts for the absorption and produces more workable mixes. This was followed by research

that assessed the effect of incorrect absorption results, crushing preparation and washing of recycled concrete aggregates when evaluating expansion with the accelerated mortar bar test. An RCA sourced from a demolished bridge in Laval, Quebec was selected due to the insufficient quantities of the four RCA types prepared for the interlaboratory study and its proven reactivity in accelerated mortar bar testing.

The second phase of study was designed to evaluate the effectiveness of the concrete microbar test in assessing the expansion caused by alkali silica reaction. The effect of adjusting the alkali and the effect of modifying the replacement of supplementary cementing materials were evaluated using virgin Spratt aggregate. This material was selected due to its known reactivity and status as a reference for reactivity in Ontario as well as to eliminate any potential variables that may be caused by using RCA. The effectiveness when evaluating recycled concrete aggregate in comparison to the accelerated mortar bar testing conducted in the first phase was also conducted using the same four recycled concrete aggregates as discussed previously. The ability of the concrete microbar test to evaluate the mitigation of supplementary cementing material was also assessed using Spratt RCA that was prepared for a past concrete prism test program. Using the same RCA and supplementary cementing materials from previous the concrete prism testing allowed direct comparison to the previous expansion results.

1.4 – Outline of Thesis

1. Chapter 1 introduced the topic of alkali silica reaction and the importance of accelerated tests in the acceptance of RCA use in the construction industry. It further outlines the significance of this research as well as the objectives of the different phases of the thesis.
2. Chapter 2 will be an in depth literature review that summarizes and critiques the current body of research in the applicable topics. The topics to be covered are alkali silica reaction, recycled concrete aggregates and the special considerations for alkali silica reaction in recycled concrete aggregates. The goal of this chapter is to provide sufficient background information to analyze the thesis results.

3. Chapter 3 will summarize the experimental details and materials to be used in the thesis. Detailed summaries of all test methods as well as the materials statistics relevant to testing are presented here. The goal of this chapter is to outline the test methods and the modifications applied to them in this thesis.
4. Chapter 4 will present and discuss the results of the research. Each phase of testing will be presented independently and followed by a discussion of the important results. The goal of this chapter is to present the results and analyze the results so that conclusions can be made.
5. Chapter 5 will present the conclusions of the thesis. The conclusions derived from each phase of testing will be listed as well as the overall conclusions for the thesis.
6. Chapter 6 is a summary of the references used in the Thesis.
7. Chapter 7 presents the appendices. This chapter summarizes details that were not suitable to present in the body of the research.

2 – Literature Review

2.1 – Alkali Silica Reaction in Concrete

2.1.1 – Overview of Alkali Silica Reaction

Alkali Silica Reaction (ASR) is a chemical reaction between alkalis found in cementitious materials and silica compounds found in aggregate. The result of this reaction is an amorphous gel with an affinity for water within a concrete structure. ASR can result in severe loss of serviceability in concrete structures because this gel product absorbs water and expands creating internal tensile forces that result in cracking. Over time this cracking increases and will often result in the structure deteriorating beyond acceptable service requirements. (Šachlová et al. 2010) As can be seen in Figure 2.1 the most severe cases of ASR result in complete destruction



Figure 2.1 – ASR cracking (cement.org)

of the concrete. Less intensive ASR attacks are still dangerous since they provide ingress points for other deleterious materials to enter the concrete. This leads to severe reduction in durability to chlorides, freeze-thaw, sulphate and carbonation. (Mindess 2003)

2.1.2 – Mechanism & Effect on Concrete

The source reactants for ASR are “naturally occurring” materials in a concrete mix, meaning the reaction is not dependant on external reactants. The alkali derives from the raw materials used in the manufacturing of Portland cement. They are found as Sodium and Potassium compounds and are generally reported as an equivalent mass of Na_2O_e . Na_2O_e is calculated as the following; $\% \text{Na}_2\text{O}_e = \% \text{Na}_2\text{O} + 0.658 * \% \text{K}_2\text{O}$, due to the relative molecular masses of Sodium and Potassium. (West, 1996) The alkali oxides found in the raw materials usually volatilize in the kiln and are carried away from the clinkering process. Ironically, the environmental controls that are designed to reduce emissions are actually the cause of the higher alkali content in cement today. Before these controls were emplaced, the alkali would mostly exit the stack at the exhaust of the kiln.

Today, raw material preheating and other processes actually bring the exhaust gases into direct contact with the fresh raw material, depositing the volatilized alkalis onto the raw feed where it stays through the clinkering and into the final product. (Mindess 2003) The silica is found in the natural crystals in the aggregate. The silica responsible for reacting in ASR is only the amorphous or open structured forms of crystalline silica. A dense silica crystal formation does

not allow for sufficient ingress and reaction with alkalis to have deleterious effects. If however a reactive form of silica is available, alkali from the cement is able to access the silica and the reaction begins. The reactive silica in the aggregate forms siloxane networks that are susceptible to the alkali attack. The alkali ion (A^+) and its corresponding hydroxide (OH^-) break the bond between the oxygen and silica atoms. The alkali silicate formed in this reaction is highly hygroscopic and will immediately hydrate utilizing available water molecules. Figure 2.2 shows the simplified reaction mechanism (Ichikawa and Miura 2007). The model is generally agreed upon as a good representation of the formation of alkali silica gel. However the mechanism by which the alkali-silica gel exerts the pressure necessary to cause damage to the concrete structure is less understood.

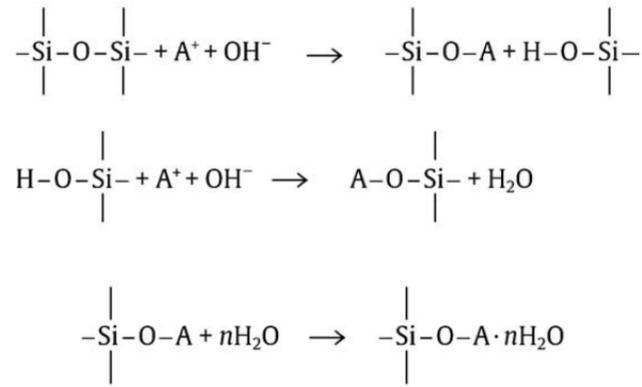


Figure 2.2 – Simplified ASR chemical model (Ichikawa 2009)

Garcia-Diaz et al. 2006 proposed a mechanism by which the swelling of aggregate due to inherent volume increase when the normal siloxane, called Q₄ tetrahedrons, are broken down by the alkali to form Q₃ tetrahedrons. Q₄ tetrahedrons are defined as a silica atom sharing four oxygen atoms with four neighbouring silica atoms. Q₃ tetrahedrons are the first stage of breakdown in Figure 2.3 where the silica has a negative charge (satisfied by the alkali cation A).

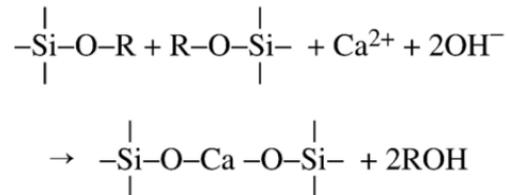


Figure 2.3 – Alkali silica gel reaction with calcium (Ichikawa and Miura 2007)

The Q₃ tetrahedrons formed from the breakdown of Q₄ require more space and can exert a force capable of expanding the aggregate and inducing cracking. The problem is that the alkali-silica gel is an aqueous product and will not exert pressure so long as it is able to move through the cement or aggregate structure. Thus there must be some mechanism that allows the aqueous gel to develop the pressures required to deteriorate concrete.

The diffusion barrier was proposed by Ichikawa & Miura 2007 as the reaction product of aqueous alkali-silica gel analogous to the Q₃ tetrahedron in Garcia-Diaz et al. 2006 and calcium ions from portlandite that dissolve to release OH⁻ to maintain the pH balance of pore the solution. Figure 2.3 shows the chemical reaction that forms the Alkali Calcium Silicate Hydrates (ACSH). The difference between this material and the alkali-silica gel is that the ACSH

precipitates from solution and does not remain in aqueous suspension (Feng et. al. 2010). This precipitation occurs and creates a hardened shell around the aggregate that allows for the continued ingress of alkalis to continue the alkali-silica reaction but prevents the diffusion of the aqueous gel. This forms the membrane that is described by both Garcia- Diaz et al. 2006 and Ichikawa & Miura 2007 as the requirement for expansive pressures to develop.

As the reaction continues, more aqueous gel forms from the reactive silica found in the aggregate and fights to fill the space encompassed by the ACSH membrane and the pressure increases. Once the pressure exceeds capacity of the ACSH membrane, aggregate and surrounding paste, the entire system will crack to relieve the pressure. The crack propagates through the network and provides a new vector for continued reaction. It should be noted that while this model represents the ASR reaction in many aggregates, it is not suitable for all aggregates. Rivard et. al. 2002 showed that in the case of Potsdam aggregate, a siliceous sandstone, that the reaction rim actually forms within the aggregate particle. That theory however did make note of the presence and internal movement of calcium ions within the aggregate throughout their test before the Ichikawa and Miura presented their research. (Rivard et al. 2002) The importance of calcium in the formation of expansive products is supported by many other studies as well (Chatterji 2005) (Monteiro et. al. 1997) and (Jun & Jin 2010).

2.1.3 – Testing of Aggregate for Alkali Silica Reaction

The potential severity of ASR requires that potential reactive aggregates be quickly and accurately detected and categorized. The depletion of the most desirable aggregate resources has resulted in the proliferation of marginal sources of aggregate to supply the demand when the cost of premium aggregates is prohibitive. Some of these materials are simply less suitable due to physical properties like hardness and strength, while others are avoided due to durability concerns like potential for ASR. There are many ways to screen aggregates for ASR susceptibility ranging from standardized laboratory tests requiring two years to near instant visual analysis by highly trained experts.

2.1.3.1 – Petrographic Analysis

The fastest screening test is petrographic analysis. This method's speed is entirely dependent on the knowledge and experience of the person (petrographer) conducting the inspection. The test involves inspection under an optical microscope with various filters that allow the petrographer to identify various minerals and mineral phases in the aggregate specimen. The petrographic features can be correlated to expansiveness when the material is well known. (Mo & Fournier 2007) The specimens can be further investigated using scanning electron microscopy (SEM) if required. The samples can be whole, mounted in polished sections, coloured for contrast and even etched with weak acid to help expose the minerals for study. (Monnin et al. 2006) The advantages of this test are its obvious speed and the minimal amount of preparation and work to complete the testing. The disadvantages are quite severe and limit the application of petrography as the sole screening test for ASR. The first problem is the skill required to properly assess the material. The petrographer needs to be experienced with the type of material and specifically aware of the level of ASR potential for the individual minerals. Furthermore, the test only recognizes the reactive materials and cannot assess the potential expansion of the material in field conditions. (Jensen & Lorenzi 1999) As such, petrography should be used as a tool to determine the next step for testing of an aggregate.

2.1.3.2 – Concrete Prism Test

The Concrete Prism Test (CPT) is widely recognized as one of the most realistic tests for the real world expansion caused by ASR. The test uses 285mm x 75mm square prisms with small steel studs moulded into the top and bottom. The concrete is made using a standardized gradation, water to cement/cementitious materials ratio (w/cm) and alkali content to provide comparable results for every test. Once prepared, the prisms are stored at 38°C at 100% RH and tested at set intervals, gauge studs provide a smooth and non-wearing surface for measurement on a comparator. The results at 1 year are reported in comparison to an expansion limit of 0.04% which has been specified as the limit of expansion with a low likelihood of deleterious effects in field conditions (CSA A23.2-14A). This test is the most desirable because of its repeatability,

relative simplicity and accurate prediction of field conditions. However, if the test is being conducted to study the efficacy of SCM, the expansion limit of 0.04% applies at 2 years instead. The ASTM test standard specifies a maximum expansion of 0.04% at 1 year, which is more generous than the CSA test in the case of SCM testing, but is still a significant length of time to wait (ASTM C1293).

A drawback of the CPT is the alkali leaching that takes place during testing and reduces the alkali concentrations in the prisms over time until the ASR reaction stops, limiting the effective test duration (Thomas 2010) and (Duchesne & Bérubé 2001). Another limitation is the sensitivity to the storage conditions during testing, it was seen that the expansion of specimens was lower when cured with a larger number of specimens in a single container (Jensen & Fournier 2000). However, the CPT still provides the best correlation to field trials for reactive aggregates (Gratten-Bellew et. al. 2004).

2.1.3.3 – Accelerated Mortar Bar Test

The CPT is still limited by the 1 year minimum test duration. In many cases this is simply too long to be required to wait due to scheduling and waiting a year or two for results is unacceptable; for this reason, the Accelerated Mortar Bar Test (AMBT) was created. While debate is still active on the reliability of the test, it is generally accepted to provide a reliable determination of the reactivity of a given material. The debate is based on the lack of correlation between it and the CPT, which is the current standard for representing real world expansion (Lu et al. 2006). The AMBT uses 285mm x 25mm square prisms with small steel studs moulded into the top and bottom like the CPT. The AMBT is also made with a standard gradation, water to cement/cementitious materials ratio (w/cm) to provide comparable results for every test. Once set, the prisms are placed in water at 80°C to condition the specimens. After 24h the bars are placed in a 1N NaOH solution to force alkali into the system and thus react with any reactive silica. The bars are measured like those of the CPT and compared to the expansion limit of 0.1% at 14 days (ASTM C1260). The high alkali solution ensures a rapid expansion if any reactive silica is present, providing prompt test results.

The obvious advantage of the AMBT is its short duration and immediate results in terms of the reactivity of the suspect aggregate even for slow reacting aggregates that are not compatible with the standard mortar bar test (Jun & Jin 2010). The disadvantage is the sporadic results and the potential to provide false results with certain aggregates. The AMBT usually provides acceptable pass/fail results when testing but in most cases the results are considered too close to the expansion limit to be confident (Gratten-Bellew et. al. 2004) and (Thomas et. al. 2006). Thomas et. al. 2006 reinforces the recommendation that any failing results in the AMBT be confirmed by CPT testing. Further, the overall correlation of expansion between the AMBT and CPT is considered to be strongly suspect when evaluating SCM (Innis and Thomas 1999). The over-processing of the aggregate prior to testing is another major concern. Some aggregates have been shown to not react when they have been crushed to the AMBT gradation resulting in a false positive result.

2.1.3.4 – Concrete Microbar Test

The Concrete Microbar Test (CMBT) was developed from a Chinese accelerated test which used a fine gradation of aggregate similar to the AMBT using a larger specimen size. However, research discovered that larger aggregate sizes were more sensitive to ASR expansion (Lu et. al 2006). This work led to the development of the CMBT using similar aggregate sizes to the CPT. To minimize the required aggregate processing the largest possible aggregate size is required however, this led to a decrease in sensitivity to expansion (Thomas et. al. 2006) and (Cakir et. al. 2009). Currently there is no unified standard for the CMBT as even the specimen size is subject to selection. The RILEM AAR-5 standard recommends 160mm x 40mm prisms for testing. However, due to the standardized 285mm gauge length in North America, research conducted in Canadian and American labs have generally used 285mm x 40mm prisms. In Gratten-Bellew et. al. 2003 it was suggested that the change in gauge length would not have adverse effects on the expansion results. The research of Gratten-Bellew et. al. 2003 & 2004 proposed several different expansion limits from 0.14% for siliceous limestones to 0.04% for other reactive aggregates. Cakir et. al. 2009 suggested that the CMBT underestimates the expansion of an aggregate

compared to the AMBT. As such, the author selected a general 0.1% expansion limit for this test program in the absence of a generally accepted standard.

Cakir et. al. 2009 suggested that the CMBT may be compatible with evaluating the mitigating effect of SCM since they found some correlation with AMBT results. However, the author suggests that the standard microbar test may require modifications to be more compatible. The first problem is that the test uses a greatly reduced water to cement ratio in comparison to both the CPT and AMBT. As seen in Table 2.1. the water to cement ratio in the CMBT is 0.322 whereas the CPT uses a water to cement ratio of 0.42 - 0.45 and the AMBT uses a water to cement ratio of 0.47. Thus the CMBT specimens will be expected to have a significantly reduced permeability. As the CMBT relies on external alkalis to accelerate the Alkali-silica reaction, a reduced permeability will result in a stunted reaction. Also, the reduced permeability prevents external moisture from reaching the silica gel, thus preventing increased expansion of the gel products. The ratio of cementitious materials to reactive aggregate (CM/Reactive) is significantly higher in the CMBT indicating that a tendency for higher alkali binding capacity may exist. As such the author will test the effect of factoring the SCM addition to more closely mimic the ratio of CM/Reactive Aggregate in the CPT and AMBT.

Table 2.1 – CPT, AMBT and CMBT mix proportions

| Mix Variable | CPT (AVG) | AMBT | CMBT |
|----------------------|------------------|-------------|-------------|
| W/C Ratio | 0.435 | 0.470 | 0.322 |
| % Reactive Aggregate | 44.270 | 60.484 | 43.062 |
| % CM | 18.261 | 26.882 | 43.062 |
| CM/Reactive | 0.0041 | 0.0044 | 0.010 |

2.1.4 – Amelioration of Alkali Silica Reaction

When testing detects and categorizes a reactive aggregate it is sometimes possible to design a mix to mitigate the expansion caused by ASR. The test results allow for recommendations of any of the well documented modes of mitigating ASR. But, as always careful investigations of the cost generally dictate the material selections.

2.1.4.1 – Aggregate and Cement Selection

The most obvious mitigation of ASR is to simply avoid the use of the reactive material in concrete. But as previously discussed, the depletion of the most desirable aggregate resources has resulted in the proliferation of marginal sources of aggregate to supply the demand when the cost of premium aggregates is prohibitive. When the cost of the mitigation is greater than the cost of obtaining a non-reactive aggregate, it is easiest to avoid the reactive aggregate. For less reactive aggregates, simply replacing part of the aggregate volume with a non-reactive aggregate can prevent deleterious expansion. Similarly, if low-alkali cement is readily available and the aggregate is shown to be non-reactive at that level of alkali, the reactive aggregate can be used. When these simple mitigating techniques are not feasible, other avenues need to be explored.

2.1.4.2 – Use of Supplementary Cementing Materials

The selection of the right blend of Supplementary Cementing Materials (SCM) has a well documented history as an effective mitigation measure for ASR. The most important factor to consider when selecting the required SCM is the properties of the SCM itself. The alkali content of the cement and of the SCM are secondary to the composition of the SCM (Shehata & Thomas 2010) and (Malvar & Lenke 2006). The alkali content in the system does play a role in the potential expansion but it is secondary (Duchesne & Bérubé 2004). The mostly commonly accepted mechanism by which SCM mitigates ASR expansion follows below (Moser et. al. 2010) and (Xu et. al. 1995)

1. The refinement and densification of the microstructure by SCM hydration products, resulting in a less permeable paste.
2. Binding of alkali ions during the formation of the SCM hydration products thereby reducing the alkali available to react in the system.
3. Dilution of alkali since the volume of PC and thus the contribution of alkalis is reduced; however, this is only applicable where the SCM selected has lower alkali content.
4. Consumption of portlandite which reduced the available volume of Ca^+ in the system.
5. The increase in strength common to SCM mixes creates a more resistant concrete.

The SCM's used for the mitigation of ASR in this study are Silica Fume (SF), Fly Ash (FA) and Ground Granulated Blast Furnace Slag (Slag). Research has shown that SF alone may not be the most effective SCM since it may only delay the ASR reaction since it has been shown to contribute to the alkali in the pore solution in long term studies (Duchesne & Bérubé 2004). FA is a very commonly selected SCM but comes in different varieties that range from very effective to ineffective. Shehata & Thomas 2010 showed that FA with minimal CaO and low alkali will be extremely effective in mitigating ASR. Moser et. al 2010 also indicate that low calcium FA is among the most effective SCM's available. When the CaO content of FA increases, the effectiveness is reduced and most high calcium FA is not very effective in mitigating ASR and requires much higher replacement (Bleszynski et. al. 2002). The use of FA in mitigating ASR is a clear representation of the importance of the SCM properties. Slag has been used but has similar drawbacks to high calcium FA and so is not very effective and requires higher replacement (Moser et. al. 2010).

As would be expected, as mix reactivity increases the required replacement of SCM increases. Likewise, as the effectiveness of the SCM decreases, the required replacement increases (Thomas 2010) and (Duchesne & Bérubé 2004). The exception to this rule comes in ternary blends. Ternary blends combine two different SCM's with the PC to increase the overall effectiveness of the individual SCM's. This synergistic behaviour has been well documented in other performance criteria and has proven to be effective in mitigating ASR as well. SF and Slag are not the most effective materials when used alone but when combined in a ternary blend

provide significant mitigation at reduce replacement levels (Bleszynski et. al. 2002). Thomas 2010 also showed improvements when using SF and FA blends.

2.1.4.3 – Use of Chemical Admixtures

Lithium based chemical admixtures have proven to be effective mitigation techniques against ASR. Lithium is added to the concrete in variance compounds but especially salts. The problem is that some of the salts can have detrimental effects on the concrete. The most common held theory is that the Lithium takes the place of the Calcium in the ACSH forming an ALiSH. It is thought that this ALiSH does not absorb water and swell like ACSH and thus forms and remains inert without any change in size (Mo & Fournier 2007) and (Feng et. al. 2010). Feng et. al. 2010 suggests that the ALiSH crystals form over the surface of the reactive aggregate and as the Lithium depletes, the production of ACSH begins to fill in the voids forming a high density layer that acts as a barrier and eventually isolates the aggregate from the alkali, thus severely limiting further reaction.

2.2 – Recycled Concrete Aggregate

The use of recycled concrete aggregate is becoming more and more important in the developing culture of sustainability. Natural aggregate requires the quarrying of enormous volumes of aggregate that is becoming less available. The energy required to quarry and then transport this aggregate to the consumer is also immense. Finally, the disposal of construction waste requires vast volumes of space that are also increasingly difficult to find. The use of RCA addresses all of these concerns by replacing raw aggregate, being available nearer to consumers and as a by-product of existing demolition work and finally, diverting material from landfill (Oikonomou 2005).

2.2.1 – Sources of Recycled Concrete Aggregate

RCA is created by taking demolition waste, usually old concrete, and crushing it using the same techniques as natural aggregates. The crushers are able to produce the required size fraction of aggregate from large coarse particles down to fines and dust. Coarse RCA is the most simple to use aggregate and since it makes up the largest fraction in a concrete mix, is the most effective use. Fine RCA can be used as well but has more drawbacks in use. In general, RCA requires some modification to the mix design to maximize its effectiveness in concrete and prevent any deleterious effects (Gomes & de Brito 2009) and (Yang et. al. 2010). Fines in particular present specific challenges that make it more difficult to incorporate into a concrete mix (Shayan & Xu 2003). Due to the variable nature of concrete derived from waste sources it is critical that the properties of the RCA be thoroughly evaluated prior to use (Limbachiya et. al. 2000). In general good quality RCA is generally one with can be obtained from demolished structural concrete due to the design requirements for that type of concrete. This would be a normal 30MPa concrete with a W/C ratio of 0.45 or less.

2.2.2 – Physical Characteristics of Recycled Concrete Aggregate

RCA that has been derived from demolished concrete inherits the physical properties of all the materials. While it is possible to simply apply a 1:1 substitution with some loss in performance, the different constituents in a given RCA particle require a more calculated approach to provide the optimal performance. A given RCA particle might consist of virgin coarse and fine aggregate, along with adhered paste. A good understanding of the material allows for modifications to the mix design to compensate will ensure negligible changes in concrete performance (Abbas et. al. 2009). The most detrimental material found in a given RCA particle is the paste component. The high porosity of the paste and relative weakness compared to the virgin aggregate creates the most serious effects on the material properties. The adherence of the paste creates weak planes in the RCA particle that reduce the overall strength and the paste itself increases the absorption. Since fine RCA generally consists of higher paste content due to the relative weakness during crushing, the absorption is significantly higher. When not assessed and

compensated for, this increased absorption creates significant workability issues. This is further exacerbated by the generally angular nature of processed fine aggregate (Achtemichuk et. al. 2009) and (Shayan & Xu 2003). The same problem applies to coarse aggregate, the higher absorption can also reduce the workability significantly if not assessed and compensated for (Yang et. al. 2010).

2.2.3 – Strength of Concrete made with Recycled Concrete Aggregate

As stated previously, a direct 1:1 substitution of RCA for virgin aggregate will produce a mix with poorer performance. However, it has been generally shown that partial substitution of coarse RCA for virgin aggregate can produce concrete with negligible loss in strength without mix modifications (Limbachiya et. al 2000). Limbachiya et. al. 2004 suggests that using up to 30% replacement of a good quality coarse RCA will yield negligible change in strength and workability without changing the mix design. Likewise, Gonçalves et. al. 2004 showed that up to 50% replacement with a good quality coarse RCA will result in a less than 5% strength reduction and similar workability without a change in mix design. In general fine RCA requires compensation in the mix design to produce workable mixes. However, research by Abbas et. al. 2009 showed that the creation of mix designs that compensate especially for the properties of RCA can produce concrete that equals or improves upon the performance of an equivalent concrete made with virgin aggregate. Their method accounts for the volume of adhered paste on the RCA when proportioning the mix. It has also been shown that the use of SCM with RCA will improve the strength of concrete made with RCA (Shayan & Xu 2003). When testing for the strength of RCA, the use of NDT equipment was found to be suspect. Although tests such as the impact hammer have proven reliable, the use of ultrasonic pulse velocity will significantly underestimate placed concrete strength when using RCA (Sriravindraiah et. al. 1988). The problem is that the different RCA constituents have different transmission speeds. It is well known that the transmission speed in paste is lower than that of stone. Therefore in RCA where the aggregate particle is partially made of paste the transmission speed will be reduced. Furthermore, since transmission speed is affected by the number of transitions between materials, the additional transitions in the RCA particles may also affect the transmission speed.

Therefore, additional knowledge is required when taking in-situ strength measurements to ensure the actual material strength is assessed.

2.2.4 – Durability of Concrete Made with Recycled Concrete Aggregate

The higher absorption and increased porosity of RCA particles result in concrete that is more susceptible to deterioration. Even though research has shown the strength of concrete is not affected by partial replacements of RCA in concrete, the long-term durability will be affected. A concerning issue is the effect that RCA has on creep. Creep is critical when used for structural elements since long term deformations can exceed serviceability limits and force a structure to be abandoned (Limbachiya et. al. 2004). This is concerning since it makes it more difficult to utilize RCA for structural applications and thus limits its acceptance. The same concern applies to durability against environmental factors as well. Gonçalves et. al. 2004 still found that RCA produced concrete of lesser performance in resisting environmental deterioration. The modified mix design introduced by Abbas et. al. 2009 was able to produce similar resistance to normal concrete indicating that mix modification does provide an avenue for potential mitigation. Furthermore, the use of SCM produces nearly identical performance in RCA concrete to normal concrete. The factors discussed previously that make SCM effective isolate the RCA particles and prevent external environmental factors from reaching the RCA (Shayan & Xu 2003). It should be noted that research by Limbachiya et. al. 2000 showed that the partial replacement RCA derived from high-performance concrete provided equal strength and durability to normal concrete. This is due to the properties of High-Performance Concrete (HPC). The high strength and low permeability inherent to HPC, due to factors such as low W/C ratio and use of SCM, limit the weaknesses of normal RCA. Since the adhered paste is stronger and less porous and permeable, it will obviously be more resistant. The problem is that HPC is not common and thus not a viable resource for every project that wishes to use RCA.

2.3 – Alkali Silica Reaction in Recycled Concrete Aggregate

ASR can be severe enough to cause a concrete structure to be abandoned and require new construction to take place. The demolished structure will need to be disposed of in landfill unless the material can be diverted. The most sustainable alternative is to utilize the waste from the original structure to build the new structure. The new structure will simply inherit the same ASR condition from the original material. Research consistently shows that the expansion of RCA made from ASR virgin aggregate will exhibit equal and often greater expansion in testing. Li & Gress 2006 and Shehata et. al. 2010 both reported results where RCA derived from ASR virgin aggregate exhibited similar expansion to the virgin aggregate. Scott IV & Gress 2004 and Gratten-Bellew 1995 reported results where the expansion of RCA derived from ASR virgin aggregate was greater than the virgin aggregate. Li & Gress 2006 suggested that the greatest concerns of utilizing ASR RCA were the following.

1. The reactivation of ASR due to the increased alkali content of modern cements.
2. The expansion of existing ASR products that were desiccated during the processing of the RCA.
3. Exposure of unused reactive silica in coarse aggregate during crushing.

2.3.1 – Considerations for the Mechanism and Effect of ASR in RCA

The first consideration for ASR in RCA is the existence of reactive silica. In a very-mildly reactive virgin fine aggregate used in a high alkali cement, it is possible that the vast majority of the reactive silica will be utilized and that the remnants will be rendered inert, resulting in a non-reactive RCA. This same effect is not likely to occur for reactive coarse aggregate since the internal reactive silica is rarely fully utilized. The formation of a reaction ring around certain aggregates can delay the ASR but when processed the newly exposed surfaces allow for immediate reactivation. If the expansion was monitored and assumed to have depleted the reactive products, the RCA could be used without sufficient mitigation and the exposed faces created during processing would be available to react.

It has been shown that the paste constituents in the RCA particles retain alkali as well as calcium. It has been suggested that the alkali is insufficient to increase the pore solution concentration and thus will not greatly affect the ASR (Li & Gress 2006). But research has shown that the alkali and calcium concentration is sufficient to induce pozzolanic reactions in SCM (Achtemichuk et. al. 2009). Thus it is likely sufficient to produce some effect on the ASR in some RCA's. Li & Gress 2006 suggested that the residual ASR gel products could also induce expansion in new concrete. This is particularly concerning since ASR gel only requires water to produce expansion and would do so independent of any mitigation applied to the concrete. The cracking mechanism in RCA will be similar to that of the virgin aggregate as discussed in Section 2.1.1. The differences lie in the formation of the gel membranes. Where a gel membrane already exists around a particle in the RCA the ASR gel production needs only to be sufficient to fill any new voids in the membrane before the expansive forces begin to develop. Since the volume of new gel required to create the solid membrane is lower the expansive forces can develop at an earlier age. This may also provide an explanation for the increased reactivity discussed in Section 2.3. However, if the membrane remains intact during the processing it is possible to limit the ingress of new alkali and water and thus limit the reactivity (Shayan 1992).

2.3.2 – Considerations for the Testing of ASR in RCA

The same tests that apply for the testing of ASR in virgin aggregate are still applicable for the screening of RCA. Since there are some changes in the properties of already reacted ASR RCA it is necessary to validate the test procedures to ensure reliable results. Petrography is still effective to screen RCA as discussed in Section 2.1.2.1 since a trained Petrographer would easily be able to distinguish reactive constituents and be able to easily recognize and evaluate ASR gel products as well as cement paste.

2.3.2.1 – Considerations for the Concrete Prism Test

Since the CPT is considered to be the most reliable comparison to field conditions and the basis of comparison for the effectiveness of most accelerated test methods, the variations caused by the use of RCA need to be well understood. A major concern for the CPT using RCA is the suggestion that the expansion recorded is not directly a result of ASR. It has been suggested that the adherent paste if mixed from the dry condition will absorb water and swell causing resulting in early expansion (Shehata et. al. 2010). This was also observed by Scott IV & Gress 2004 who suggested that pre-soaking the RCA to ensure the adhered paste was saturated prior to mixing would limit this effect. Shehata et. al. 2010 still indicates that the CPT still provides a valid screening of ASR expansion. When Shayan & Xu 2003 compared the expansion of ASR RCA to its original virgin aggregate, they found the expansion to be similar. The problem of leaching discussed in Section 2.1.2.2 suggests that the residual alkali may change the effective test duration. Where leaching will eventually starve the ASR reaction in the CPT, the extra alkali provided by the RCA will increase the duration in which there is sufficient alkali. This could be the reason for the increased expansion seen for RCA in the CPT results. Scott IV & Gress 2004 also observed that the CPT produced reasonable results for CPT prisms made with SCM.

2.3.2.2 – Considerations for the Accelerated Mortar Bar Test

The AMBT has been a reasonably effective screening test for ASR but faces different challenges in evaluating ASR. Shehata et. al. 2010 indicated that fine RCA produced less expansion than coarse RCA from the same source. They recommended that coarse RCA be processed by the tester to evaluate AMBT expansion results. This is explained as a result of an overabundance of paste when fine RCA is tested which is a result of paste breaking down to fine grades more easily than the stone. When the specimens are properly prepared, the AMBT will provide an acceptable screening for ASR RCA (Shehata et. al. 2010) and (Shayan & Xu 2003). Since the AMBT uses an alkali solution to provide an abundance of alkali to the specimens, the additional alkali supplied by the residual paste become redundant and therefore results in negligible changes in expansion. The main drawback of the AMBT is the gradation used. Beyond the

potential for receiving an unrepresentative sample, the well known difficulty in workability of mixes with fine RCA cause special concerns for the test. Adjustments to the mortar mix need to be minimized since the standard requirements of the test must be met. However, with proper care, results have shown that the AMBT provides comparable results to the CPT for ASR RCA (Scott IV & Gress 2004).

2.3.2.3 – Considerations for the Concrete Microbar Test

The CMBT has immediately addresses some of the concerns that face the CPT and the AMBT. Like the AMBT, the alkali solution provides the alkali which removes the potential for excess alkali reducing leaching and increasing effective test duration. It also addresses the major concerns of using fine RCA like in the AMBT since the CMBT uses coarse RCA. There is a lack of available research on the effectiveness of the CMBT in evaluating ASR RCA. Shehata et. al. 2010 provided limited results which showed that ASR RCA behaves similarly to virgin aggregate in the CMBT. This means we should expect the ASR RCA to exhibit greater expansion than the virgin aggregate, but underestimate the results shown in the CPT and AMBT. As was postulated in Section 2.1.2.4, the overabundance of SCM in the CMBT mix may have an increased effect in the expansion results. The alkali binding capacity is likely to have even more prominent effects. This is because the RCA has its own alkalis that add to the available alkali in the mix. The alkali binding capacity of the CMBT mix is likely higher and thus may be able to bind more alkali from the RCA. Since this is the most direct source of alkali for the reactive silica in the original stone, this would potentially reduce the reaction forming ASR gel.

2.3.3 – Amelioration of Alkali Silica Reaction in Recycled Concrete Aggregates

The concerns about strength and durability with using non-reactive RCA indicate that special consideration is required to produce equivalent performance concrete. In many cases, the mitigating measure to improve RCA concrete performance will also be effective in mitigating

ASR. Avoidance of ASR RCA is still the most effective method of preventing ASR expansion but SCM and chemical admixtures should remain effective.

2.3.3.1 – Use of Supplementary Cementing Materials with RCA

Research using SCM with non-reactive RCA showed that the properties of the concrete were improved and provided good strength and durability. Since using the correct blend of SCM has been shown to mitigate ASR expansion as well it can be assumed that the correct dosage of SCM will provide a mitigation of expansion and produce a stronger and more durable concrete than a normal aggregate concrete without SCM. Research into the expansion of concrete made from ASR RCA has shown that the level of expansion is similar to or greater than that of virgin aggregates for many different materials. This explains the results which showed that greater replacements of SCM were required to mitigate the expansion compared to the virgin aggregate (Shehata et. al. 2010) and (Scott IV & Gress 2004). This suggests that the postulate of Li & Gress 2006 may be incorrect that the contribution of alkali from the RCA is insufficient to change the pore solution concentration. This is supported by Shehata & Thomas 2006 who suggested that the pore solution concentration is the controlling factor in the CPT test, which is the test responsible for most currently available research results. Overall, it has been shown that the use of SCM will be effective in the mitigation of ASR.

2.3.3.2 – Use of Chemical Admixtures with RCA

The use of Lithium was shown to be effective in reducing ASR in RCA by Shehata et. al. 2010 and was the only research discovered by the author on this topic. However, the chemical reaction that makes Lithium an effective mitigation for ASR remains the same. Like for SCM it is likely that higher doses may be required due to the greater availability of alkali. Lithium may also be effective in a pre-treatment of reactive RCA however it would require alkali in the treatment to encourage the formation of amorphous gel to react with the Lithium and create the ALiSH barrier discussed in Section 2.1.3.3 prior to the RCA being used in concrete.

3 – Experimental Details and Materials

3.1 – Accelerated Mortar Bar Interlaboratory Study Procedures

3.1.1 – Objectives

To investigate the effectiveness and variation of the AMBT in evaluating the reactivity of RCA derived from reactive virgin aggregate. Tests were conducted individually at Laval University, Oregon State University, University of Wyoming and Ryerson University.

Testing was conducted at all locations using the same materials supplied for the test program by CANMET. The Portland cement was a Type I general use cement with a high alkali content that conformed to the ASTM C1260 requirements. The chemical analysis of this cement (PC ILS) can be found in Table 3.8 in Section 3.6. The RCA was produced from the long term exposure testing blocks that were crushed and prepared in Summer 2009. Four different RCA samples were produced from virgin aggregates to be found below in Table 3.1. The RCA was delivered in 4 gradations from this crushing, $\frac{3}{4}$ " – $\frac{1}{2}$ " ($\frac{3}{4}$ RCA), $\frac{1}{2}$ " – $\frac{3}{8}$ " ($\frac{1}{2}$ RCA), $\frac{3}{8}$ " – $\frac{1}{4}$ " ($\frac{3}{8}$ RCA) and $>\#4$ sieve sizes (RCA crusher's Fines). A non-reactive granitic sand was also provided

Table 3.1 – List of RCA samples provided by CANMET

| RCA | Virgin Aggregate Type | Source Location |
|------------|------------------------------|-------------------------------------|
| Alberta | Natural Gravel | Montreal, Quebec |
| Bernier | Argillaceous Limestone | Fredericton, New Brunswick |
| Potsdam | Siliceous Sandstone | St-Jean sur le Richelieu, Quebec |
| Springhill | Greywacke and Argilite | Calgary, Alberta |

The coarse RCA samples, $\frac{3}{4}$ RCA, ($\frac{1}{2}$ RCA) and ($\frac{3}{8}$ RCA) were to be crushed and sieved to the standard ASTM C1260 gradation then washed to remove adhered fines by each participating lab to evaluate variation due to crushing methods. The crusher's fines were sieved to the required C1260 gradation then washed to remove adhered fines. Testing of the RCA was conducted in accordance to ASTM C1260 with some modifications to account for the properties of RCA.

3.1.2 – Preliminary Preparation of RCA Samples

The coarse RCA samples were crushed and graded at the Ontario Ministry of Transportation materials labs in Toronto, Ontario. The remaining processing was completed in the Ryerson Civil Engineering labs. The procedure for preparing the coarse RCA samples is as follows.

1. Approximately 2kg of RCA comprised of equal parts of $\frac{3}{4}$ RCA, $\frac{1}{2}$ RCA and $\frac{3}{8}$ RCA were separated for crushing.
2. The sample was passed through a large jaw crusher to reduce the nominal maximum aggregate size to $\frac{3}{8}$ "
3. The sample was collected and passed through a small bench-top jaw crusher to reduce the nominal maximum size to $\frac{1}{4}$ "
4. The sample was collected and passed through a rotary disc type pulveriser to further produce the fine gradations of RCA.
5. After the first pass through the pulveriser, the sample was sieved for the required ASTM C1260 gradation on the following (coarse to fine) nest of sieves, #4 - #8 - #16 - #30 - #50 - #100 - Pan.
6. The material retained on the #8, #16, #30, #50, #100 were weighed and set aside.
7. Material retained on the #4 sieve and sample in excess of the required masses on other sieves were collected to be passed through the pulveriser again. Material retained on the pan was disposed of.
8. When the sample had been pulverised and sieved 3 times any remaining material was disposed of.
9. If the required mass of each gradation was not collected, steps 1-7 were repeated until a sufficient mass of sample was collected for each gradation.
10. Each gradation was stored in doubled sealable plastic bags until needed.
11. Each gradation was washed on its corresponding sieve size under a "fanned" spray pattern nozzle for the prescribed time as follows.
 - a. #8 Sieve – 3.5 Minutes
 - b. #16 Sieve – 5 Minutes
 - c. #30 Sieve – 6 Minutes

- d. #50 Sieve – 7 Minutes
 - e. #100 Sieve – 8 Minutes
12. Each gradation was placed in an oven at 105°C for 24h ±h to dry and then placed in clean double sealable plastic bags until mixing.

The fine RCA and non-reactive sand samples were prepared in the Ryerson Civil Engineering labs. The procedure for preparing the fine RCA samples and non-reactive sand is as follows.

1. Approximately 1kg of the RCA crusher's fines or non-reactive sand were sieved for the required ASTM C1260 gradation on the following (coarse to fine) nest of sieves, #4 - #8 - #16 - #30 - #50 - #100 - Pan.
2. The material retained on the #8, #16, #30, #50, #100 sieves were weighed and set aside.
3. Material retained on the #4 sieve and material retained on the pan was stored.
4. Steps 1-3 were repeated until a sufficient mass of sample was collected for each gradation.
5. Each gradation was stored in doubled sealable plastic bags until washing.
6. Each gradation was washed on its corresponding sieve size under a “fanned” spray pattern nozzle for the prescribed time as follows.
 - #8 Sieve – 3.5 Minutes
 - #16 Sieve – 5 Minutes
 - #30 Sieve – 6 Minutes
 - #50 Sieve – 7 Minutes
 - #100 Sieve – 8 Minutes
7. Each gradation was placed in an oven at 105°C for 24h ±h to dry and then placed in clean double sealable plastic bags until mixing.

3.1.3 – Preparation of Samples for Mixing

The RCA and non-reactive sand samples were further prepared immediately prior to mixing to account for the increased absorption and water demand of RCA to ensure consistent and

workable mortar. The ASTM C1260 gradation for the different batches can be found in Table 3.2 below and the details of the batches can be found in Appendix A. The steps for preparing the aggregate for mixing follow below. A time of 30 minutes was selected to allow for the absorption of at least 85% of the RCA absorption capacity.

Table 3.2 – Aggregate and cement mix proportions for AMBT testing

| RCA Blend | 100% RCA | 50% RCA | | 25% RCA | |
|----------------|-----------------|-----------------|------------------|-----------------|------------------|
| Retained Sieve | Mass of RCA (g) | Mass of RCA (g) | Mass of Sand (g) | Mass of RCA (g) | Mass of Sand (g) |
| #8 | 99.0 | 49.5 | 49.5 | 24.7 | 74.3 |
| #16 | 247.5 | 123.8 | 123.8 | 61.9 | 185.6 |
| #30 | 247.5 | 123.8 | 123.8 | 61.9 | 185.6 |
| #50 | 247.5 | 123.8 | 123.8 | 61.9 | 185.6 |
| #100 | 148.5 | 74.2 | 74.2 | 37.1 | 111.4 |
| Total Mass | 990 | 990.2 | | 990 | |
| Cement | 440 | 440 | | 440 | |

1. Individual gradations of RCA and non-reactive sand were combined according to Table 3.2 and homogenized in a sealable plastic container.
2. Water was added to the container at a rate of

$$206.8g + (\text{Mass of RCA}_x) * (\text{Absorption of RCA}_x)$$
3. The aggregate and water were homogenized and allowed to stand in the sealed plastic container for 30 minutes.

3.1.4 – Mixing Procedure

The procedure for the mixing of mortar is modified from the standard ASTM C1260. The mix time remains constant at 4 minutes but due to the pre-mixing of the aggregate and water the overall procedure is changed. A small countertop Hobart brand mixer was used for all tests. The modified mix procedure is as follows.

1. The prepared aggregate and water mixture is added to the moistened mixing bowl followed by the cement and the mixing paddle was attached.

2. The mixer was set to slow speed for 60 seconds to allow the cement, aggregate and water to fold together without loss of material.
3. After 60 seconds, the mixer was accelerated to medium speed for 30 seconds to vigorously mix the materials.
4. The mixer was then switched off and immediately the bowl was scraped with a stiff spatula to remove any material adhering to the bowl. Within 15 seconds of stopping, the bowl was covered with a damp cloth to prevent evaporation and the mortar was allowed to rest.
5. 90 seconds after stopping (3 minutes elapsed time) the mixer is started at medium speed for a further 60 seconds to complete the mixing process.

3.1.5 – Mortar Bar Moulding and Preparation Procedure

The procedure for the moulding and curing of mortar bar specimens is the same as in ASTM C1260 and follows below.

1. Bar moulds were assembled and coated with a thin layer of form release. The gauge studs were fitted and adjusted to a gauge length of 265mm as measured by an engineer's scale.
2. Immediately after batching, a first lift of mortar filling half of the mould depth was placed in each of three bar moulds.
3. The first lift was tamped at least 50 times with a standard tamper and also tamped with a trowel edge around the studs to create a homogeneous layer.
4. A second lift was placed to slightly overflowing of the mould depth to ensure sufficient material for compaction.
5. The second lift was tamped at least 50 times with a standard tamper to create a nearly flush surface.
6. The excess material was removed with a trowel and cleaned to a completely flush surface.

7. The finished specimens were draped in labelled plastic sheets and covered with solid plastic lids to ensure flow of humid air in the curing room but prevent direct contact with water droplets.
8. The specimens were allowed to cure for $24\text{h} \pm 0.5\text{h}$ before being demoulded.

3.1.6 – NaOH Test Solution Preparation

The 1N NaOH test solution used for testing was prepared according to the following procedure.

1. A clean 20L container with a tap was filled with 18.5 ± 0.1 kg of cold tap water.
2. The water was weighed and the temperature was measured so as to be converted to volume using standard relative densities.
3. The required mass of NaOH was calculated using the procedure below.
 - a. $(\text{Volume} * 39.9925\text{g} / \text{mol NaOH}) / 99.5\% \text{ Purity}$
4. The required mass of NaOH was added to the water and mixed thoroughly until no NaOH pellets were visible.
5. The solution was stored for at least 24h before use and mixed thoroughly before each use.
6. The correct volume of solution was added to each container using a measure with $\pm 1\%$ accuracy.
7. The containers with solution were sealed with the adhesive plastic wrap and placed in the oven 24h prior to use to reach 80°C before the specimens are placed into them.

3.1.7 – AMBT Testing Procedure

Once cured, the samples were conditioned and tested according to ASTM C1260. Measurements were taken to ensure consistent results at the following ages; 0, 1, 3, 5, 7, 10, 12, 14, 17, 21, 24 and 28 days. The procedure for the specimen testing duration is outlined as follows.

1. Demoulded samples were labelled with permanent markers and placed in a hot water bath at 80°C for 24h ± 0.5h to condition the samples.
2. Conditioned samples were then placed in a 2L solution of 1N Sodium Hydroxide, prepared according to 3.1.6, for the duration of testing at 80°C in a convection oven.
3. The containers were 5.5L volume with rubber gaskets and were sealed with adhesive backed plastic wrap to ensure an airtight seal.
4. On the designated test days the samples were tested for changes of length using a Digital Length Comparator with 0.002mm accuracy.
5. Time from removal to return to the oven was limited to less than 3 minutes.
6. Solution temperature was checked using a digital immersion thermometer at least 3 times weekly to ensure the correct temperature.

3.2 – Accelerated Mortar Bar Variable Testing Procedures

3.2.1 – Objectives

To determine the effect of controllable variables on the expansion of RCA in the AMBT. The first variable to be investigated is the effect of effective W/C ratio caused by errors in the measurement of RCA absorption. Another variable tested was the effect of crushing method on expansion. The effect of washing the RCA on expansion was also tested.

The Portland cement was a Type I general use cement with a high alkali content that conformed to the ASTM C1260 requirements. The chemical analysis of this cement (PC B) can be found in Table 3.8 in Section 3.6. The RCA used was a combination of Laval RCA sourced from ASR affected bridges in Quebec as well as prepared Spratt RCA from Ryerson University. The Laval RCA was delivered in three gradations, $\frac{3}{4}'' - \frac{1}{2}''$ ($\frac{3}{4}$ RCA), $\frac{1}{2}'' - \frac{3}{8}''$ ($\frac{1}{2}$ RCA) and $\frac{3}{8}'' - \frac{1}{4}''$ ($\frac{3}{8}$ RCA) while the prepared spratt was already crushed and separated in the standard ASTM C1260 gradations.

The Laval RCA was crushed to gradation in two ways to evaluate the variation and one sample was washed. The Spratt RCA was washed for testing. Testing was conducted according to ASTM C1260.

3.2.2 – Preliminary Preparation of RCA Samples

The coarse Laval RCA samples were crushed and graded at the Ontario Ministry of Transportation materials labs in Toronto, Ontario. The procedure for preparing the Laval RCA samples is as follows.

1. Approximately 2kg of RCA comprised of equal parts of $\frac{3}{4}$ RCA, $\frac{1}{2}$ RCA and $\frac{3}{8}$ RCA were separated for crushing.

2. The sample was passed through a large jaw crusher to reduce the nominal maximum aggregate size to $\frac{3}{8}$ "
3. The sample was collected and passed through a small bench-top jaw crusher to reduce the nominal maximum size to $\frac{1}{4}$ "
4. The sample was collected and passed through a rotary disc type pulveriser to further produce the fine gradations of RCA.
5. After the first pass through the pulveriser, the sample was sieved for the required ASTM C1260 gradation on the following (coarse to fine) nest of sieves, #4 - #8 - #16 - #30 - #50 - #100 - Pan.
6. The material retained on the #8, #16, #30, #50, #100 were weighed and set aside.
7. Material retained on the #4 sieve and sample in excess of the required masses on other sieves were collected to be passed through the pulveriser again. Material retained on the pan was disposed of.
8. When the sample had been pulverised and sieved 3 times any remaining material was disposed of.
9. If the required mass of each gradation was not collected, steps 1-7 were repeated until a sufficient mass of sample was collected for each gradation.
10. Each gradation was stored in doubled sealable plastic bags until needed.

One sample of Laval RCA and the Spratt RCA were washed according to the following procedure.

1. Each gradation was washed on its corresponding sieve size under a "fanned" spray pattern nozzle for the prescribed time as follows.
 - #8 Sieve – 3.5 Minutes
 - #16 Sieve – 5 Minutes
 - #30 Sieve – 6 Minutes
 - #50 Sieve – 7 Minutes
 - #100 Sieve – 8 Minutes
2. Each gradation was placed in an oven at 105°C for 24h \pm h to dry and then placed in clean double sealable plastic bags until mixing.

The second form of crushing was completed in the Ryerson Civil Engineering labs. The procedure for preparing the Laval RCA alternate crushing samples is as follows.

1. A 4” proctor mould with a solid base and a 2” round steel plate with diameter slightly smaller than the proctor were prepared.
2. Equal masses of $\frac{3}{4}$ RCA, $\frac{1}{2}$ RCA and $\frac{3}{8}$ RCA were blended and placed in the proctor with the steel plate on top.
3. The setup was placed in the compressive test machine and loaded at a rate of approximately 2kN/s.
4. The sample was loaded to a total of 300kN and then removed from the compressive test machine and proctor mould.
5. The sample was sieved for the required ASTM C1260 gradation on the following (coarse to fine) nest of sieves, #4 - #8 - #16 - #30 - #50 - #100 - Pan.
6. The material retained on the #8, #16, #30, #50, #100 sieves were weighed and set aside.
7. Material retained on the #4 sieve and sample in excess of the required masses on other sieves were collected to be further crushed in the compressive test machine. Material retained on the pan was disposed of.
8. Remaining space in the proctor mould was filled with new $\frac{3}{4}$ RCA, $\frac{1}{2}$ RCA and $\frac{3}{8}$ RCA blend with the crushed material at the top of the proctor.
9. If the required mass of each gradation was not collected, steps 1-8 were repeated until a sufficient mass of sample was collected for each gradation.
10. Each gradation was stored in doubled sealable plastic bags until needed.

3.2.3 – Preparation of Samples for Mixing

The RCA samples were further prepared immediately prior to mixing to account for the increased absorption and water demand of RCA. For the mixes used to evaluate variance in effective water content the following corrections were applied.

1. For absorption greater than actual by 1%
 - $206.8g + (\text{Mass of RCA}_X) * (\text{Absorption of RCA}_X + 1\%)$
2. For tested absorption
 - $206.8g + (\text{Mass of RCA}_X) * (\text{Absorption of RCA}_X)$
3. For absorption less than actual by 1%
 - $206.8g + (\text{Mass of RCA}_X) * (\text{Absorption of RCA}_X - 1\%)$

All of the samples were then prepared for mixing as follows.

1. Individual gradations of RCA were combined according to ASTM C1260 gradation as seen in Table 3.2 for 100% RCA.
2. The corrected mass of water was added to the RCA.
3. The aggregate and water were homogenized and allowed to stand in the sealed plastic container for 30 minutes.

3.2.4 – AMBT Mixing, Moulding & Preparation, and Testing Procedures

The procedures are identical to the procedures outlined in 3.1.4, 3.1.5 and 3.1.6 with the exception of the testing ages. In this program the testing dates at 17 and 24 days were omitted.

3.3 – Concrete Microbar Testing Procedures

3.3.1 – Objectives

The overall goal of this section of study was to evaluate the effectiveness of the CMBT for evaluating ASR. The first objective was to evaluate the variables affecting the CMBT in evaluating ASR reactivity and the perceived over-dosage of SCM if used in the CMBT. The second objective was to determine the efficacy of the CMBT in evaluating the reactivity of RCA and to determine if the CMBT can evaluate the effectiveness of SCM in mitigating expansion due to ASR. Evaluation of the importance of cement alkali content in the CMBT was evaluated using virgin Spratt aggregate due its abundance and well documented reactivity. The perceived over-dosage of SCM in the CMBT was evaluated by reducing the replacement level of SCM in the mix by a factor of 0.425 and comparing the results to normally dosed specimens.

The effectiveness of the CMBT in evaluating the reactivity of RCA, was conducted using RCA derived from concrete made with Spratt aggregate and the four types of RCA described in 3.1.1. The four RCA Types in 3.1.1 were also used to evaluate the variation in the test results caused by the size of aggregate selected for testing. The Spratt RCA was used to evaluate the effectiveness of the CMBT in screening SCM blends used to mitigate ASR by comparing the results to an existing database of CPT results from the same aggregate.

The Portland cements used were Type I general use cements with a high alkali content that conformed to the ASTM C1260 requirements. The chemical analysis of this cement (PC A and PC B) can be found in Table 3.8 in Section 3.6. The SCM's used included High Calcium Fly Ash (HCFA) and Low Calcium Fly Ash (LCFA), Blast Furnace Slag (Slag) and Silica Fume (SF). These SCM's were obtained from Ryerson stockpiles used in previous studies. The chemical analysis of these SCM's can be found in Table 3.8 in Section 3.6.

3.3.2 – Preparation of Virgin Spratt Specimens

The virgin Spratt aggregate was delivered in the standard 20mm nominal maximum gradation and needed to be sieved to obtain the required particle sizes. A Gilson floor sieve shaker was used for the gradation using the following procedure.

1. A 5kg sample of aggregate was obtained from the bulk sample and placed on the Gilson sieve shaker nest of sieves with the following Coarse to fine gradation; 26.5mm – 19mm – 13.2mm – 9.5mm – 4.75mm - Pan.
2. The sieve shaker was run for 10 minutes to obtain a thoroughly separated sample.
3. Material retained on the 9.5mm (10mm aggregate) and 4.75mm (5mm aggregate) were retained for testing and the remaining material was stored.

3.3.3 – Preparation of RCA Specimens

As was discussed in 3.1.1, the four RCA specimens from CANMET were delivered in pre-graded coarse fractions. The aggregate sizes were $\frac{3}{4}$ " – $\frac{1}{2}$ " (14mm RCA), $\frac{1}{2}$ " – $\frac{3}{8}$ " (10mm RCA), $\frac{3}{8}$ " – $\frac{1}{4}$ " (5mm RCA) therefore no processing was required. Similarly, the Spratt RCA had been pre-graded and stored in $\frac{1}{2}$ " – $\frac{3}{8}$ " (10mm RCA), $\frac{3}{8}$ " – $\frac{1}{4}$ " (5mm RCA) size fractions. As such, the correct size fraction were simply blended from these supplies prior to testing.

3.3.4 – Preparation of Samples for Mixing

The CMBT test specimens were prepared for mixing in large sealable plastic bags according to their designations. The standard batch can be found in Table 3.3 below with the details of individual batches found in Appendix A. Since the paste volume is so high in the CMBT, the high absorption of RCA had no appreciable effect on the workability and so pre-saturating the RCA was not necessary. The procedure follows below.

Table 3.3 – Standard batch for CMBT

| | Aggregate Size A (g) | Aggregate Size B (g) | CM (g) | Water (g) |
|----------------|----------------------|----------------------|--------|------------------------|
| Standard Batch | 810 | 810 | 1620 | 522 + (1620 * Abs%) |

1. Aggregate was blended and homogenized in a sealable plastic bag prior to mixing.
2. Cement and SCM blends were homogenized in a sealable plastic bag prior to mixing.
3. Immediately prior to mixing, water was prepared in a sealable plastic container.

3.3.5 – Mixing Procedure

Due to the small overall volume of the batches, mixing needed to be completed using the same Hobart mixer as in 3.1.4. However, the large aggregate size made it impossible to mix the aggregates into the paste. Thus a modified mixing method conforming to the RILEM AAR-5 draft method was created through trial and error to produce consistent batches.

1. The water is added to the moistened mixing bowl followed by the cement and the mixing paddle was attached.
2. The mixer was set to slow speed for 30 seconds to allow the cement and water to fold together without loss of material.
3. The mixer was then switched off and immediately the bowl was scraped with a stiff spatula to remove any material adhering to the bowl. Within 15 seconds of stopping, the mixer was restarted at medium speed until the total elapsed mixing time reached two minutes.
4. The mixer was then switched off and removed from the mixer.
5. The prepared aggregate was added to the blended paste folded into the paste with a stiff spatula for 30 second by which time all the aggregate particles were adhered to paste.
6. The final mixing was conducted by hand for 2 minutes using the procedure outlined below.

- a. An open hand contacted the mix and pressed down lightly to remove voids in the mix before closing around a handful of material while rotating the hand.
 - b. The bowl was turned 90° and step (a) was repeated.
 - c. After rotating the full 360° the sides of the bowl were scraped using the edge of the hand.
 - d. Steps (a-c) were repeated until two minutes elapsed.
7. The mix was checked for consistency to ensure no uncoated aggregates were visible.

3.3.6 – Micro-Bar Moulding and Preparation Procedure

The procedure for the moulding and curing of micro-bar specimens is similar to that found in 3.1.5 and follows below.

1. Bar moulds were assembled and coated with a thin layer of form release. The gauge studs were fitted and adjusted to a gauge length of 265mm as measured by an engineer's scale.
2. Immediately after batching, a first lift of mortar filling half of the mould depth was placed in each of three bar moulds.
3. The first lift was tamped at least 50 times using the tips of three fingers to allow for manipulation of aggregate particles. Particles were manipulated to ensure fitting of aggregate and filling paste around the gauge studs.
4. A second lift was placed to slightly overflowing of the mould depth to ensure sufficient material for compaction.
5. The second lift was tamped at least 50 times using the tips of three fingers to allow for manipulation of aggregate particles to create a nearly flush surface.
6. The excess material was removed with a trowel and cleaned to a completely flush surface.
7. The finished specimens were draped in labelled plastic sheets and covered with solid plastic lids to ensure flow of humid air in the curing room but prevent direct contact with water droplets.
8. The specimens were allowed to cure for 24h ± 0.5h before being demoulded.

3.3.7 – CMBT Testing Procedure

Once cured, the samples were conditioned and tested according to RILEM AAR-5. Measurements were taken to ensure consistent results at the following ages; 0, 1, 3, 5, 7, 10, 12, 14, 21, 28, 35, 42, 49 and 56 days. In two cases, some of the testing ages were modified due to circumstances where the author or an associate were unavailable to complete testing on the specified date. The procedure for the specimen testing duration is outlined as follows.

1. Demoulded samples were labelled with permanent markers and placed in a hot water bath at 80°C for $24\text{h} \pm 0.5\text{h}$ to condition the samples.
2. Conditioned samples were then placed in a 3.5L solution of 1N Sodium Hydroxide, prepared according to 3.1.6, for the duration of testing at 80°C in a convection oven.
3. The containers were 5.5L volume with rubber gaskets and were sealed with adhesive backed plastic wrap to ensure an airtight seal.
4. The mass of these containers were taken to the nearest gram and labelled on the top of the container.
5. On the designated test days the samples were tested for changes of length using a Digital Length Comparator with 0.002mm accuracy.
6. During the tests at the weekly intervals, the samples were reweighed and water was added to return the weight to $\pm 5\text{g}$ of the initial mass on the top of the container to correct for evaporation.
7. Time from removal to return to the oven was limited to less than 3 minutes.
8. Solution temperature was checked using a digital immersion thermometer at least 3 times weekly to ensure the correct temperature.

3.4 – Porosity and Permeability Test Procedures

3.4.1 – Objectives

To provide supporting results for the AMBT and CMBT results. This phase required evaluation of AMBT, CMBT and CPT specimens for porosity and permeability.

The porosity and permeability specimens were prepared using the same Type I general use cement as previous tests. The chemical analysis of this cement (PC B) can be found in Table 3.8 in Section 3.6. The same Low Calcium Fly Ash (LCFA) as previous tests was selected as the SCM used during these evaluations. The chemical analysis of LCFA can be found in Table 3.8 in Section 3.6. The main aggregate was virgin Spratt aggregate prepared for the required grades and several AMBT specimens were prepared using standard Ottawa sand.

3.4.2 – Aggregate Preparation of Porosity and Permeability AMBT Specimens

The AMBT specimens were made using Spratt aggregate and Ottawa Sand. The Spratt aggregate was crushed and sieved to the required gradation using the procedure shown in 3.2.2. The Ottawa Sand was sieved to the required gradation using the procedure shown in 3.1.2 for fine RCA and non-reactive sand.

3.4.3 – Sample Preparation for AMBT Specimens

The AMBT specimens were combined as seen in Table 3.4 below prior to testing. Since the size of the required specimen is larger, the required masses are not the same as the standard ASTM C1260 test. The details of individual batches are found in Appendix A. The steps for preparing the aggregate for mixing follow below.

Table 3.4 – AMBT aggregate gradation for porosity and permeability specimens

| Standard Test Mix | |
|-------------------|-----------------|
| Retained Sieve | Mass of RCA (g) |
| #8 | 282.9 |
| #16 | 707.1 |
| #30 | 707.1 |
| #50 | 707.1 |
| #100 | 424.4 |
| Total Mass | 2828.6 |
| CM | 1257.1 |

1. Individual gradations of were combined according to Table 3.4 and homogenized in a sealable plastic bag.
2. 590.9g of water was prepared in a sealable plastic container prior to testing.

3.4.4 – Mixing Procedure for AMBT Specimens

The mixing procedure for the Spratt and Ottawa Specimens follows the standard procedure of ASTM C1260 since the aggregate does not require pre-absorption time. A small countertop Hobart brand mixer was used for all tests. The mixing procedure follows below.

1. The water is added to the moistened mixing bowl followed by the cement and the mixing paddle was attached.
2. The mixer was set to slow speed for 30 seconds to allow the cement and water to fold together without loss of material.
3. Between 30 and 60 seconds, the aggregate is slowly added while the mixing continues.
4. After 60 seconds elapsed time, the mixer is accelerated to medium speed and run for 30 seconds.
5. The mixer was then switched off and immediately the bowl was scraped with a stiff spatula to remove any material adhering to the bowl. Within 15 seconds of stopping, the bowl was covered with a damp cloth to prevent evaporation and the mortar was allowed to rest.

6. 90 seconds after stopping (3 minutes elapsed time) the mixer is started at medium speed for a further 60 seconds to complete the mixing process.

3.4.5 – Cylinder Moulding for AMBT Specimens

The AMBT specimens were cast into 100mm x 200mm cylinder moulds according to the following procedure.

1. A volume of mix approximately equal to $\frac{1}{3}$ the mould volume was placed in the mould.
2. The sample was tamped 25 times with a 15mm tamping rod to a sufficient depth to thoroughly compact the layer without striking the bottom of the mould.
3. The sides of the mould were struck several times to close any voids left by the tamping rod.
4. The next $\frac{1}{3}$ volume of mix was placed in the mould.
5. The sample was tamped 25 times with a 15mm tamping rod to a sufficient depth to penetrate 25mm into the first layer of mix.
6. The sides of the mould were struck several times to close any voids left by the tamping rod.
7. The final $\frac{1}{3}$ volume of mix was placed in the mould with enough excess to slightly overflow.
8. The sample was tamped 25 times with a 15mm tamping rod to a sufficient depth to penetrate 25mm into the second layer of mix.
9. The sides of the mould were struck several times to close any voids left by the tamping rod.
10. The surface was struck off with a trowel to leave a clean finish.
11. The finished specimens were draped in labelled plastic sheets and covered with solid plastic lids to ensure flow of humid air in the curing room but prevent direct contact with water droplets.
12. The specimens were allowed to cure for $24\text{h} \pm 0.5\text{h}$ before being demoulded.

3.4.6 – Curing Procedure for AMBT Specimens

After demoulding, the AMBT specimens cut down using a 12” diamond blade, water cooled concrete saw in preparation to curing using the following procedure.

1. The samples were demoulded using compressed air and labelled with temporary wax crayons.
2. The sample was placed on the saw traverse and approximately 25mm of the specimen was measured for removal.
3. The specimen was cut down and any irregularities caused by cutting induced breakage were ground flat with the saw blade.
4. Three 50mm sections were cut from each remaining specimen and the ends were discarded. The 50mm specimens were labelled with permanent marker and set aside for testing.

The 23°C specimens were stored in a curing chamber with 100% RH at 23°C for 8 days until testing.

The remaining specimens were cured similar to the ASTM C1260 standard and the procedure is outlined below.

1. The cut specimens were placed in a hot water bath at 80°C for 24h ± 0.5h to condition the samples.
2. Conditioned samples were then placed in a 3.5L solution of 1N Sodium Hydroxide, prepared according to 3.1.6, for 7 days at 80°C in a convection oven.
3. The containers were 5.5L volume with rubber gaskets and were sealed with adhesive backed plastic wrap to ensure an airtight seal.
4. After 7 days, the specimens were removed for testing.

3.4.7 – Aggregate Preparation of Porosity and Permeability CMBT Specimens

The CMBT specimens were made using Spratt aggregate. The Spratt aggregate was sieved to the required gradation using the procedure shown in 3.3.2.

3.4.8 – Sample Preparation for CMBT Specimens

The CMBT specimens were combined as seen in Table 3.5 below prior to testing. Since the size of the required specimen is larger, the required masses are not the same as the standard RILEM AAR-5 test. The details of individual batches are found in Appendix A. The steps for preparing the aggregate for mixing follow below.

Table 3.5 – CMBT standard mix design for porosity and permeability specimens

| | Aggregate Size A (g) | Aggregate Size B (g) | CM (g) | Water (g) |
|----------------|-------------------------|-------------------------|--------|-----------|
| Standard Batch | 2000 | 2000 | 4000 | 1289 |

1. Individual gradations of were combined according to Table 3.5 and homogenized in a sealable plastic bag.
2. 1289g of water was prepared in a sealable plastic container prior to testing.

3.4.9 – Mixing Procedure for CMBT Specimens

The mix procedure for the CMBT testing was identical to that presented in 3.3.5.

3.4.10 – Cylinder Moulding for CMBT Specimens

The procedure used for moulding the CMBT cylinders was identical to that presented in 3.4.5.

3.4.11 – Curing Procedure for CMBT Specimens

The procedure used for curing the CMBT cylinders was identical to that presented in 3.4.6.

3.4.12 – Aggregate Preparation of Porosity and Permeability CPT Specimens

The CPT specimens were made using Spratt aggregate for the coarse aggregate and a non-reactive sand for the fine aggregate. The Spratt aggregate was sieved to the required gradation using the procedure shown in 3.3.2. The fine aggregate was used as delivered. The alkali content of the Type I cement was boosted to 1.25% Na₂O_e as per the CSA A23-14A in the procedure below.

1. Required mass of NaOH = (Mass of PC) * (1.25% - (Na₂O_e PC) * 1.291

3.4.13 – Sample Preparation for CPT Specimens

The CPT specimens were combined as seen in Table 3.6 below prior to testing. The details of individual batches are found in Appendix A. The steps for preparing the aggregate for mixing based on CSA A23.2-14A standard follows below.

Table 3.6 – CPT standard mix design for porosity and permeability specimens

| | Coarse Aggregate (kg) | Fine Aggregate (kg) | CM (kg) | Water (kg) | NaOH (g) |
|----------------|-----------------------|---------------------|---------|------------|----------|
| Standard Batch | 15.273 | 10.182 | 6.3 | 2.745 | 14.64 |

1. Individual aggregates were oven dried and placed in sealed bucket until ready for use
2. 2.745kg of water was prepared and mixed with the 14.64g of NaOH in a sealable plastic container prior to testing.

3.4.14 – Mixing Procedure for CPT Specimens

The mixing for the CPT specimens was completed using a 45L capacity drum mixer. The mixing procedure follows below.

1. The coarse and fine aggregates were loaded into the moistened drum mixer and approximately half of the water was added to control the dust.
2. The mixer was run for one minute to allow for blending of the aggregates. The angle of the mixer was changed to ensure thorough mixing.
3. The mixer was stopped and the cementitious materials were added and folded into the wet aggregate by hand to prevent loss when mixing was restarted.
4. The mixer was run for one minute again to allow for thorough blending of the material.
5. During the next half-minute the remaining water was slowly added in such a way that it washed any material at the edge of the mixer into the mix itself.
6. The mixer was run for 1.5 minutes to allow for thorough mixing of the material.
7. The mixer was stopped for two minutes during which time the sides were scraped to remove any adhered material and covered for the remainder to prevent evaporation
8. The mixer was run for two minutes to complete the mixing.

3.4.15 – Cylinder Moulding for CPT Specimens

The procedure used for moulding the CPT cylinders was identical to that presented in 3.4.5.

3.4.16 – Curing Procedure for CPT Specimens

After demoulding, the CPT specimens were cut down using a 12” diamond blade, water cooled concrete saw in preparation to curing using the following procedure.

1. The samples were demoulded using compressed air and labelled with temporary wax crayons.
2. The sample was placed on the saw traverse and approximately 25mm of the specimen was measured for removal.
3. The specimen was cut down and any irregularities caused by cutting induced breakage were ground flat with the saw blade.
4. Three 50mm sections were cut from each remaining specimen and the ends were discarded. The 50mm specimens were labelled with permanent marker and set aside for testing.

The 23°C specimens were stored in a curing chamber with 100% RH at 23°C for 34 days until testing.

The remaining specimens were cured similar to the CSA A23-14A standard and the procedure is outlined below.

1. The cut specimens were returned to the curing chamber with 100% RH at 23°C for 6 days.
2. Each set of three specimens were placed in sealed containers with 100% RH and placed in an environmental chamber maintained at 38°C for 28 days.
3. The containers were 5.5L volume with rubber gaskets and were sealed with adhesive backed plastic wrap to ensure an airtight seal and held elevated grates over water to maintain humidity and prevent direct contact with the specimens.
4. After 7 days, the specimens were removed for testing.

3.4.17 – Porosity and Permeability Test Procedures

The samples were placed in a vacuum chamber and prepared according to ASTM C1202 for the RCPT. The specimens were weighed during this preparation due to assess the porosity of the specimens. The procedure is outlined below.

1. 6 specimens were placed in a vacuum chamber and sealed inside.
2. A vacuum was drawn on the specimens for one hour to draw out and evaporate internal moisture.
3. After one hour and with the vacuum maintained, distilled water was drawn into the chamber using a tap and valve assembly to submerge the samples.
4. The vacuum was maintained on the submerged samples for 3 hours to ensure saturation of the samples.
5. The vacuum was stopped and the samples were left submerged for 16 ± 4 hours.
6. The samples were transported submerged to be weighed in water.
7. The samples were then dried to SSD condition and weighed.
8. The samples were submerged and transported to the RCPT apparatus.
9. The samples were placed in the RCPT cells and the required solutions were added to the cells.
10. The prepared cells were attached to the RCPT apparatus and analyzed.
11. The samples were removed from the cells and placed in an oven at 105°C for at least 48 hours to dry.
12. The dried samples were then weighed.

3.5 – Alkali Leaching Test Procedures

3.5.1 – Objectives

To provide supporting results for the AMBT and CMBT testing. This phase evaluated the alkali leaching from paste specimens.

The alkali leaching specimens were prepared using the same Type I general use cement as previous tests. The chemical analysis of this cement (PC B) can be found in Table 3.8 in Section 3.6. The SCM's used included High Calcium Fly Ash (HCFA) and Low Calcium Fly Ash (LCFA), Blast Furnace Slag (Slag) and Silica Fume (SF). These SCM's were obtained from Ryerson stockpiles used in previous studies. The chemical analysis of these SCM's can be found in Table 3.8 in Section 3.6. The Spratt RCA from the 5mm gradation was used for the required specimens.

3.5.2 – Preparation of RCA Specimens

The RCA particles required for this testing were 5mm Spratt RCA that was placed in an oven at 105°C for 48 hours to ensure no water was present in the samples prior to testing. The dried RCA was stored in a sealable plastic bag until needed.

3.5.3 – Preparation and Mixing of Paste Specimens

The paste specimens were prepared at a W/CM ratio of 0.5 using a high shear industrial kitchen blender. The blends of cementitious materials are outlined in Table 3.7 below. The mix procedure is outlined below.

Table 3.7 – Cementitious materials blends for alkali leaching testing

| CM Blend (A/B) | Cement (g) | SCM A (g) | SCM B (g) | Water |
|-----------------|------------|-----------|-----------|-------|
| Control | 250 | | | 125 |
| 20/30 LCFA/Slag | 125 | 50 | 75 | 125 |
| 30% HCFA | 175 | 75 | | 125 |
| 5/25 SF/Slag | 175 | 12.5 | 62.5 | 125 |
| 5/30 SF/LCFA | 162.5 | 12.5 | 75 | 125 |

1. The cementitious materials were prepared in sealable plastic bags and homogenized.
2. 125g of water was prepared in a sealed plastic container prior to testing.
3. Water was added to the blending container and the CM was added to the water.
4. The blender was pulsed at normal speed for 10 seconds to combine the water and CM gently and prevent splashing and material loss.
5. The blender was run for 20 seconds at normal speed.
6. The blender was stopped and the sides of the blending container were scraped with a small stiff spatula to remove any adhered material.
7. The blender was run for a further 90 seconds to ensure a thoroughly mixed specimen was obtained.

3.5.4 – Moulding and Curing of Paste Specimens

1. The paste was placed in doubled sealable plastic bags and cured at 23°C for 24 hours.
2. A moistened piece of cloth was placed in the plastic bag with the specimen to maintain the humidity in the bag.
3. The sealed bags were cured for 27 days at 23°C utilizing moisture from the wet cloth to maintain 100% RH.
4. The cloths were moistened twice weekly to ensure humidity remained high without allowing excessive moisture to drip onto the specimens.
5. After 28 days the specimens were removed from the plastic bags for testing.

3.5.5 – Crushing and Grading of Paste Specimens

The paste specimens required crushing to conform to the test outlined by (Shehata & Thomas 2006) The samples were crushed with a 5lb hammer and the particles from the interior of the samples were selected. These were further broken by a ceramic mortar and pestle and sieved to the correct gradation. The procedure is outlined below.

1. Samples were wrapped in 8mil plastic sheeting and again in a cotton rag.
2. A 5lb hammer was used to strike the specimens and shatter large particles.
3. The particles were selected from the centre of the specimen and struck again to a maximum thickness of 5mm.
4. The mortar and pestle were cleaned prior to every use by the following procedure
 - a. Cleaned under tap water and using a plastic scrub brush to remove large particles
 - b. Rinsed twice under distilled water using a second scrub brush to remove remaining particles
 - c. Cleaned with a rag soaked in 99% Methanol to remove any trace material
 - d. Allowed to rest until methanol traces evaporate
5. The 5 mm particles were transferred to the cleaned mortar and pestle and large particles were crushed by pestle blows.
6. Once the large particles are broken down by the pestle blows, the pestle is used to grind the specimens to pass the 1.18mm sieve
7. Once the majority of particles appear to be able to pass, the sample is transferred to a nest of sieves consisting of the 1.18mm, 150 μ m and pan.
8. Material passing the 1.18mm and retained on the 150 μ m sieve are immediately transferred to a sealable plastic bag to prevent loss of moisture before testing.
9. Material in the pan is disposed of and material retained on the 1.18mm sieve is returned to the mortar with additional particles.
10. Steps 5-9 are repeated until sufficient sample is obtained.

3.5.6 – Testing for Evaporable Water in Paste Specimens

The evaporable water content is needed to calculate the alkali leaching results. A sample of the crushed paste specimens are used for this test. The procedure is outlined below.

1. A sample of crushed paste was obtained from the sealed plastic bags and weighed.
2. The sample was placed in a 105°C oven for 48 hours to allow for the evaporable water to escape.
3. The sample was removed and cooled in a desiccator before being reweighed.
4. % Evaporable Water = $100\% * [(Wet\ Mass) - (Dry\ Mass)] / (Dry\ Mass)$

3.5.7 – Testing for Non-Evaporable Water in Paste Specimens

The non-evaporable water content is needed to calculate the alkali leaching results. A sample of the material from 3.5.4 Step 3 is used for this test. The procedure is outlined below.

1. A sample of the 5mm paste specimens is obtained and broken down to <1mm in any direction using a cleaned mortar and pestle.
2. The sample was placed in a 105°C oven for 48 hours to allow for the evaporable water to escape.
3. The sample was removed and cooled in a desiccator before being weighed.
4. The sample was placed in a ceramic crucible and placed in an ignition furnace at 1050°C for 20 minutes to allow any remaining water to be eliminated
5. The sample was removed from the oven and cooled to a reasonable temperature in air before being transferred to a desiccator to finish cooling.
6. The cooled sample was then reweighed.
7. % Non-Evaporable Water = $100\% * [(Dry\ Mass) - (Ignited\ Mass)] / (Ignited\ Mass)$

3.5.8 – Preparation of Alkali Leaching Solution

The solution used in this testing was a 0.25N NaOH solution made using 99.5% NaOH and distilled water. A surplus quantity was made and stored for 24 hours prior to use.

3.5.9 – Preparation of Alkali Leaching Specimens

The masses of materials required for preparing the alkali leaching specimens were calculated using a spreadsheet found in Appendix E. The calculation provided a volume close to 60ml to ensure a minimum of air in the 60ml capacity specimen containers. The ratio of solution to paste was 10:1 and the ratio of RCA to paste was 2.4:1. The procedure for preparing the specimens is found below.

1. The specimen bottles were weighed and marked for the specimen to be placed.
2. The paste was weighed and added to the container
3. For RCA specimens the RCA was weighed and added to the paste.
4. The specimen bottle was placed on a balance accurate to 0.01g and zeroed.
5. 90% of the required solution was added from a second bottle to prevent overfilling
6. The remaining solution was added using a 1 ml capacity syringe to the correct mass.
7. Two blank solution specimens were prepared.
8. All specimen bottles were sealed with adhesive plastic wrap to ensure an airtight seal.
9. The specimen bottles were weighed to check for evaporation loss then placed in a double sealable plastic bag.
10. The bags were placed in an environmental chamber at 38°C for 28 before being removed for testing.
11. Due to a delay, the specimen bottles were refrigerated at 4°C between 28 days and the test date to prevent further reaction and evaporation.
12. Immediately prior to testing the specimen bottles were weighed to check for evaporation loss.

3.5.10 – Preparation of Alkali Leaching Flame Photometer Specimens

The solution in the alkali leaching specimens required dilution prior to testing. A dilution of 200:1 was selected to reduce the concentration to readable levels. The dilution was completed using distilled water identical to the previous steps. The procedure follows below.

1. 0.5ml \pm 0.001ml of solution was drawn from the specimen bottle using an ultra-fine tip disposal pipette.
2. The solution was added to a 100ml \pm 0.03ml burette.
3. The burette was topped up to 98% of capacity using a second bottle with distilled water.
4. The remainder of the distilled water was added using a 1 ml syringe to ensure the correct volume.
5. The burette was thoroughly mixed and the solution transferred to a new specimen bottle and sealed with adhesive plastic wrap until testing.

3.5.11 – Testing of Alkali Leaching Flame Photometer Specimens

The alkali leaching specimens were tested by flame photometer to determine the concentrations of Na⁺ and K⁺ ions in solution. The concentrations of Na⁺ and K⁺ ions were tested separately to ensure optimal results. 100ppm Na⁺ and K⁺ calibration solutions were used for the offset high calibration. A recalibration of offsets and zero point were completed every 5 specimens. The test procedure follows below.

The cleaning of the sample tip for the flame photometer is conducted before a new specimen is tested and follows below.

1. The sample is removed from the specimen and rinsed in distilled water bath A
2. The sample is removed and dried using a lint free wipe.
3. The sample is rinsed in distilled water bath B and allowed to draw for 10 seconds to clear the system.

4. The sample was returned to the zero solution until the next specimen was ready for testing.

The calibration procedure follows below.

1. A sample of 0ppm distilled water was used to calibrate the zero point.
2. The sample tip was placed in the distilled water and allowed to draw for 10 seconds to clear the system.
3. The reading for the zero point was taken by the apparatus.
4. The high calibration point was set to 100ppm for Na^+ and K^+ test parameters.
5. The sample tip was placed in the 100ppm Na^+ solution and allowed to draw for 10 seconds to clear the system.
6. The reading for the Na^+ high calibration was taken.
7. The sample tip was placed in the 100ppm K^+ solution and allowed to draw for 10 seconds to clear the system.
8. The reading for the K^+ high calibration was taken.
9. The concentrations of the distilled water, and Na^+ and K^+ solutions were checked to ensure an accurate calibration.

The alkali leaching flame photometer specimen test procedure follows below.

1. The sample tip was placed in the specimen and allowed to draw for 10 seconds to clear the system.
2. The reading of concentration was taken 6 times for Na^+ and 6 times K^+ without removing the sample tip.
3. Any anomalous results were discarded and a new reading was immediately taken.

The results are calculated using the correction procedure found in Appendix F.

3.6 – Chemical Analysis

Table 3.8 – Major oxide composition of cementitious materials

| CM Sample | CaO | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | MgO | SO ₃ | K ₂ O | Na ₂ O | TiO ₂ | P ₂ O ₅ | Na ₂ O _e |
|-----------|------|------------------|--------------------------------|--------------------------------|------|-----------------|------------------|-------------------|------------------|-------------------------------|--------------------------------|
| PC ILS | 60.8 | 19.6 | 4.88 | 2.91 | 2.52 | 3.3 | 0.97 | 0.27 | - | - | 0.91 |
| PC A | 63.3 | 19.9 | 5.22 | 2.73 | 2.64 | 4.7 | 1.20 | 0.24 | 0.27 | 0.14 | 1.03 |
| PC B | 62.8 | 20.6 | 5.58 | 2.28 | 2.34 | 4.6 | 1.20 | 0.28 | 0.27 | 0.13 | 1.07 |
| LCFA | 4.43 | 55.7 | 27.4 | 5.59 | 1.56 | 0.26 | 2.29 | 0.44 | 0.67 | 0.31 | 1.95 |
| HCFA | 28.7 | 33.3 | 18.2 | 6.45 | 5.32 | 2.59 | 0.33 | 1.94 | 1.45 | 0.88 | 2.16 |
| Slag | 43.2 | 34.4 | 7.4 | 0.94 | 9.3 | 0.83 | 0.58 | 0.57 | 0.44 | 0 | 0.95 |
| SF | 0.27 | 95.2 | 0.35 | 0.10 | 0.91 | 0.25 | 0.51 | 0.21 | 0.13 | 0.13 | 0.55 |

4 – Results and Discussion

4.1 – Accelerated Mortar Bar Testing Results and Analysis

4.1.1 – Scope of Accelerated Mortar Bar Testing

This section of study is devoted to the effectiveness of the AMBT in evaluating RCA for deleterious expansion. A portion of this was conducted in tandem with several other Universities to provide data on the multi-laboratory variation of the AMBT. It was also analyzed to evaluate the effect of material selection on the results of the AMBT. The testing focused on four different reactive RCA materials that were tested solely and when diluted with non-reactive aggregates. For each RCA at least one of the sets was repeated to check individual variability in the lab. The information available for the virgin aggregate from which the RCA was made is found in Table 4.1.

Table 4.1 – Virgin Aggregate Information for RCA Interlab Study

| Aggregate | Rock Type | Source Location | AMBT Expansion % 14d | AMBT Expansion % 28d | CPT Expansion % 1y |
|------------|------------------------|------------------------------|-------------------------|-------------------------|-----------------------|
| Alberta | Natural Gravel | Calgary, AB | 0.360 | 0.603 | 0.09 |
| Bernier | Argillaceous Limestone | St-Jean sur le Richelieu, QC | 0.170 | 0.210 | 0.07 |
| Potsdam | Siliceous Sandstone | Montreal, QC | 0.093 | 0.190 | 0.13 |
| Springhill | Greywacke and Argilite | Fredericton, NB | 0.460 | 0.700 | 0.22 |

The four RCA samples were obtained by processing the CANMET outdoor exposure blocks that were placed in 1995 for long term environmental expansion testing, in summer 2009. Two distinct samples of each RCA were prepared according to the method prescribed by the inter-laboratory testing instructions. The first samples were prepared from the “crusher’s fines” material that was gathered from the crusher when the RCA blocks were processed into the coarse RCA. The second samples were the processed coarse RCA itself, in 3/4in, 1/2in and 3/8in size

fractions. These were further processed by each individual lab to obtain the required ASTM C1260 Gradation.

Further testing was conducted with another RCA obtained from Laval University. This material was obtained from the demolition of a bridge in Quebec that was deteriorating from ASR. The RCA was delivered in coarse 3/4in, 1/2in and 3/8in size fractions and was processed to the required ASTM C1260 gradation. This material was used to assess the variation in expansion when the test conditions were changed to simulate preparation errors. Test varied the W/C ratio by assuming incorrect RCA absorption measurements. The method of crushing aggregate was assessed by preparing the gradation by two methods. The final variable was the effect of washing RCA to remove adhered fines.

4.1.2 – Interlab Crusher’s Fines Accelerated Mortar Bar Testing

4.1.2.1 – Interlab Alberta Crusher’s Fines AMBT Results

The Alberta RCA crusher’s fines specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Alberta RCA, two sets of 50% RCA and two sets of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Alberta RCA to be 5.95% and 7.36% respectively, so the average of these values, 6.66%, was used for the moisture correction. The consistency of the mortar using this value was very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.1. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.2. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in expansion at 14 days age for the 50% Alberta RCA specimens is 0.0186% which is greater than

the 0.0116% (8.3% of mean expansion) allowed by ASTM C1260. The 14 and 28 day expansion results for the 25% Alberta and 25% Alberta repeat specimen COV's were calculated to be 0.075 and 0.089 respectively. The variation in expansion at 14 days age for the 25% Alberta RCA specimens is 0.0131% which is greater than the 0.0095% (8.3% of mean expansion) allowed by ASTM C1260.

Table 4.2 – Expansion and COV of Alberta Crusher's Fines RCA AMBT

| Alberta | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|---|-----------|-------|-----------|-------|-----------------|
| RCA Content | Expansion | COV | Expansion | COV | |
| 100% | 0.1655 | 0.049 | 0.2820 | 0.043 | Fail |
| 50% | 0.1494 | 0.020 | 0.2204 | 0.021 | Fail |
| 50% (Rep) | 0.1308 | 0.012 | 0.2204 | 0.016 | Fail |
| 25% | 0.1077 | 0.036 | 0.1535 | 0.035 | Fail |
| 25% (Rep) | 0.1208 | 0.051 | 0.1786 | 0.037 | Fail |
| Variation for 50% @ 14 Days = 0.074 , @ 28 Days = 0.017 | | | | | |
| Variation for 25% @ 14 Days = 0.075 , @ 28 Days = 0.089 | | | | | |

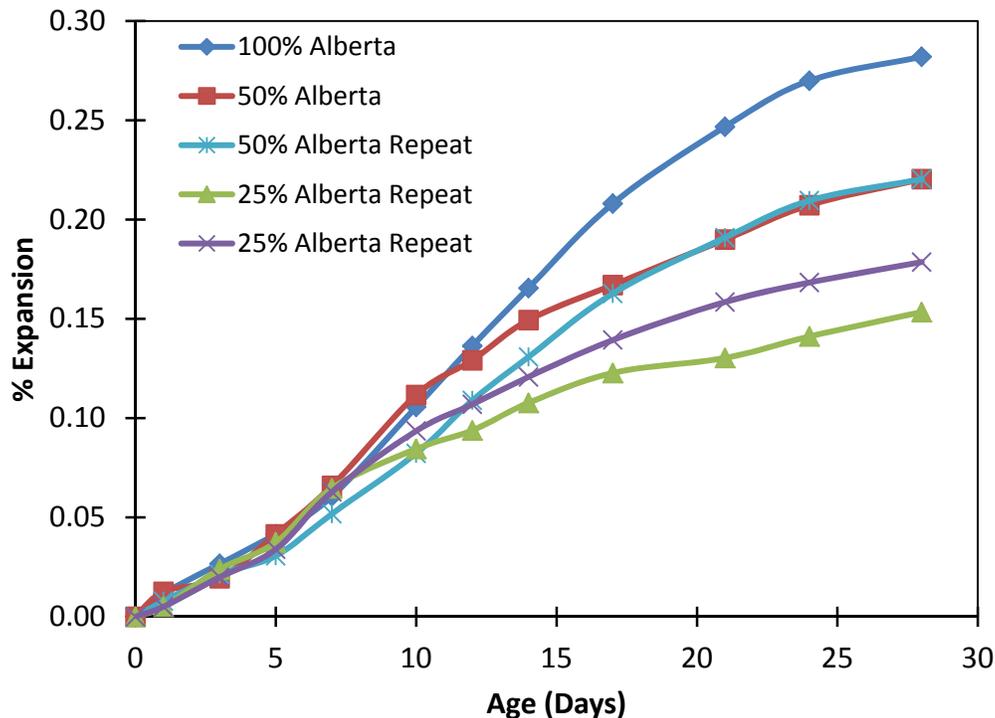


Figure 4.1 – Expansion of Alberta Crusher's Fines RCA AMBT

4.1.2.2 – Interlab Bernier Crusher’s Fines AMBT Results

The Bernier RCA crusher’s fines specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Bernier RCA, two sets of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Bernier RCA to be 5.03% and 7.32% respectively, so the average of these values, 6.18%, was used for the moisture correction. The consistency of the mortar using this value was also very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.2. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.3. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in expansion at 14 days age for the 50% Bernier RCA specimens is 0.0045% which is greater than the 0.0035% (8.3% of mean expansion) allowed by ASTM C1260. Figure 4.2 also shows an unusual trend where the expansions of 100% Bernier RCA and 25% Bernier RCA have twice the 14 day expansion of 50% Bernier RCA. The expectation would be that the expansion of would decrease with the availability of reactive aggregate. This result will be further discussed in Section 4.1.7.

Table 4.3 – Expansion and COV of Bernier Crusher’s Fines RCA AMBT

| Bernier RCA Content | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|--|-----------|-------|-----------|-------|--------------------|
| | Expansion | COV | Expansion | COV | |
| 100% | 0.0938 | 0.009 | 0.1079 | 0.012 | Pass |
| 50% | 0.0445 | 0.045 | 0.0797 | 0.022 | Pass |
| 50% (Rep) | 0.0400 | 0.050 | 0.0682 | 0.013 | Pass |
| 25% | 0.0843 | 0.029 | 0.1074 | 0.021 | Pass |
| Variation for 50% @ 14 Days = 0.072, @ 28 Days = 0.083 | | | | | |

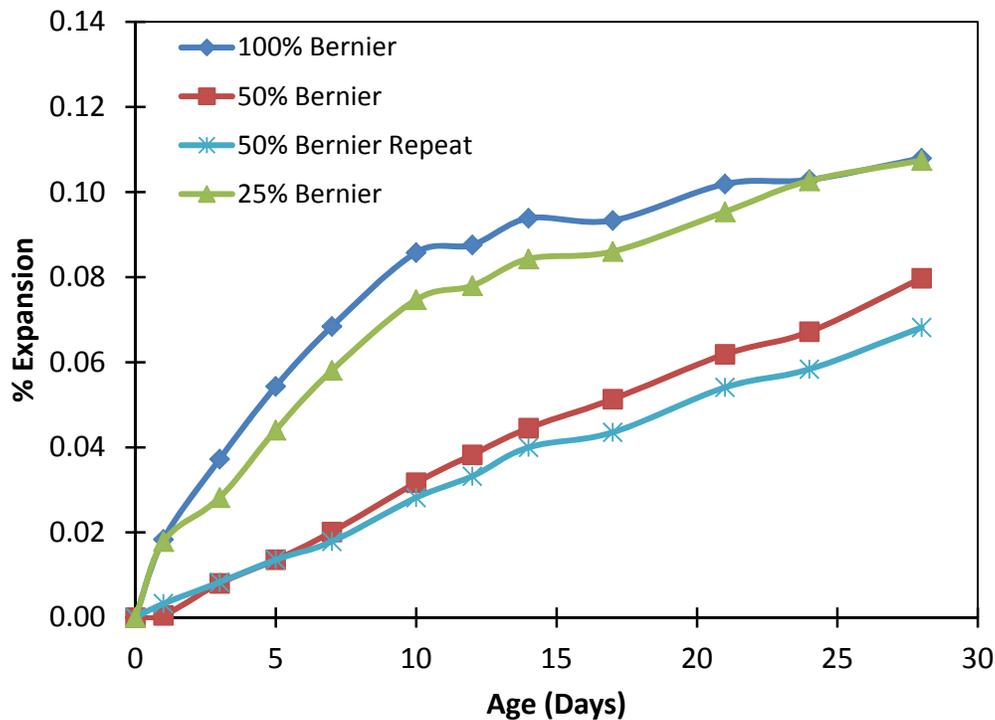


Figure 4.2 – Expansion of Bernier Crusher’s Fines RCA AMBT

4.1.2.3 – Interlab Potsdam Crusher’s Fines AMBT Results

The Potsdam RCA crusher’s fines specimens tested for the interlab study were tested by the modified ASTM C1260 outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Potsdam RCA, one set of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Potsdam RCA to be 3.48% and 4.96% respectively, so the average of these values, 4.22%, was used for the moisture correction. The consistency of the mortar using this value was slightly less workable than the previous specimens but no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.3. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.4. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. Figure 4.3 clearly

shows that any use of Potsdam RCA will result in similar expansion values at 14 days. It should be noted that virgin Potsdam aggregate has been shown to pass the 14 day AMBT requirement even though it is seen to be very expansive in the CPT seen in Table 4.1 so it is likely that this result is incorrect and that Potsdam RCA is likely to cause deleterious expansion at any replacement level. These results will be further discussed in Section 4.1.7.

Table 4.4 – Expansion and COV of Potsdam Crusher’s Fines RCA AMBT

| Potsdam | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|-------------|-----------|-------|-----------|-------|-----------------|
| RCA Content | Expansion | COV | Expansion | COV | |
| 100% | 0.0725 | 0.028 | 0.1313 | 0.006 | Pass |
| 50% | 0.0800 | 0.025 | 0.1338 | 0.028 | Pass |
| 25% | 0.0785 | 0.017 | 0.1361 | 0.007 | Pass |

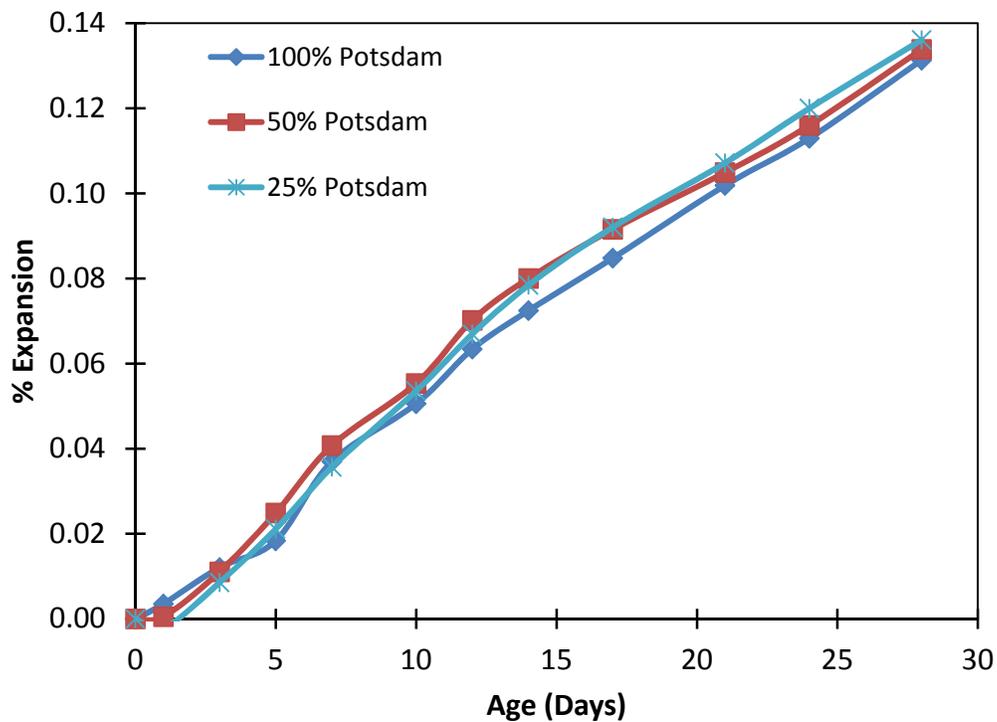


Figure 4.3 – Expansion of Potsdam Crusher’s Fines RCA AMBT

4.1.2.4 – Interlab Springhill Crusher’s Fines AMBT Results

The Springhill RCA crusher’s fines specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with two sets of 100% Springhill RCA, one set of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Springhill RCA to be 7.35% and 8.21% respectively, so the average of these values, 7.78%, was used for the moisture correction. The consistency of the mortar using this value was very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.4. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.5. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in expansion at 14 days age for the 100% Springhill RCA specimens is 0.0549% which is much greater than the 0.0066% (8.3% of mean expansion) allowed by ASTM C1260. Figure 4.4 and Table 4.5 clearly show the discrepancy between the repeat tests for 100% Springhill RCA and that 50% Springhill RCA yields that greatest expansion. These results will be further discussed in section 4.1.7.

Table 4.5 – Expansion and COV of Springhill Crusher’s Fines RCA AMBT

| Springhill RCA Content | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|---|-----------|-------|-----------|-------|--------------------|
| | Expansion | COV | Expansion | COV | |
| 100% | 0.0523 | 0.055 | 0.0958 | 0.031 | Pass |
| 100% (Rep) | 0.1072 | 0.032 | 0.1571 | 0.025 | Fail |
| 50% | 0.1258 | 0.053 | 0.1826 | 0.050 | Fail |
| 25% | 0.0994 | 0.057 | 0.1663 | 0.069 | Pass |
| Variation for 100% @ 14 Days = 0.378, @ 28 Days = 0.254 | | | | | |

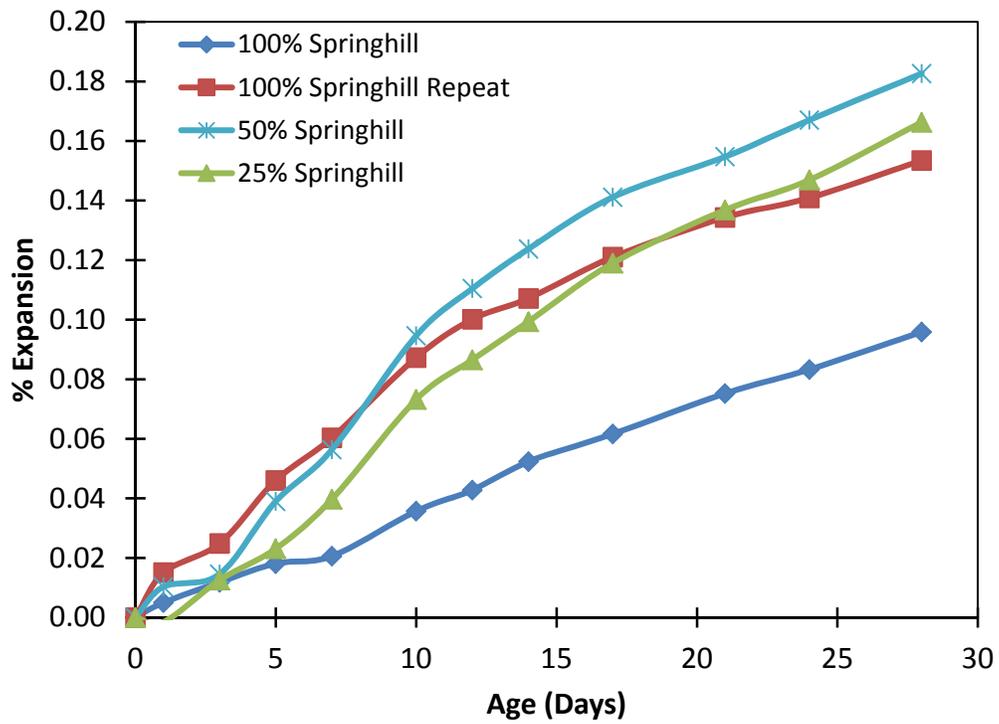


Figure 4.4 – Expansion of Springhill Crusher’s Fines RCA AMBT

4.1.3 – Interlab Coarse Accelerated Mortar Bar Testing

4.1.3.1 – Interlab Alberta Coarse AMBT Results

The Alberta RCA coarse specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Alberta RCA, two sets of 50% RCA and two sets of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Alberta RCA to be 5.95% and 7.36% respectively, so the average of these values, 6.66%, was used for the moisture correction. The consistency of the mortar using this value was very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.5. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.6. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in expansion at 14 days age for the 50% Alberta RCA specimens is 0.0078% which is less than the 0.0259% (8.3% of mean expansion) allowed by ASTM C1260. The variation in expansion at 14 days age for the 25% Alberta RCA specimens is 0.0050% which is less than the 0.0194% (8.3% of mean expansion) allowed by ASTM C1260.

Table 4.6 – Expansion and COV of Alberta Coarse RCA AMBT

| Alberta RCA Content | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|---|-----------|-------|-----------|-------|--------------------|
| | Expansion | COV | Expansion | COV | |
| 100% | 0.3384 | 0.019 | 0.4906 | 0.013 | Fail |
| 50% | 0.3157 | 0.019 | 0.4274 | 0.035 | Fail |
| 50% (Rep) | 0.3079 | 0.012 | 0.4116 | 0.018 | Fail |
| 25% | 0.2312 | 0.026 | 0.3155 | 0.027 | Fail |
| 25% (Rep) | 0.2362 | 0.026 | 0.3215 | 0.026 | Fail |
| Variation for 50% @ 14 Days = 0.0200 , @ 28 Days = 0.0325 | | | | | |
| Variation for 25% @ 14 Days = 0.0263 , @ 28 Days = 0.0260 | | | | | |

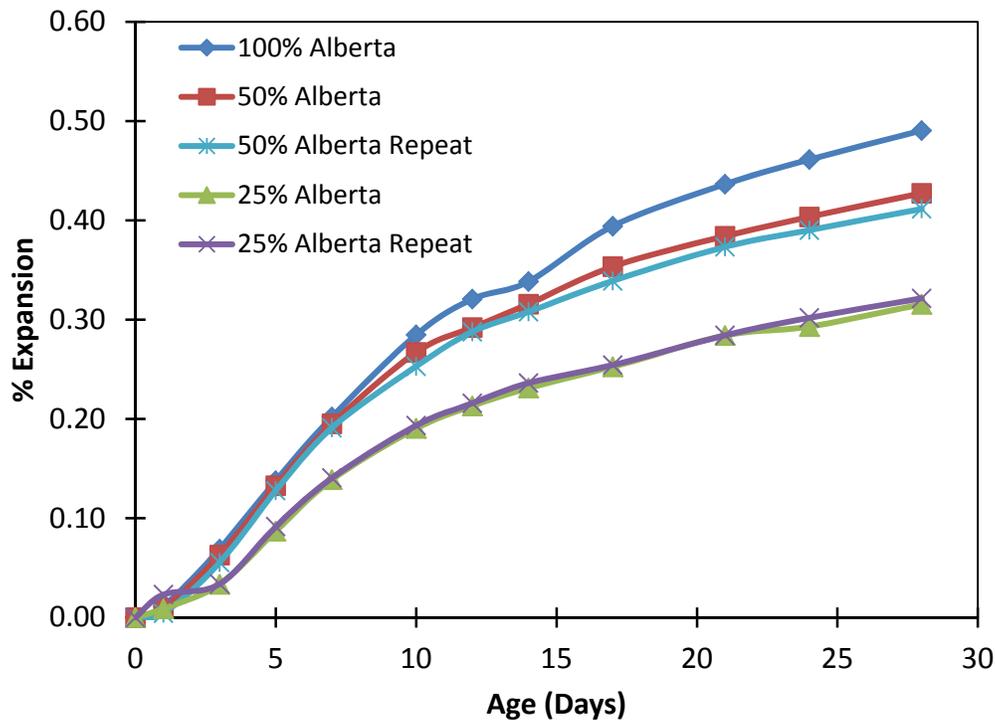


Figure 4.5 – Expansion of Alberta Coarse RCA AMBT

4.1.3.2 – Interlab Bernier Coarse AMBT Results

The Bernier RCA coarse specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Bernier RCA, two sets of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Bernier RCA to be 5.03% and 7.32% respectively, so the average of these values, 6.18%, was used for the moisture correction. The consistency of the mortar using this value was also very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.6. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens shown in Table 4.7. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in

expansion at 14 days age for the 50% Bernier RCA specimens is 0.0028% which is less than the 0.0068% (8.3% of mean expansion) allowed by ASTM C1260. Figure 4.6 shows that the unusual trend seen in Figure 4.2 is not an anomaly attributable to the Coarse Bernier RCA. This result will be further discussed in Section 4.1.7.

Table 4.7 – Expansion and COV of Bernier Coarse RCA AMBT

| Bernier | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|---|-----------|-------|-----------|-------|-----------------|
| RCA Content | Expansion | COV | Expansion | COV | |
| 100% | 0.1318 | 0.037 | 0.1605 | 0.026 | Fail |
| 50% | 0.0833 | 0.074 | 0.1187 | 0.052 | Pass |
| 50% (Rep) | 0.0805 | 0.078 | 0.1192 | 0.079 | Pass |
| 25% | 0.0737 | 0.053 | 0.1253 | 0.038 | Pass |
| Variation for 50% @ 14 Days = 0.0704 , @ 28 Days = 0.0599 | | | | | |

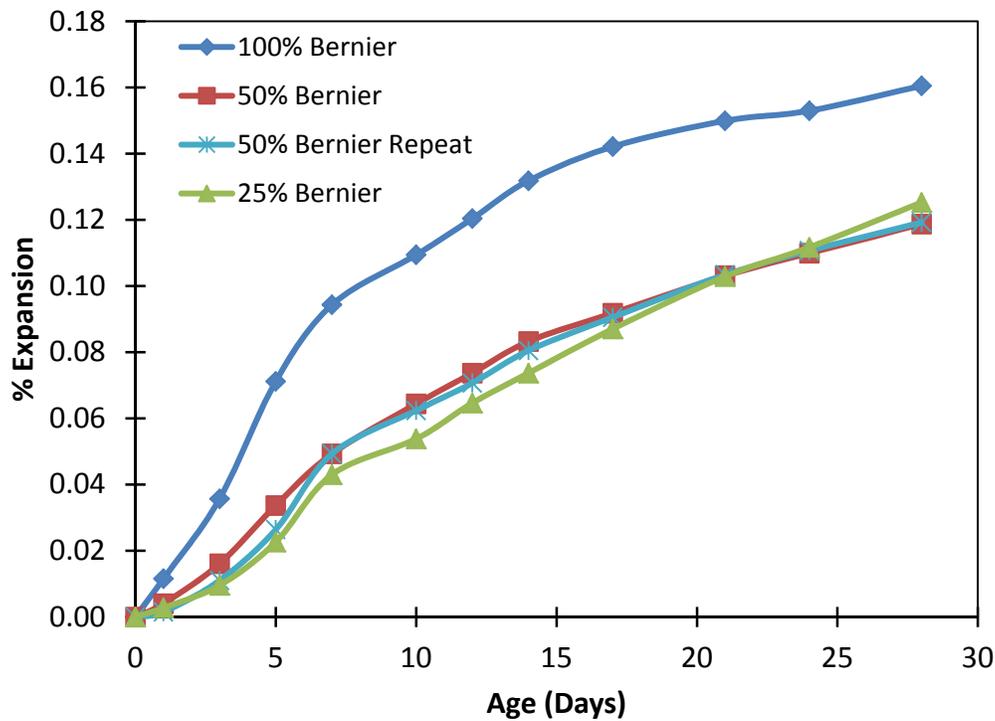


Figure 4.6 – Expansion of Bernier Coarse RCA AMBT

4.1.3.3 – Interlab Potsdam Coarse AMBT Results

The Potsdam RCA coarse specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with one set of 100% Potsdam RCA, one set of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Potsdam RCA to be 3.48% and 4.96% respectively, so the average of these values, 4.22%, was used for the moisture correction. The consistency of the mortar using this value was good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.7. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.8. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. Figure 4.7 clearly shows that any use of Potsdam RCA will result in similar expansion values at 14 days. It should be noted that virgin Potsdam aggregate has been shown to pass the 14 day AMBT requirement even though it is seen to be very expansive in the CPT seen in Table 4.1 so it is likely that this result is incorrect and that Potsdam RCA is likely to cause deleterious expansion at any replacement level.

Table 4.8 – Expansion and COV of Potsdam Coarse RCA AMBT

| Potsdam RCA Content | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|------------------------|-----------|-------|-----------|-------|--------------------|
| | Expansion | COV | Expansion | COV | |
| 100% | 0.0730 | 0.016 | 0.1291 | 0.015 | Pass |
| 50% | 0.0664 | 0.030 | 0.1223 | 0.016 | Pass |
| 25% | 0.0652 | 0.048 | 0.1220 | 0.013 | Pass |

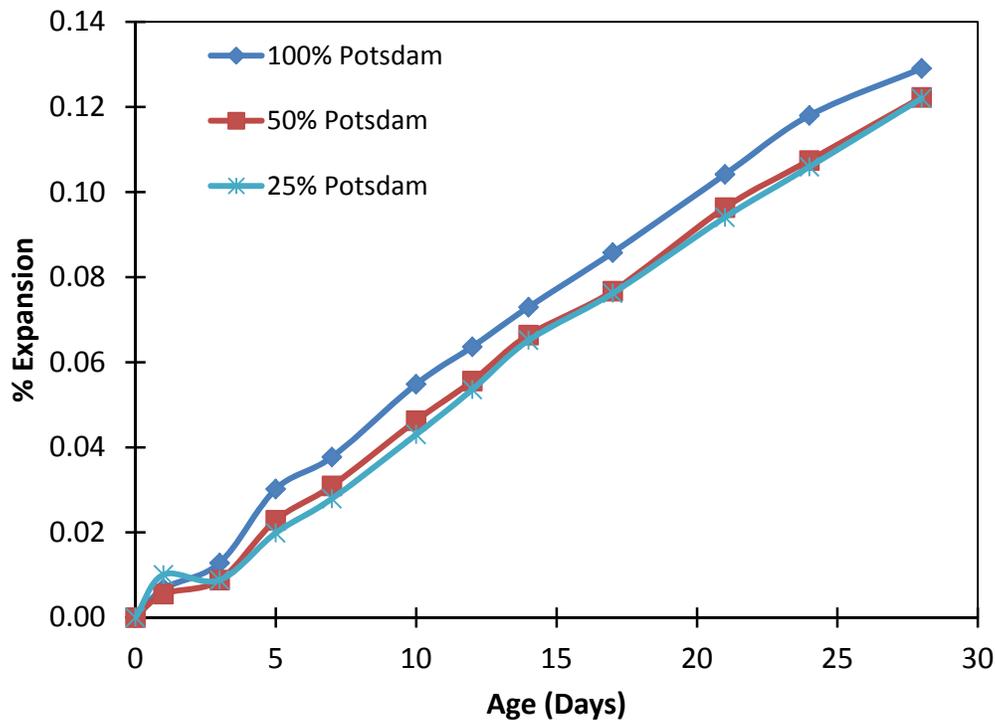


Figure 4.7 – Expansion of Potsdam Coarse RCA AMBT

4.1.3.4 – Interlab Springhill Coarse AMBT Results

The Springhill RCA coarse specimens tested for the interlab study were tested by the modified ASTM C1260 test outlined in Section 3.1. The test program required the RCA be tested at different replacement levels with three sets of 100% Springhill RCA one of which was crushed in a separate batch from the other two, one set of 50% RCA and one set of 25% RCA. Testing conducted by Oregon State University and the Quebec Ministry of Transportation determined the absorption of the Springhill RCA to be 7.35% and 8.21% respectively, so the average of these values, 7.78%, was used for the moisture correction. The consistency of the mortar using this value was very good and no issues with workability were noticeable for all of the batches.

The % expansion graph of the AMBT test specimens to an age of 28 days is shown in Figure 4.8. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.9. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation in

expansion at 14 days age for the 100% Springhill RCA specimens is 0.0168% which is less than the 0.0303% (8.3% of mean expansion) allowed by ASTM C1260. The variation in expansion due to crushing to the first batch at 14 days age is 0.0588 which is greater than the 0.0320% (8.3% of mean expansion) allowed by ASTM C1260. The variation in expansion due to crushing to the second batch at 14 days age is 0.0420% which is greater than the 0.0327% (8.3% of mean expansion) allowed by ASTM C1260. Figure 4.8 shows that the unusual trend seen in Figure 4.4 is not an anomaly attributable to the Coarse Springhill RCA. This result will be further discussed in Section 4.1.7.

Table 4.9 – Expansion and COV of Springhill Coarse RCA AMBT

| Springhill | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|--|-----------|-------|-----------|-------|-----------------|
| RCA Content | Expansion | COV | Expansion | COV | |
| 100% | 0.3565 | 0.004 | 0.4669 | 0.008 | Fail |
| 100% (Rep) | 0.3733 | 0.013 | 0.5001 | 0.011 | Fail |
| 100% (SC) | 0.4153 | 0.020 | 0.5530 | 0.018 | Fail |
| 50% | 0.2996 | 0.033 | 0.4033 | 0.026 | Fail |
| 25% | 0.2204 | 0.061 | 0.3064 | 0.051 | Fail |
| Variation for 100% @ 14 Days = 0.0268 , @ 28 Days = 0.0386 | | | | | |
| Variation for Crushing @ 14 Days = 0.0700 , @ 28 Days = 0.0751 | | | | | |

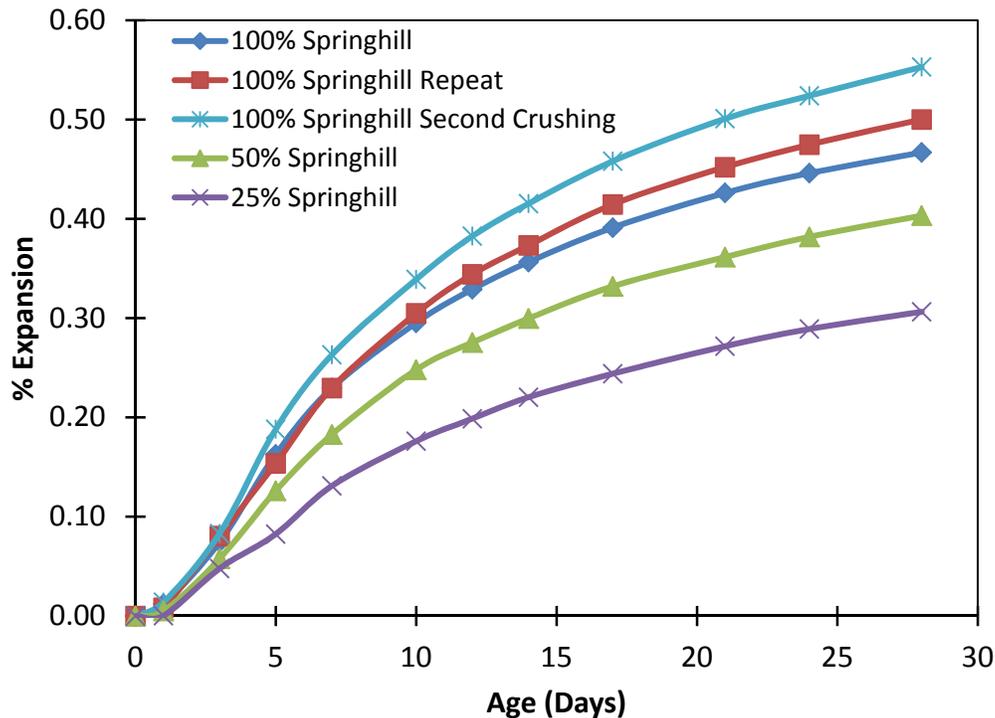


Figure 4.8 – Expansion of Springhill Coarse RCA AMBT

4.1.4 – Variance of RCA Test Size on Accelerated Mortar Bar Test

4.1.4.1 – Interlab Alberta AMBT Results

The graphs seen in Figure 4.9 and Figure 4.10 show a clear discrepancy between the expansions of Alberta RCA depending on the original size of the material they were derived from. The overall results concur that plain concrete made with 100% Alberta RCA is likely to cause deleterious expansion. However, the expansion of the 100% Alberta Coarse RCA batch is 74% greater than the crusher's fine batch. The overall results also concur that plain concrete made with 50% Alberta RCA is likely to cause deleterious expansion. However, the expansion of the 50% Alberta Coarse RCA batches is 123% greater than the crusher's fine batches. The overall results again concur that plain concrete made with 25% Alberta RCA is likely to cause deleterious expansion. However, the expansion of the 25% Alberta coarse RCA batches is 104% greater than the crusher's fine batches. The results indicate that in the case of Alberta RCA, the selection of material to be used for AMBT testing will have a significant impact on the expansion results but will provide a valid screening of the RCA on the pass/fail result.

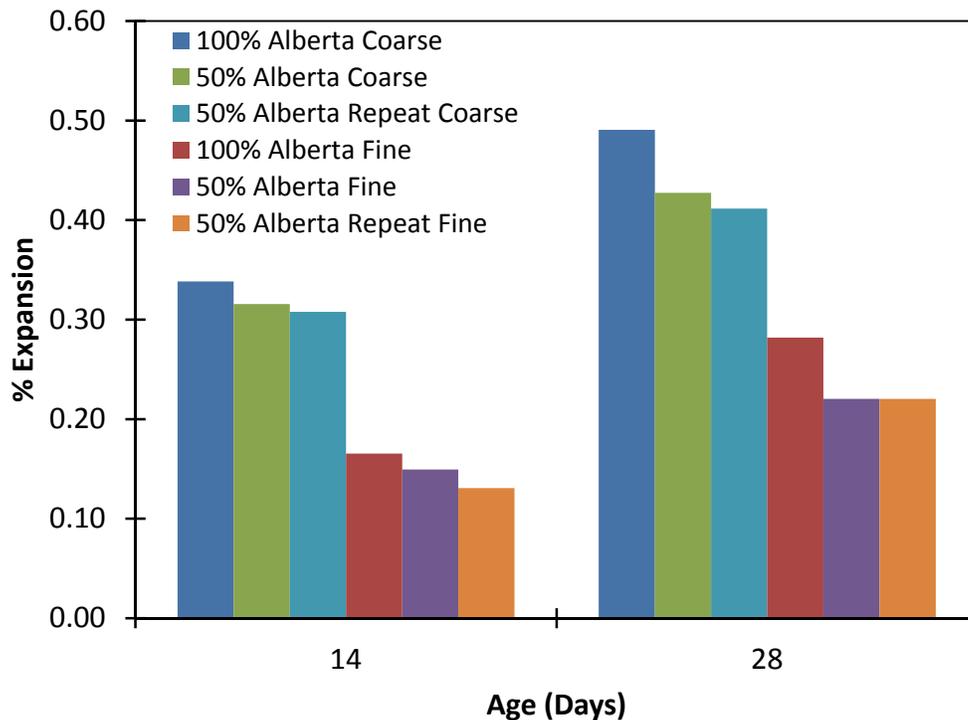


Figure 4.9 Expansion of 100% and 50% Alberta RCA AMBT

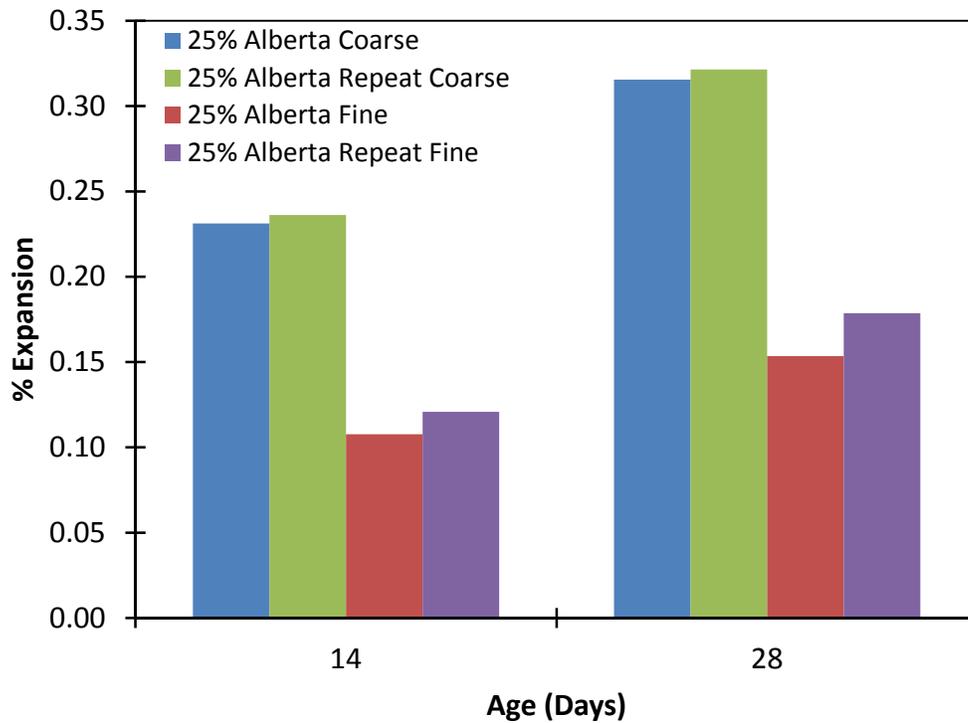


Figure 4.10 Expansion of 25% Alberta RCA AMBT

4.1.4.2 – Interlab Bernier AMBT Results

The graphs seen in Figure 4.11 and Figure 4.12 show a clear discrepancy between the expansions of Bernier RCA depending on the original size of the material they were derived from. The overall results do not concur that plain concrete made with 100% Bernier RCA is likely to cause deleterious expansion. The expansion of the 100% Bernier coarse RCA batch is 41% greater than the crusher's fine batch. This 41% increase straddles the 0.1% expansion limit for the ASTM C1260 test. The overall results do concur that plain concrete made with 50% Bernier RCA is not likely to cause deleterious expansion. However, the expansion of the 50% Bernier coarse RCA batches is 94% greater than the crusher's fine batches. The overall results also concur that plain concrete made with 25% Bernier RCA is likely to cause deleterious expansion. However, the expansion of the 25% Bernier coarse RCA batches is 13% less than the crusher's fine batches. This result is completely contradictory to the results at higher RCA replacements and highlights

the anomalous results for Bernier crusher's fines RCA. These results indicate that in the case of Bernier RCA, the selection of material to be used for AMBT testing will have a significant impact on the expansion results and may cause an invalid screening of the RCA on the pass/fail result.

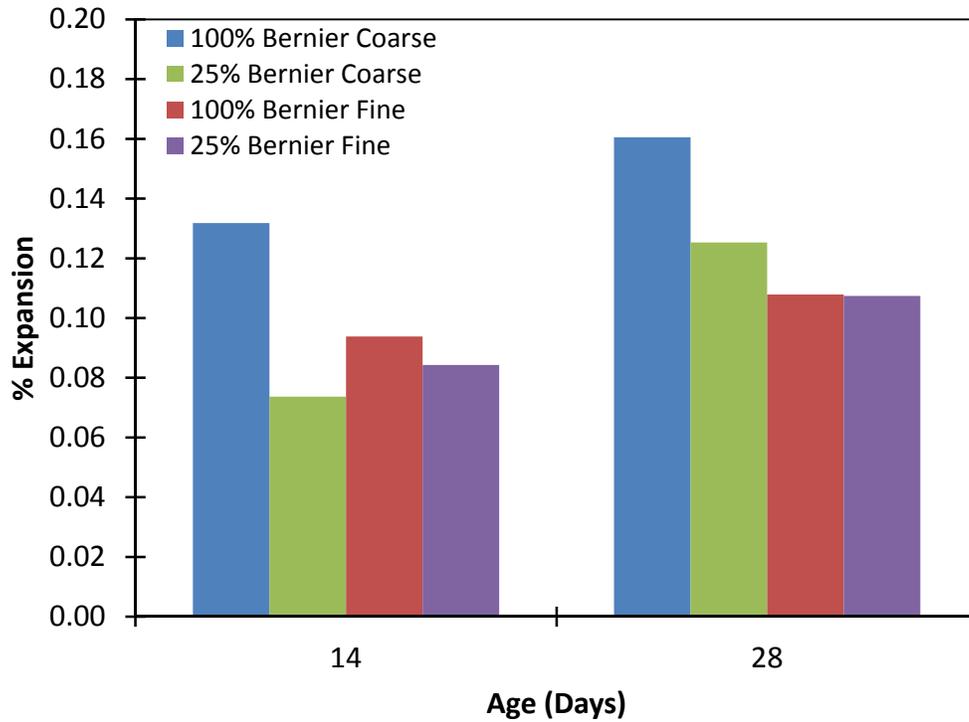


Figure 4.11 – Expansion of 100% and 25% Bernier RCA AMBT

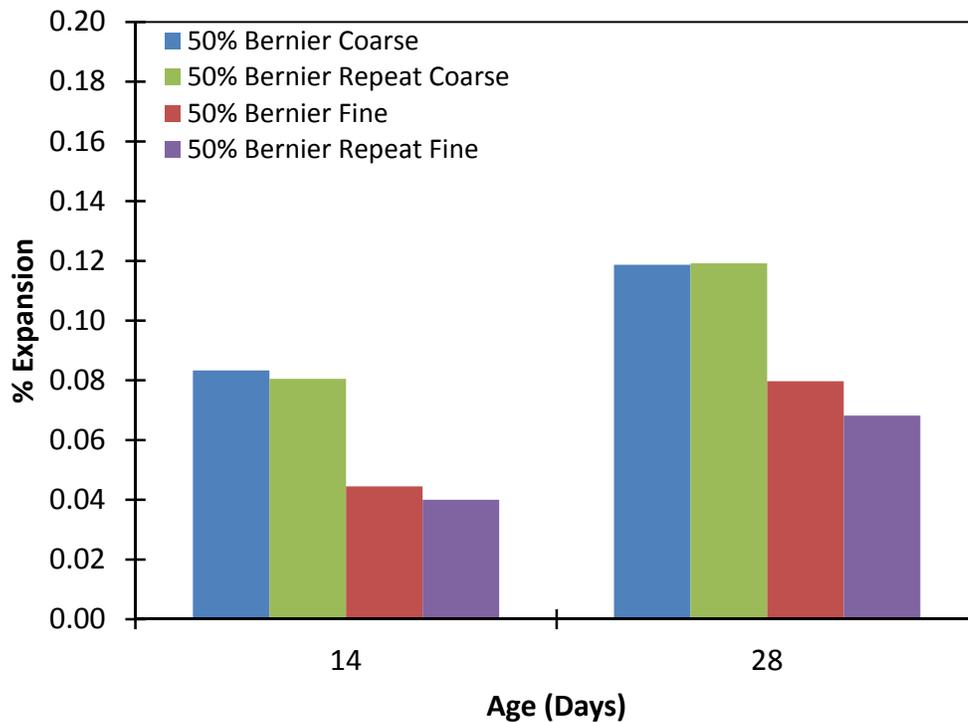


Figure 4.12 – Expansion of 50% Bernier RCA AMBT

4.1.4.3 – Interlab Potsdam AMBT Results

The graph seen in Figure 4.13 does not show any significant discrepancy between the expansions of Potsdam RCA at any replacement level. The overall results concur that plain concrete made with 100% Potsdam RCA is not likely to cause deleterious expansion. The overall results also concur that plain concrete made with 50% Potsdam RCA is not likely to cause deleterious expansion. The overall results again concur that plain concrete made with 25% Potsdam RCA is not likely to cause deleterious expansion. The largest change in expansion between the crusher’s fines and coarse RCA is 17% which is minimal compared to the other RCA comparisons. These results indicate that in the case of Potsdam RCA, the selection of material to be used for AMBT testing will not significantly impact the expansion results. However, as was previously discussed, the AMBT results of virgin Potsdam aggregate provide misleading results that suggest Potsdam aggregate is innocuous when it is expansive under CPT testing as seen in Figure 4.14. It is likely the case that the Potsdam RCA will also be expansive under CPT testing even though it passes the AMBT.

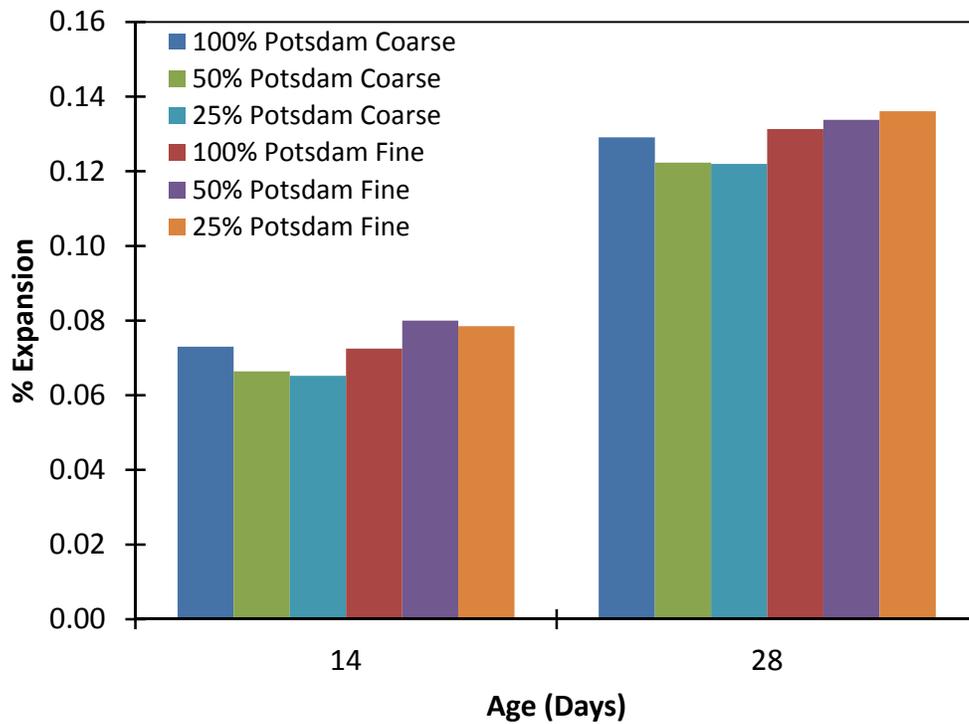


Figure 4.13 – Expansion of Potsdam RCA AMBT

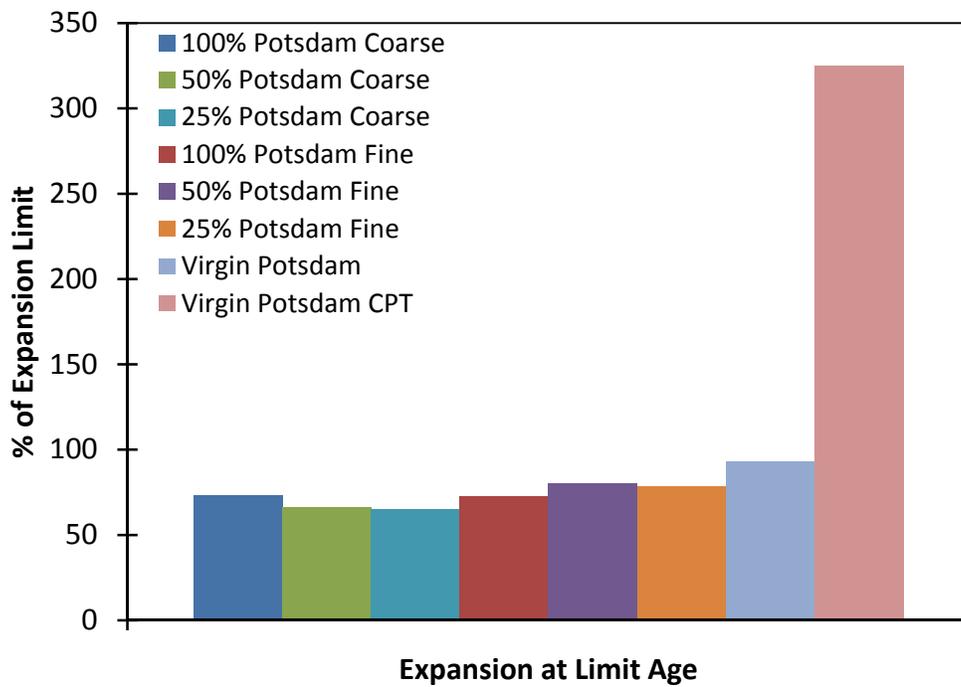


Figure 4.14 – Expansion of Potsdam RCA for AMBT and Virgin Potsdam for CPT

4.1.4.4 – Interlab Springhill AMBT Results

The graphs seen in Figure 4.15 and Figure 4.16 show a clear discrepancy between the expansions of Springhill RCA depending on the original size of the material they were derived from. The overall results do not concur that plain concrete made with 100% Springhill RCA is likely to cause deleterious expansion. The expansion of the 100% Springhill coarse RCA batch is 378% greater than the crusher's fine batch. This 378% increase straddles the 0.1% expansion limit for the ASTM C1260 test. The overall results do concur that plain concrete made with 50% Springhill RCA is likely to cause deleterious expansion. However, the expansion of the 50% Springhill coarse RCA batches is 138% greater than the crusher's fine batches. The overall results also do not concur that plain concrete made with 25% Springhill RCA is likely to cause deleterious expansion, however the fines value is close enough to the limit to warrant further testing. The expansion of the 25% Bernier coarse RCA batches is 122% greater than the crusher's fine batches. These results indicate that in the case of Springhill RCA, the selection of material to be used for AMBT testing will have a significant impact on the expansion results and may cause an invalid screening of the RCA on the pass/fail result.

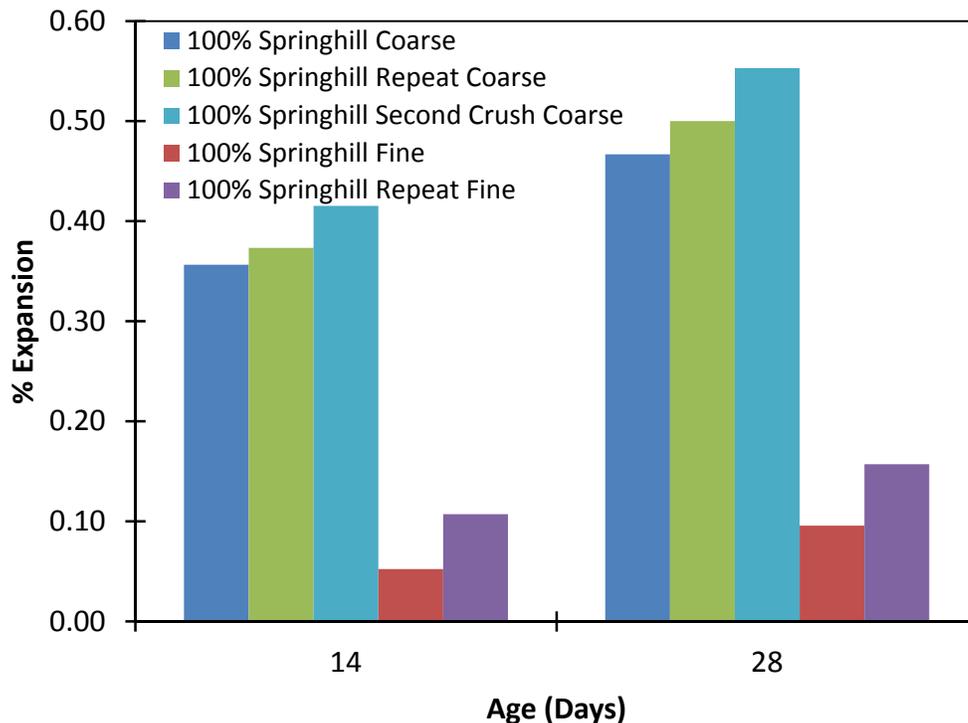


Figure 4.15 – Expansion of 100% Springhill RCA AMBT

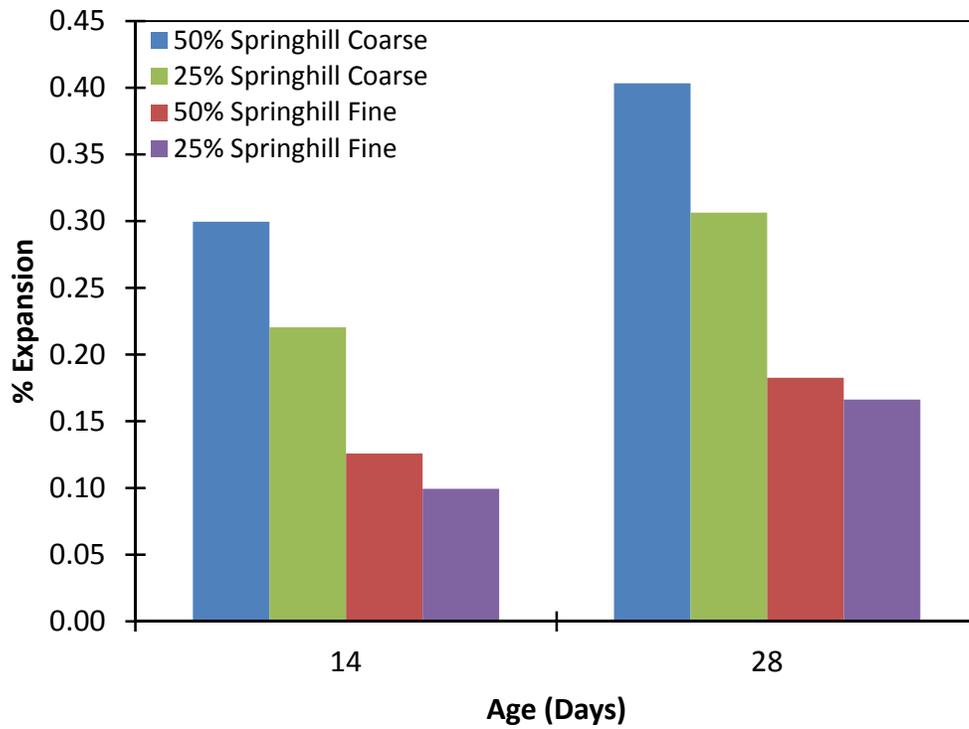


Figure 4.16 – Expansion of 50% and 25% Springhill RCA AMBT

4.1.5 – Interlab Variance of Accelerated Mortar Bar Test

4.1.5.1 – Interlab Variance of Alberta AMBT Results

The results for all four labs were analysed and according to the guidelines for multi-laboratory precision in ASTM C1260. These guidelines suggest that the difference between two tests should not be greater in magnitude than 43% of the mean expansion. The mean interlab expansions and the upper and lower boundaries for the 43% limits of Alberta crusher's fines and crushed coarse RCA AMBT specimens are seen in Table 4.10. The graphs seen in Figures 4.17, 4.18 and 4.19, compare the expansion of Ryerson specimens and the mean expansion of the interlab (ILS) specimens.

Figure 4.17 shows some variation between the mean Ryerson 100% Alberta RCA results for both crushed coarse and crusher's fines specimens. The variation for 100% Alberta crushed coarse and crusher's fines are 7.8% and 11.1% respectively. Referring to Table 4.10 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.18 shows some variation between the Ryerson 50% Alberta RCA results for both crushed coarse and crusher's fines specimens. The variation for 50% Alberta crushed coarse and crusher's fines are 12% & 9.2% and 9.1% & 4.5% respectively. Referring to Table 4.10 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.19 shows some variation between the Ryerson 25% Alberta RCA results for both crushed coarse and crusher's fines specimens. The variation for 25% Alberta crushed coarse and crusher's fines are 14% & 16% and 4.6% & 17% respectively. Referring to Table 4.10 shows that all results fall comfortably within the 43% range required by ASTM C1260.

Overall the results of the Ryerson interlab testing satisfy the multi-laboratory variability requirements of ASTM C1260 for Alberta RCA of both crushed coarse and crusher's fines aggregates. The COV results shown in Table 4.10 indicate that the crushed coarse specimens were more consistent than the crusher's fines specimens for Alberta RCA.

Table 4.10 – Mean and allowable range of expansion for Alberta RCA specimens

| Crushed Coarse RCA AMBT Specimens | | | % Expansion Allowable Range | |
|------------------------------------|---------------------------|-------|-----------------------------|-------------|
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Alberta | 0.314 | 0.115 | 0.450 | 0.179 |
| 50% Alberta | 0.282 | 0.115 | 0.403 | 0.161 |
| 25% Alberta | 0.203 | 0.058 | 0.291 | 0.116 |
| Crusher's Fines RCA AMBT Specimens | | | % Expansion Allowable Range | |
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Alberta | 0.149 | 0.190 | 0.213 | 0.085 |
| 50% Alberta | 0.137 | 0.276 | 0.196 | 0.078 |
| 25% Alberta | 0.103 | 0.211 | 0.147 | 0.059 |

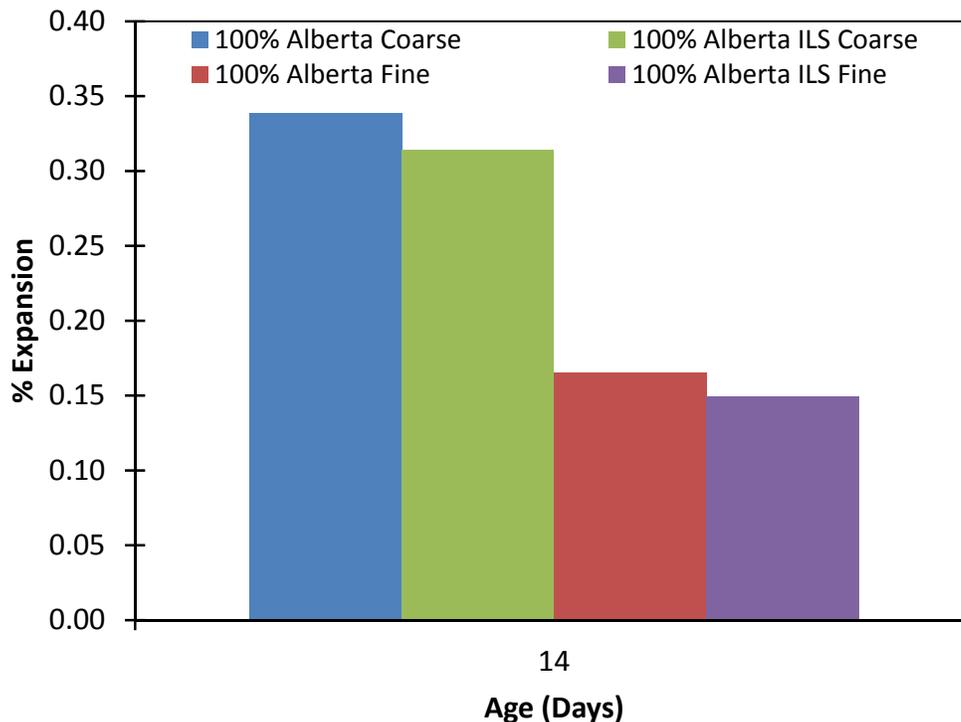


Figure 4.17 – Mean expansion of Ryerson and overall interlab 100% Alberta RCA specimens

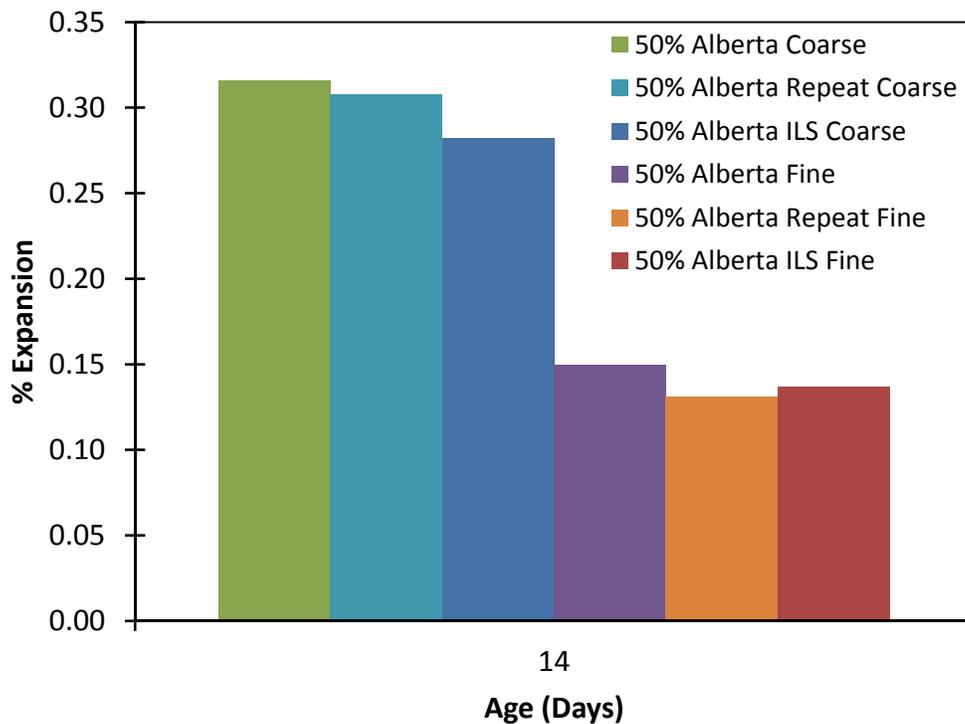


Figure 4.18 – Mean expansion of Ryerson and overall interlab 50% Alberta RCA specimens

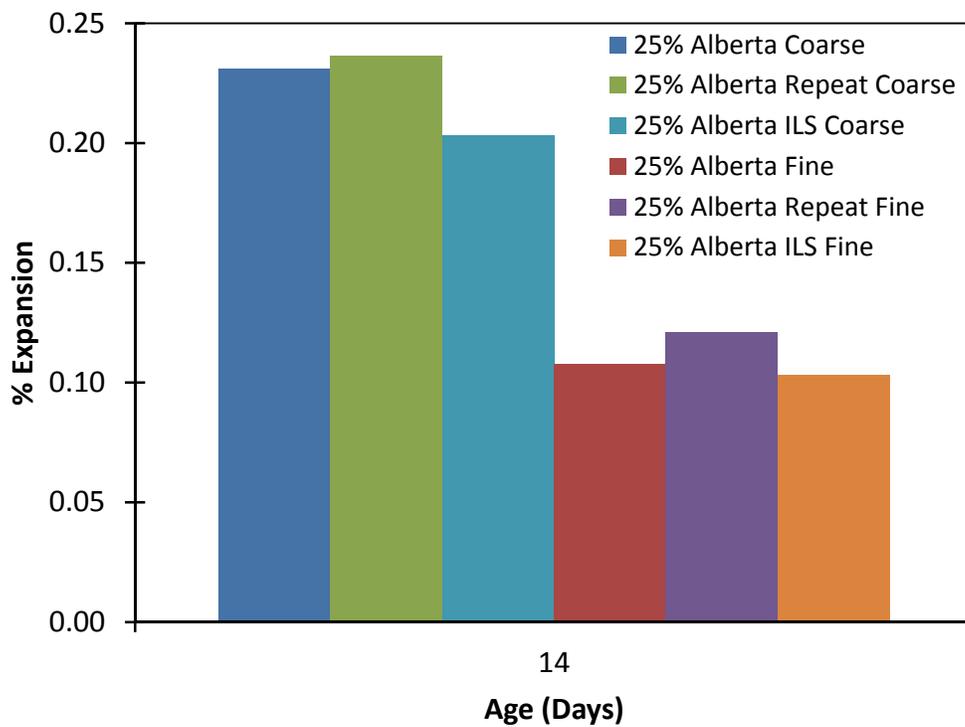


Figure 4.19 – Mean expansion of Ryerson and overall interlab 25% Alberta RCA specimens

4.1.5.2 – Interlab Variance of Bernier AMBT Results

The mean interlab expansions and the upper and lower boundaries for the 43% limits of Bernier crusher's fines and crushed coarse RCA AMBT specimens are seen in Table 4.11. The graphs seen in Figures 4.20, 4.21 and 4.22 compare the expansion of Ryerson specimens and the mean expansion of the interlab (ILS) specimens.

Figure 4.20 shows some variation between the mean Ryerson 100% Bernier RCA results for both crushed coarse and crusher's fines specimens. The variation for 100% Bernier crushed coarse and crusher's fines are 17% and 22% respectively. Referring to Table 4.11 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.21 shows some variation between the Ryerson 50% Bernier RCA results for both crushed coarse and crusher's fines specimens. The variation for 50% Bernier crushed coarse and crusher's fines are 8.5% & 12% and 25% & 32% respectively. Referring to Table 4.11 shows that all results fall within the 43% range required by ASTM C1260, however the crusher's fines results show a significant increase in variation compared to the coarse results. Figure 4.22 shows some variation between the Ryerson 25% Bernier RCA results for both crushed coarse and crusher's fines specimens. The variation for 25% Bernier crushed coarse and crusher's fines is 1.7% and 28% respectively. Referring to Table 4.11 shows that all results fall within the 43% range required by ASTM C1260, however the crusher's fines results again show a significant increase in variation compared to the coarse results.

Overall the results of the Ryerson interlab testing satisfy the multi-laboratory variability requirements of ASTM C1260 for Alberta RCA of both crushed coarse and crusher's fine aggregates. . The COV results shown in Table 4.11 indicate that the crushed coarse specimens were only slightly more consistent than the crusher's fines specimens for Alberta RCA. It should be noted that the inaccuracy is more likely attributable to the reduced expansion since COV calculations are more sensitive to small mean values. The small expansions also contribute to the increased variation since a small difference in expansion creates a larger % variation if the mean is small. The fact that the coarse results had reduced variances does indicate that the crusher's fines results may be anomalous as was previously suggested.

Table 4.11 – Mean and allowable range of expansion for Bernier RCA specimens

| Coarse RCA AMBT Specimens | | | % Expansion Allowable Range | |
|---------------------------|---------------------------|-------|-----------------------------|-------------|
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Bernier | 0.113 | 0.228 | 0.161 | 0.064 |
| 50% Bernier | 0.091 | 0.085 | 0.131 | 0.052 |
| 25% Bernier | 0.075 | 0.175 | 0.107 | 0.043 |
| Fine RCA AMBT Specimens | | | % Expansion Allowable Range | |
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Bernier | 0.077 | 0.205 | 0.111 | 0.044 |
| 50% Bernier | 0.059 | 0.210 | 0.084 | 0.034 |
| 25% Bernier | 0.066 | 0.169 | 0.095 | 0.038 |

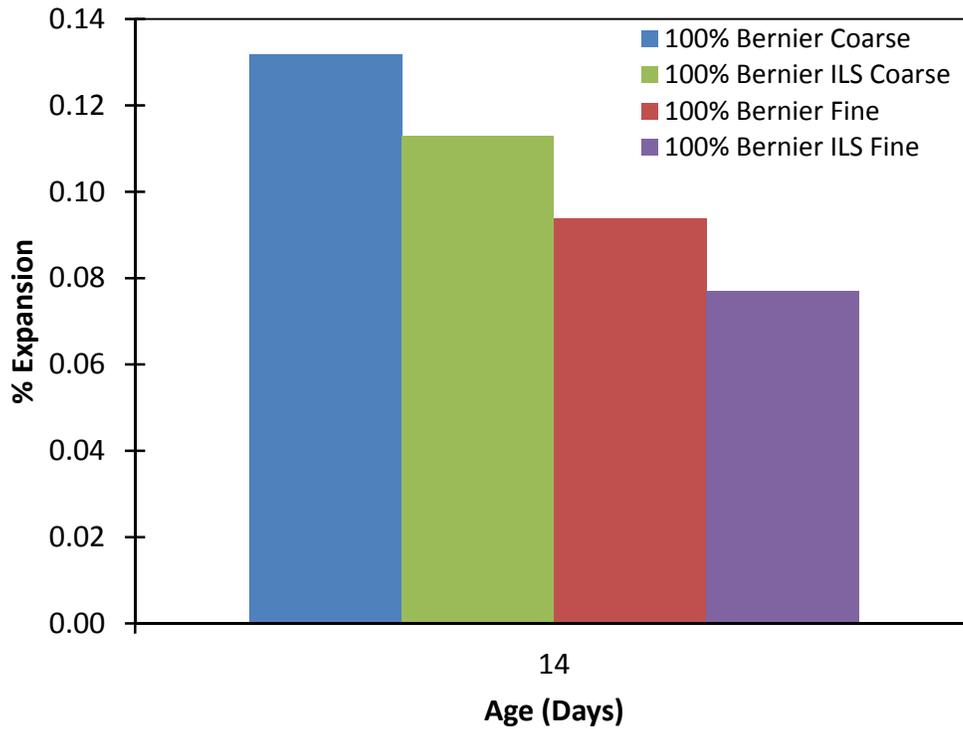


Figure 4.20 – Mean expansion of Ryerson and overall interlab 100% Bernier RCA specimens

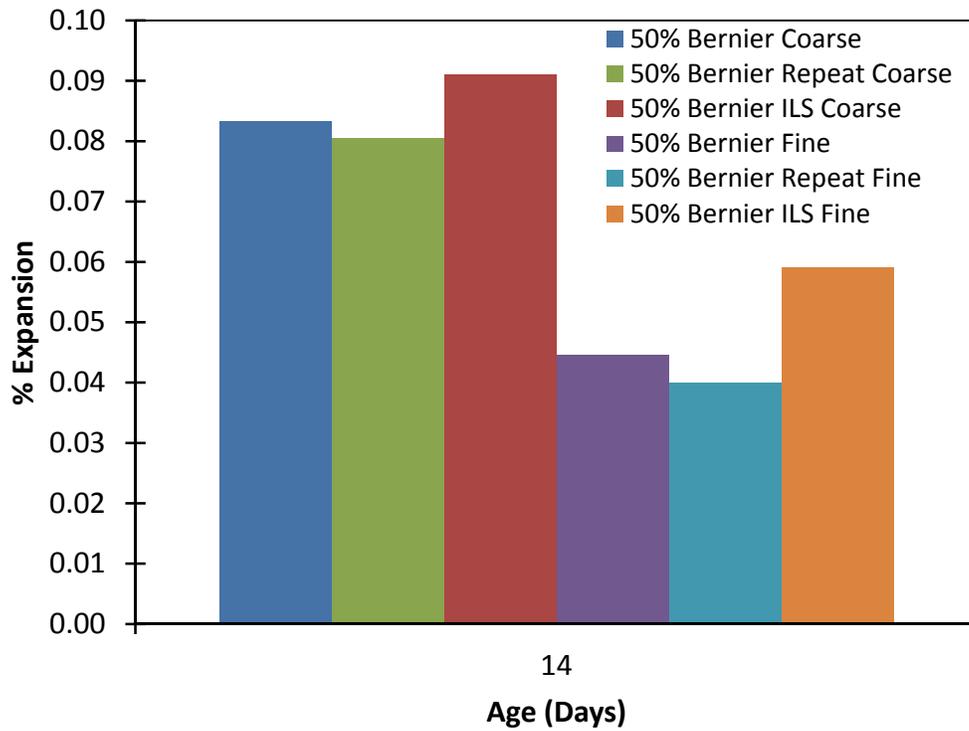


Figure 4.21 – Mean expansion of Ryerson and overall interlab 50% Bernier RCA specimens

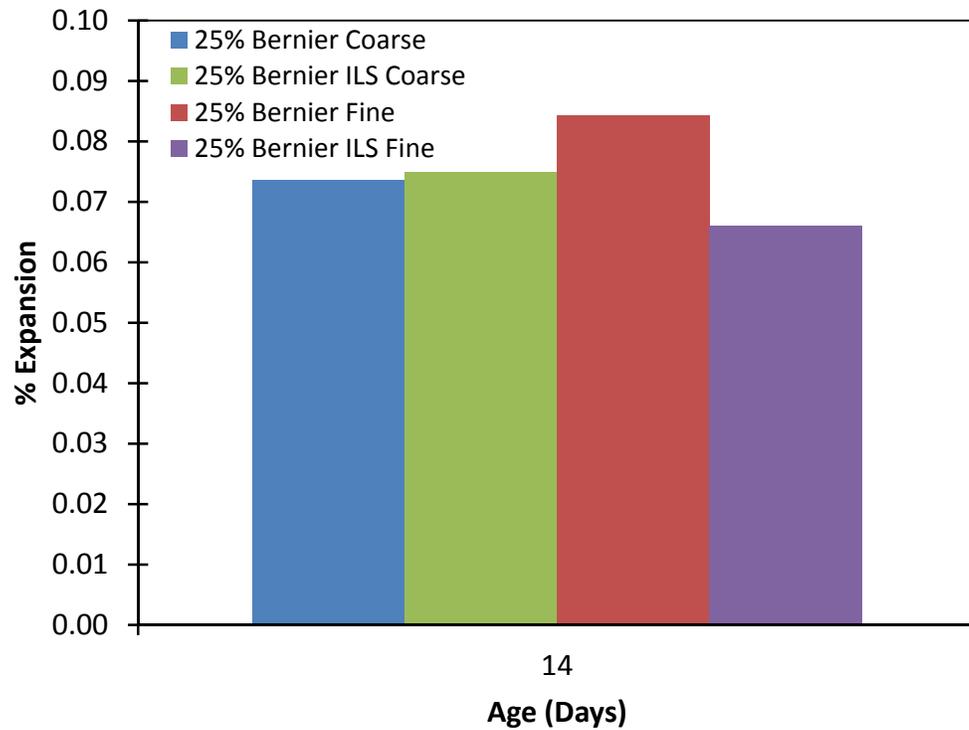


Figure 4.22 – Mean expansion of Ryerson and overall interlab 25% Bernier RCA specimens

4.1.5.3 – Interlab Variance of Potsdam AMBT Results

The mean interlab expansions and the upper and lower boundaries for the 43% limits of Potsdam crusher's fines and crushed coarse RCA AMBT specimens are seen in Table 4.12. The graphs seen in Figures 4.23, 4.24 and 4.25 compare the expansion of Ryerson specimens and the mean expansion of the interlab (ILS) specimens.

Figure 4.23 shows little variation between the mean Ryerson 100% Potsdam RCA results for both crushed coarse and crusher's fines specimens. The variation for 100% Potsdam crushed coarse and crusher's fines are 2.8% and 4.6% respectively. Referring to Table 4.12 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.24 shows some variation between the Ryerson 50% Potsdam RCA results for both crushed coarse and crusher's fines specimens. The variation for 50% Potsdam crushed coarse and crusher's fines is 7.1% and 14% respectively. Referring to Table 4.12 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.25 shows some variation between the Ryerson 25% Potsdam RCA results for both crushed coarse and crusher's fines specimens. The variation for 25% Potsdam crushed coarse and crusher's fines is 42% and 27% respectively. Referring to Table 4.12 shows that all results fall within the 43% range required by ASTM C1260, however the crushed coarse result show a significant increase in variation that is within 1% of the specified limit.

Overall the results of the Ryerson interlab testing satisfy the multi-laboratory variability requirements of ASTM C1260 for Potsdam RCA of both crushed coarse and crusher's fine aggregates. The COV results shown in Table 4.12 indicate that the crushed coarse specimens were as equally consistent as the crusher's fines specimens for Potsdam RCA. As was previously discussed, the AMBT is ineffective in evaluating the expansion risk of Potsdam aggregate since it does not expand under the AMBT conditions. The inaccuracy is more likely attributable to this reduced expansion since COV calculations are more sensitive to small mean values. The small expansions also contribute to the increased variation since a small difference in expansion creates a larger % variation if the mean is small.

Table 4.12 – Mean and allowable range of expansion for interlab Potsdam RCA specimens

| Coarse RCA AMBT Specimens | | | % Expansion Allowable Range | |
|---------------------------|---------------------------|-------|-----------------------------|-------------|
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Potsdam | 0.071 | 0.275 | 0.101 | 0.040 |
| 50% Potsdam | 0.062 | 0.073 | 0.088 | 0.035 |
| 25% Potsdam | 0.046 | 0.104 | 0.066 | 0.026 |
| Fine RCA AMBT Specimens | | | % Expansion Allowable Range | |
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Potsdam | 0.062 | 0.229 | 0.109 | 0.043 |
| 50% Potsdam | 0.070 | 0.131 | 0.101 | 0.040 |
| 25% Potsdam | 0.076 | 0.108 | 0.089 | 0.036 |

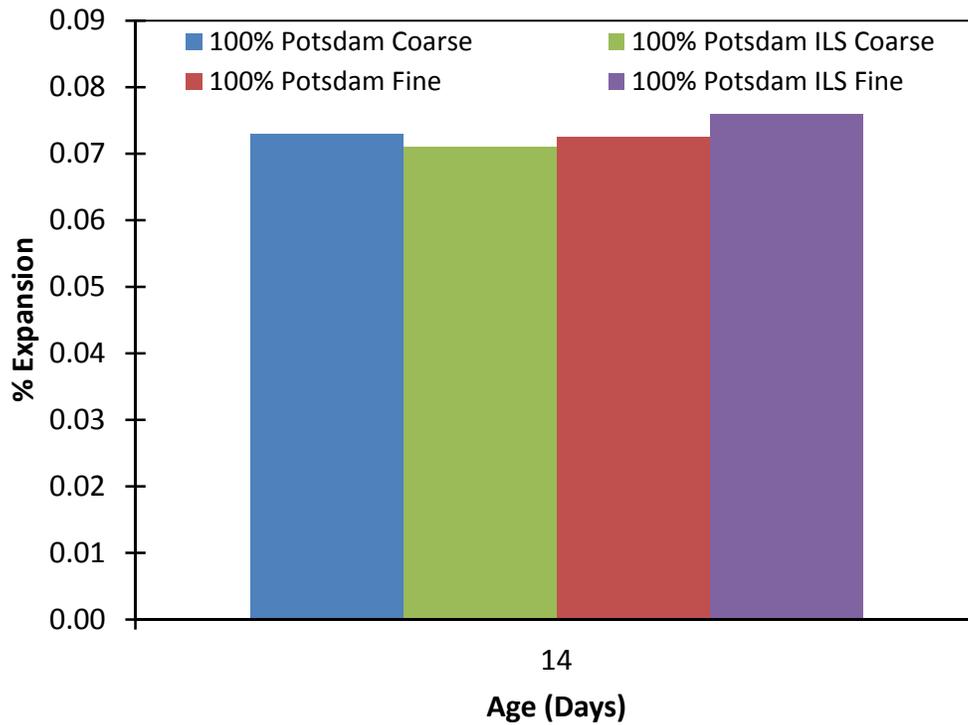


Figure 4.23 – Mean expansion of Ryerson and overall interlab 100% Potsdam RCA specimens

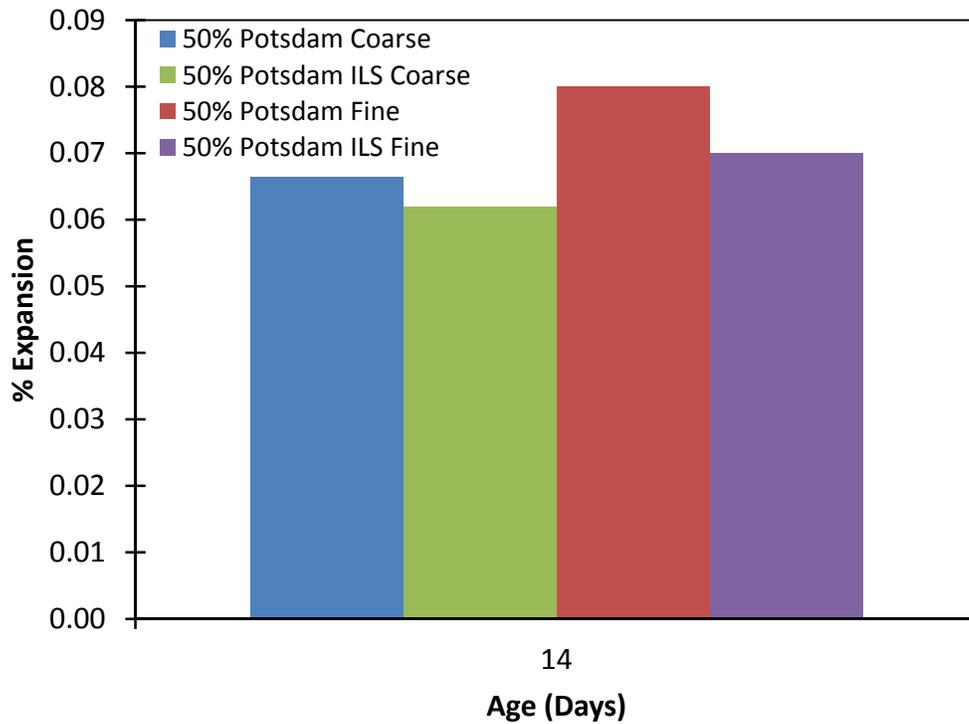


Figure 4.24 – Mean expansion of Ryerson and overall interlab 50% Potsdam RCA specimens

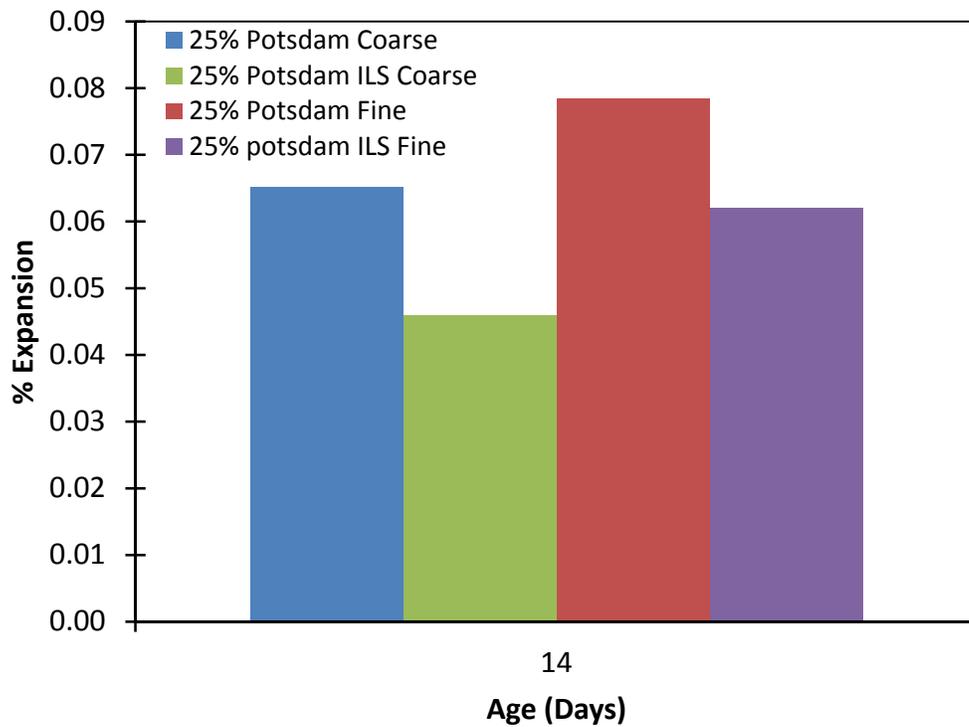


Figure 4.25 – Mean expansion of Ryerson and overall interlab 25% Potsdam RCA specimens

4.1.5.4 – Interlab Variance of Springhill AMBT Results

The mean interlab expansions and the upper and lower boundaries for the 43% limits of Springhill crusher's fines and crushed coarse RCA AMBT specimens are seen in Table 4.13. The graphs seen in Figures 4.26, 4.27, 4.28 and 4.29 compare the expansion of Ryerson specimens and the mean expansion of the interlab (ILS) specimens.

Figures 4.26 and 4.27 shows some variation between the mean Ryerson 100% Springhill RCA results for both crushed coarse and crusher's fines specimens. The variation for 100% Springhill crushed coarse and crusher's fines are 11%, 17% & 30% and 39% & 25% respectively. Referring to Table 4.13 shows that all the results fall within the 43% range required by ASTM C1260. Figure 4.28 shows little variation between the Ryerson 50% Springhill RCA results for both crushed coarse and crusher's fines specimens. The variation for 50% Springhill crushed coarse and crusher's fines is 5.1% and 10% respectively. Referring to Table 4.13 shows that all results fall comfortably within the 43% range required by ASTM C1260. Figure 4.29 shows some variation between the Ryerson 25% Springhill RCA results for both crushed coarse and crusher's fines specimens. The variation for 25% Springhill crushed coarse and crusher's fines is 13% and 24% respectively. Referring to Table 4.13 shows that all the results fall within the 43% range required by ASTM C1260.

Overall the results of the Ryerson interlab testing satisfy the multi-laboratory variability requirements of ASTM C1260 for Springhill RCA of both crushed coarse and crusher's fine aggregates. The COV results shown in Table 4.13 indicate that the crushed coarse specimens were more consistent than the crusher's fines specimens for Springhill RCA.

Table 4.13 – Mean and allowable range of expansion for Springhill RCA specimens

| Coarse RCA AMBT Specimens | | | % Expansion Allowable Range | |
|---------------------------|---------------------------|-------|-----------------------------|-------------|
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Springhill | 0.320 | 0.202 | 0.457 | 0.182 |
| 50% Springhill | 0.285 | 0.079 | 0.407 | 0.162 |
| 25% Springhill | 0.195 | 0.165 | 0.278 | 0.111 |
| Fine RCA AMBT Specimens | | | % Expansion Allowable Range | |
| RCA Replacement | Average % Expansion @ 14d | COV | Upper Bound | Lower Bound |
| 100% Springhill | 0.086 | 0.268 | 0.123 | 0.049 |
| 50% Springhill | 0.114 | 0.271 | 0.163 | 0.065 |
| 25% Springhill | 0.080 | 0.222 | 0.114 | 0.045 |

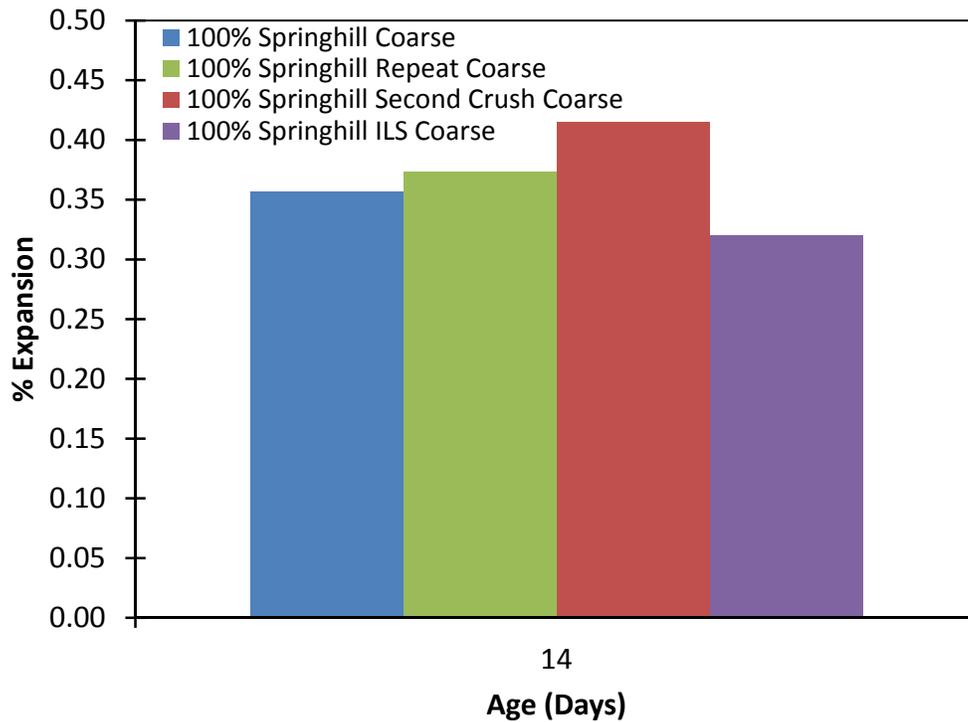


Figure 4.26 – Mean expansion of Ryerson and overall interlab 100% Springhill Coarse RCA specimens

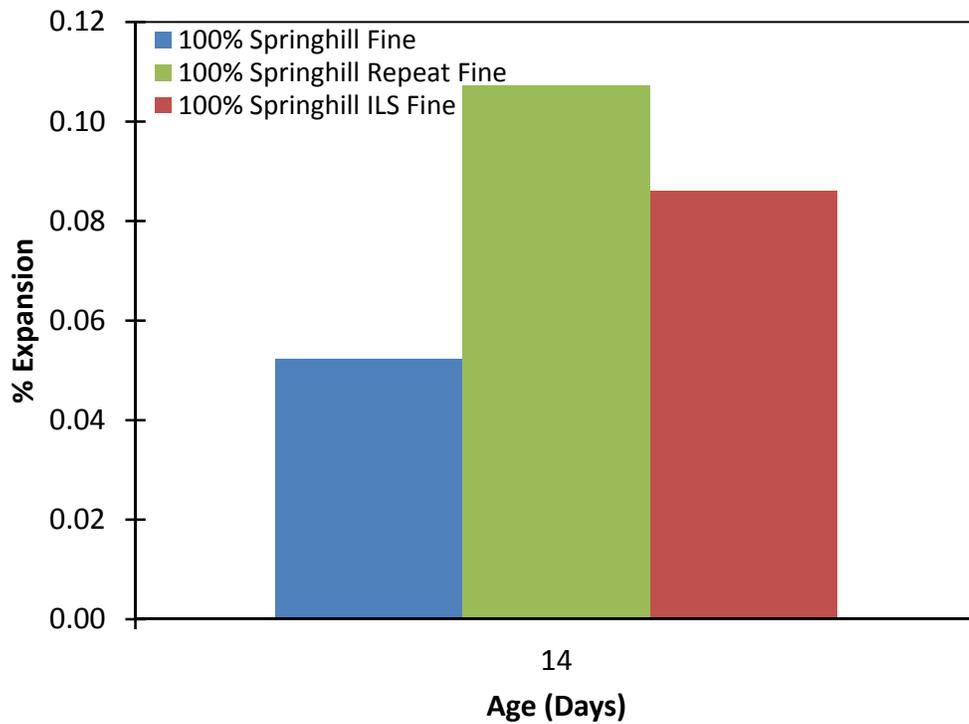


Figure 4.27 – Mean expansion of Ryerson and overall interlab 100% Springhill crusher's fines RCA specimens

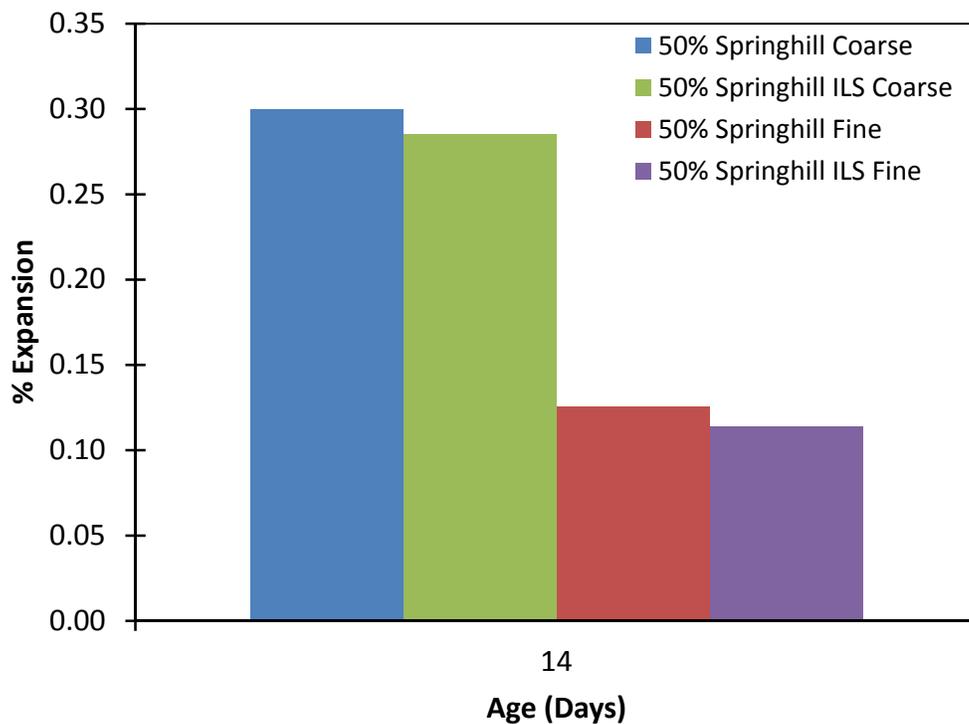


Figure 4.28 – Mean expansion of Ryerson and overall interlab 50% Springhill RCA specimens

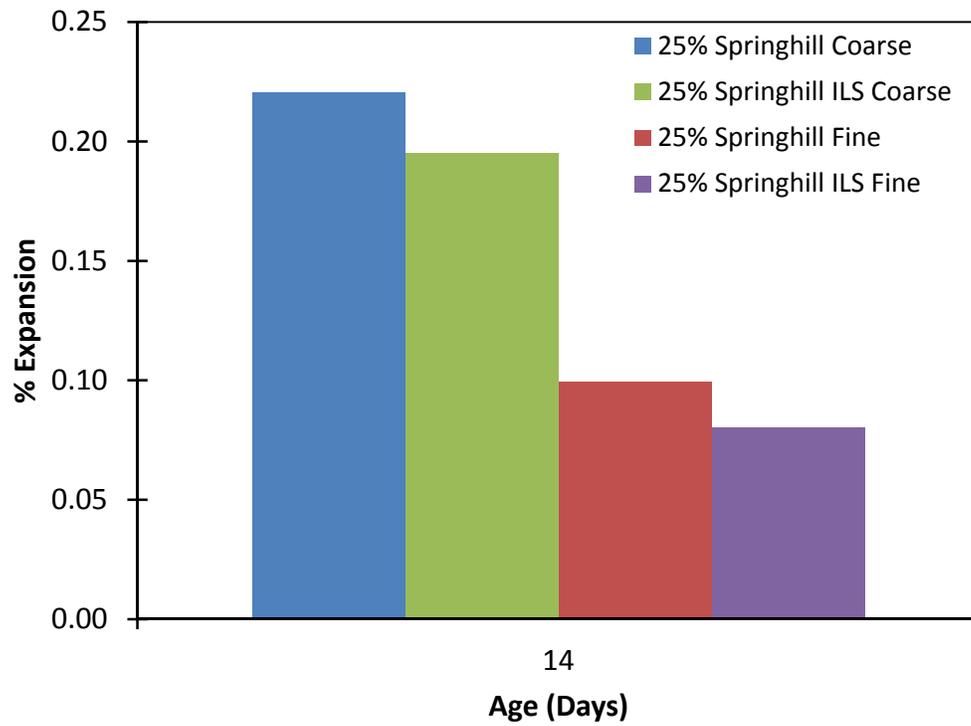


Figure 4.29 – Mean expansion of Ryerson and overall interlab 25% Springhill RCA specimens

4.1.6 – Variation in Expansion of Laval RCA due to Modified Testing Conditions

4.1.6.1 – Variation in Expansion of Laval RCA due to W/C Ratio Fluctuations

The Laval RCA specimens were tested by the modified ASTM C1260 test outlined in Section 3.2. The Laval RCA absorption of 4.9% was determined by taking the average of three absorption tests conducted according to ASTM C128. To simulate results affected by an incorrect absorption test specimens were made using water corrections of 3.9%, 4.9% (Control), and 5.9%, representing the correct absorption and a range of $\pm 1\%$ error. The consistency of the mortars using these values was good and no issues with workability were noticeable for any of the batches.

The % expansion graph of the Laval RCA test specimens to an age of 28 days is shown in Figure 4.30. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.14. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The expansion at 14 days of the reduced water specimens is 14% greater than that of the control. The expansion at 14 days of the increased water specimens is 4.6% lower than that of the control. Since we are assuming these specimens represent measurement error during the absorption test, they should all be assumed to be equal. Thus, the variation in expansion at 14 days age for the highest and lowest expansion is 0.0426% which is greater than the 0.0200% (8.3% of mean expansion) allowed by ASTM C1260. However the variation to 4.9% specimens from the 3.9% and 5.9% specimens is 0.0321% and 0.0105% respectively. When compared to the 0.0204% and 0.0186% (8.3% of mean expansion) allowed by ASTM C1260, reduced water is outside the allowable range while increased water falls within the allowable range. However, if we assumed these results were conducted at different labs, the upper and lower boundaries for the 43% limits will be satisfied for multi-laboratory precision. These results indicate that ensuring the correct absorption value will have an effect on the expansion results but will still provide valid screening of the RCA on the pass/fail result.

Table 4.14 – Expansion and COV of Laval RCA with varied water corrections

| Laval RCA Moisture Corr. | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|--------------------------------|-----------|-------|-----------|-------|--------------------|
| | Expansion | COV | Expansion | COV | |
| 3.9% | 0.2618 | 0.021 | 0.3195 | 0.014 | Fail |
| 4.9% | 0.2297 | 0.026 | 0.2823 | 0.007 | Fail |
| 5.9% | 0.2192 | 0.014 | 0.2674 | 0.017 | Fail |

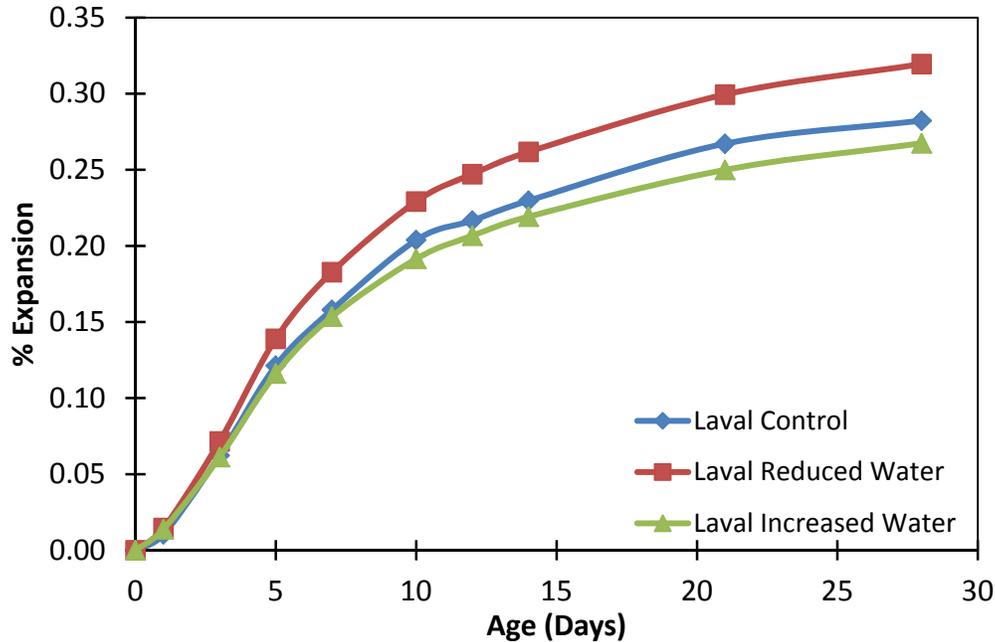


Figure 4.30 – Expansion of Laval RCA with varied water corrections

4.1.6.2 – Variation in Expansion of Laval RCA due to Method of Crushing

The Laval RCA specimens were tested by the modified ASTM C1260 test outlined in Section 3.2. The Laval RCA absorption of 4.9% was determined by taking the average of three absorption tests conducted according to ASTM C128. To simulate results affected by the method of crushing a set of specimens were created using the procedure outlined in 3.2.2 and compared to the control specimens from 4.1.6.1. The consistency of the mortar was good and no issues with workability were noticeable for this batch.

The % expansion graph of the Laval RCA test specimens to an age of 28 days is shown in Figure 4.31. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.15. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The expansion at 14 days of the compressive crushing specimens is 47% lower than that of the control. It is assumed that these specimens represent different methods of crushing that are assumed to yield comparable samples. Thus, the discrepancy in expansion at 14 days age for the highest and lowest expansion is 0.1084% which is much greater than the 0.0146% (8.3% of mean expansion) allowed by ASTM C1260. If we assumed these results were conducted at different labs, the upper and lower boundaries for the 43% limits will not be satisfied for multi-laboratory precision. These results indicate that the method of crushing will have an extremely adverse effect on the expansion results but will still provide valid screening of the RCA on the pass/fail result.

Table 4.15 – Expansion and COV of Laval RCA with varied crushing method

| Laval RCA | 14 Day | | 28 Day | | Pass/Fail @ 14d |
|-----------------|-----------|-------|-----------|-------|-----------------|
| Crushing Method | Expansion | COV | Expansion | COV | |
| Control Crush | 0.2297 | 0.026 | 0.2823 | 0.007 | Fail |
| Comp. Crush | 0.1213 | 0.010 | 0.1562 | 0.010 | Fail |

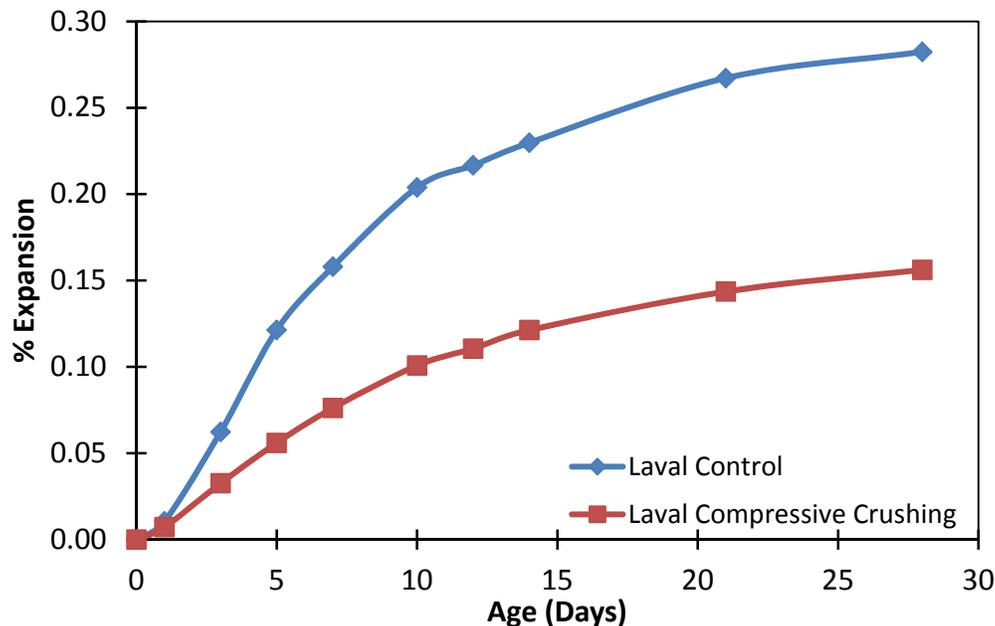


Figure 4.31 – Expansion of Laval RCA with varied crushing method

4.1.6.3 – Variation in Expansion of Laval RCA due to Washing of RCA

The Laval RCA specimens were tested by the modified ASTM C1260 test outlined in Section 3.2. The Laval RCA absorption of 4.9% was determined by taking the average of three absorption tests conducted according to ASTM C128. To simulate results affected by the method of preparing the RCA, in this case washing to remove adhered fines, a set of specimens were created using the procedure outlined in Section 3.2.2 and compared to the control specimens from 4.1.6.1. The consistency of the mortar was good and no issues with workability were noticeable for this batch.

The % expansion graph of the Laval RCA test specimens to an age of 28 days is shown in Figure 4.32. The % expansion and the COV at 14 and 28 days, as well as the pass or fail of the 0.1% expansion criteria at 14 days age of the AMBT test specimens is shown in Table 4.16. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The expansion at 14 days of the washed RCA specimens is 20% lower than that of the control. It is assumed that these specimens represent different methods of RCA preparation that are assumed to yield comparable samples. Thus, the discrepancy in expansion at 14 days age for the highest and lowest expansion is 0.0461% which is greater than the 0.0172% (8.3% of mean expansion) allowed by ASTM C1260. If we assumed these results were conducted at different labs, the upper and lower boundaries for the 43% limits will be satisfied for multi-laboratory precision. These results indicate that washing the RCA will have an effect on the expansion results but will still provide valid screening of the RCA on the pass/fail result.

Table 4.16 – Expansion and COV of Laval RCA for washed specimens

| Laval RCA | 14 Day | | 28 Day | |
|-----------|-----------|-------|-----------|-------|
| | Expansion | COV | Expansion | COV |
| Unwashed | 0.2297 | 0.026 | 0.2823 | 0.007 |
| Washed | 0.1836 | 0.013 | 0.2382 | 0.012 |

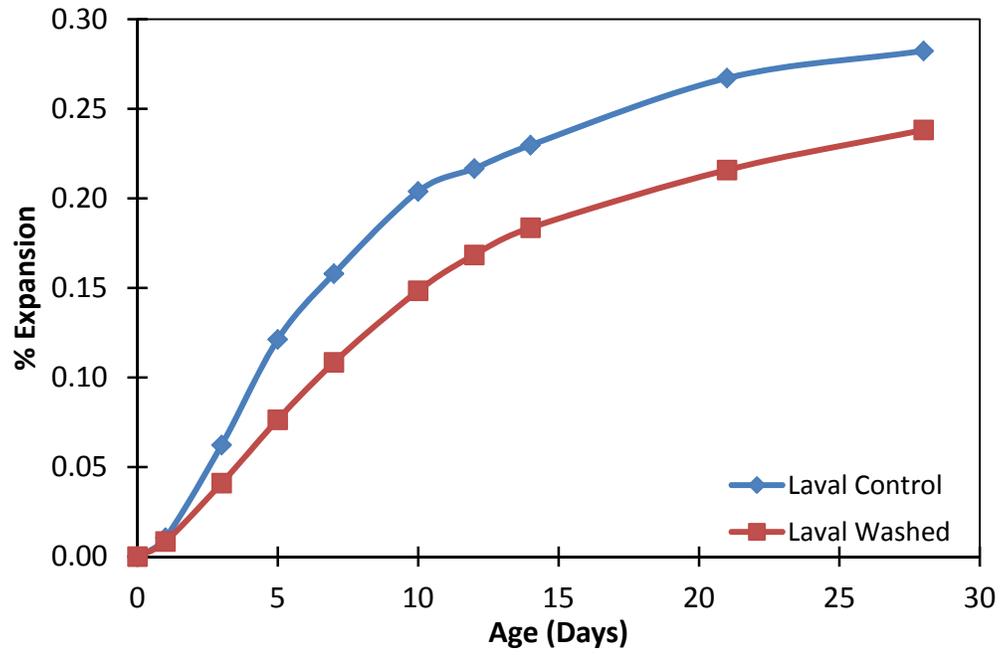


Figure 4.32 – Expansion of Laval RCA for washed specimens

4.1.7 – Discussion of AMBT Test Results

Analysis of the overall results indicates that for the testing of RCA optimum results will be obtained by testing the material as it will be used. This means that if an RCA will be delivered to the batch plant in a certain gradation, that same gradation should be delivered to the evaluating lab. Section 4.1.4 clearly indicates that the use of the crusher's fines that are created when RCA is processed will likely lead to a limited reaction that could result in a false negative reactivity result. The cause of this discrepancy is the RCA material itself. During the crushing process the original concrete is broken apart and these breaks will always form in the weakest available plane. In virgin aggregate these planes are created by imperfection in the rock or flaws in the crystal structure as applicable. In RCA, these planes will occur in the ITZ of the aggregate and paste. This means that it is more likely for paste to break away from the stone and for the weak paste to be easily crushed to the extremely small fractions. This means that the crusher's fines particles that pass the finest screens are more likely to be composed of paste. Since it is the aggregate, and not the paste which carries the reactive silica, if the ratio of aggregate to paste in the crusher's fines is significantly less than that of the normal concrete, the likely outcome is a reduced expansion.

All of the anomalous results seen in Section 4.1.2 can be attributed to the above problem. It was noted during sample preparation that the original samples of crusher's fines did not contain a significant portion of the gradation between sieve #4 and sieve #16. Although the samples were prepared for shipping to ensure an abundance of all required gradations, there was very little excess of the above mentioned gradation. At the same time, there was a general overabundance of the much finer gradations. As discussed above, this indicates a greater likelihood that the ratio of aggregate to paste does not match the original material. A further issue with the crusher's fines is the sampling method. Due to the tendency of finer grade materials to settle, sampling must take great care to ensure an equal gradation delivered to each lab. In this case it is possible that because one lab's crusher's fines sample was taken last from the original container, it contained a greater percentage of fines than other samples which could account for the variation between labs. The single laboratory variation of the repeat specimens tested for the crusher's fines RCA specimens yielded consistently varied expansions that did not pass the single

laboratory variation. This may also be a factor of the reduced expansions reducing the allowable ranges but the COV results for each individual batch were also greater in the crusher's fines specimens. The coarse results were generally more consistent overall and nearly always fell within the limits specified by ASTM C1260. The exception was the results comparing specimens created from a discrete batch of crushed coarse which fell outside the required limit. However, Section 4.1.5 showed that all of the specimens batched at Ryerson fell within the multi-laboratory variation limit specified by ASTM C1260.

Providing the as delivered gradation to the testing lab helps to alleviate this problem because the ratio of aggregate to paste will be nearly identical to the original material. However, the method of crushing the material to the required gradation must be properly selected. Section 4.1.6.2 showed that specimens created from RCA crushed in a compressive test apparatus were not comparable to those crushed with the correct equipment in the protocols outlined in Section 3.2.2. Crushing in a compressive test apparatus will create the fine particles required for the correct gradation but due to the manner in which the particles are formed it is far more likely that the fines will come from the paste. Initially, the load applied is distributed by the interlocking aggregate at the points of contact. As the load at each point of contact increases it will eventually fail and release fine particles. As the particles become finer the number of contact points increases and the load at each contact point decreases concomitantly. Since the paste is generally weaker than the aggregate, this means that once a certain number of fractures occur the load will not be sufficient to fracture the aggregate and on the past will break down. In other words, after a certain load is applied all fines will be created from paste. This is not an issue with jaw or rotary crushers because the aperture of the crusher ensures that all material will be crushed to a specific maximum size. This means that every individual particle greater than that size must be broken to pass the aperture and thus will ensure the graded material better represents the original material.

The correction applied for moisture content as seen in Section 4.1.6.1 should be completed with the best possible accuracy since small changes in the water content can affect the expansion results. If the absorption of the RCA is underestimated, the effective W/C ratio will decrease. This small decrease is sufficient to cause an increase in the expansion, most likely due to there being slightly reduced voids in which expansive gel can be contained and that the overall

permeability was not sufficiently modified to prevent the alkali ingress in to the specimens. If the absorption of the RCA is overestimated, the effective W/C ratio will increase. This small increase is sufficient to cause a decrease in the expansion, most likely due to there being slightly increased voids in which expansive gel can be contained and that the overall permeability is already greater than needed to sustain the reaction at normal W/C ratios. The results showed that underestimating the RCA absorption led to a greater change then overestimating expansion. Underestimating the absorption of one of two tests of an RCA by 1% would results in a large enough change in expansion to fall outside of the range between two tests specified by ASTM C1260 for single laboratory variability. Overestimating the absorption of one of two tests of an RCA by 1% does not result in a change in expansion that exceeds the specified limit.

The results of Section 4.1.6.3 indicate washing of RCA to remove adhered fines will also affect the expansion results. Washing RCA has the side effect of leaching alkalis from the paste portion of the RCA particles. Although the majority of alkalis should be provided by the solution the specimens are contained in, there was still a reduction in expansion when the RCA was washed prior to testing. There may also be an interaction involving dehydrated silica gel in the RCA which would cause expansion in the concrete. Regardless, it was found that washing the RCA the change in expansion was greater than the limit allowed by ASTM C1260 for single laboratory variability.

4.2. – Concrete Microbar Testing

4.2.1 – Scope of Concrete Microbar Testing

The focus of this section of the study was to evaluate the draft RILEM AAR-5 Concrete Microbar Test as an effective screening test for ASR in RCA. The test program evaluated the variables of the CMBT that may affect the results as well as suspected deficiencies. The test program evaluated the test compared to other currently accepted methods like the CPT and the AMBT. For this phase of testing an expansion limit of 0.1% at 28 days age was used as the failure criterion.

Testing was conducted using different aggregates based on availability. The first aggregates selected were virgin Spratt aggregate and a non-reactive limestone coarse aggregate which were readily available for testing. These aggregates were used to evaluate the general test variables that would be consistent throughout the test program. To evaluate the effectiveness of the test in evaluating RCA, the same RCA samples described in Section 4.1 were used. Testing was also conducted using Spratt RCA that had an available database of CPT results to correlate with. The Portland cement selected for testing was a type GU that was obtained from a local manufacturer and is representative of what is used in local construction. SCM's used for testing were the same as those used in the CPT testing.

Testing conducted on virgin Spratt evaluated the effect of cement alkali level before testing by comparing standard cement alkali to specimens with alkali raised to 1.5% Na_2O_e . Testing was also conducted on the virgin Spratt to evaluate the perceived over-dosage of SCM when used in the CMBT. Testing using the RCA from Ottawa Test blocks used in Section 4.1 was conducted to compare the effectiveness of the CMBT to the AMBT as well as the effect on the selection of gradation for the aggregate. Spratt RCA was used with SCM to evaluate the effectiveness of the CMBT in comparison to the CPT using an existing database of results.

4.2.2 – Virgin Aggregate Concrete Microbar Test Results

4.2.2.1 – Virgin Spratt Concrete Microbar Test Results

The virgin Spratt aggregate used for this phase of testing has a long and well documented history of reactivity and is considered the standard ASR test aggregate by the MTO. To evaluate the effect of cement alkali concentration, batches of microbars were made using the standard cement with alkali of approximately 1% and others with the alkali raised to 1.5% Na_2O_e (@ 1.5). Specimens were made with Spratt comprising 100%, 70%, 50%, 30%, 10% and 0% of the total aggregate, with the remainder being non-reactive coarse. Repeat tests were conducted for 50% and 30% Spratt specimens. The precision of repeat specimens will be compared to the requirement of 8.3% of the mean value for allowable variation found in the ASTM C1260 test since there is no published standard for the CMBT.

The % expansion graph of the CMBT test specimens to an age of 56 days is shown in Figures 4.33, 4.34, 4.35 and 4.36. The % expansion of the CMBT test specimens at 14, 28 and 56 days, as well as the pass or fail of the 0.1% expansion criteria at 28 days is shown in Table 4.17 below. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The variation at 28 days age between each of the 50% Spratt and 50% Spratt @ 1.5 specimens were 0.0084% and 0.0018% and the allowable variations are 0.0072% and 0.0074% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. The results for the 50% Spratt results fall outside of the required range but the 50% Spratt @ 1.5 results fall well within the required range. The variation at 28 days age between each of the 30% Spratt and 30% Spratt @ 1.5 specimens were 0.0033% and 0.0023% and the allowable variations are 0.0056% and 0.0049% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. The results for the 30% Spratt and 30% Spratt @ 1.5 fall within the required range.

The graphs seen in Figure 4.33 and Figure 4.34 show a generally linear expansion trend, unlike the AMBT tests such as those seen in Figure 4.32 which expand linearly and reach a plateau near the expansion limit age of 14 days. This is less pronounced in Figure 4.35 and Figure 4.36 which are more curved due to the higher rate of early expansion. Table 4.17 also shows that the

expansion at 56 days is lower in the raised alkali specimens. These results will be further discussed in Section 4.2.4.

Table 4.17 – Expansion of virgin Spratt aggregate

| <i>Aggregate Dilution</i> | <i>% Expansion @ Age</i> | | | <i>Pass/Fail @ 28d</i> |
|---------------------------|--------------------------|----------------|----------------|------------------------|
| | <i>14 Days</i> | <i>28 Days</i> | <i>56 Days</i> | |
| 100% Spratt | 0.0833 | 0.1415 | 0.2495 | Fail |
| 100% Spratt @ 1.5 | 0.0990 | 0.1492 | 0.2108 | Fail |
| 70% Spratt | 0.0579 | 0.1049 | 0.1833 | Fail |
| 70% Spratt @ 1.5 | 0.0708 | 0.1108 | 0.1736 | Fail |
| 50% Spratt | 0.0467 | 0.0826 | 0.1428 | Pass |
| 50% Spratt @ 1.5 | 0.0564 | 0.0903 | 0.1464 | Pass |
| 50% Spratt Repeat | 0.0500 | 0.0910 | 0.1623 | Pass |
| 50% Spratt Repeat @ 1.5 | 0.0559 | 0.0885 | 0.1362 | Pass |
| 30% Spratt | 0.0372 | 0.0654 | 0.1044 | Pass |
| 30% Spratt @ 1.5 | 0.0364 | 0.0577 | 0.0828 | Pass |
| 30% Spratt Repeat | 0.0374 | 0.0687 | 0.1164 | Pass |
| 30% Spratt Repeat @ 1.5 | 0.0374 | 0.0600 | 0.0915 | Pass |
| 10% Spratt | 0.0197 | 0.0295 | 0.0467 | Pass |
| 10% Spratt @ 1.5 | 0.0200 | 0.0282 | 0.0428 | Pass |
| Non-Reactive | 0.0151 | 0.0223 | 0.0287 | Pass |
| Non-Reactive @ 1.5 | 0.0108 | 0.0123 | 0.0172 | Pass |

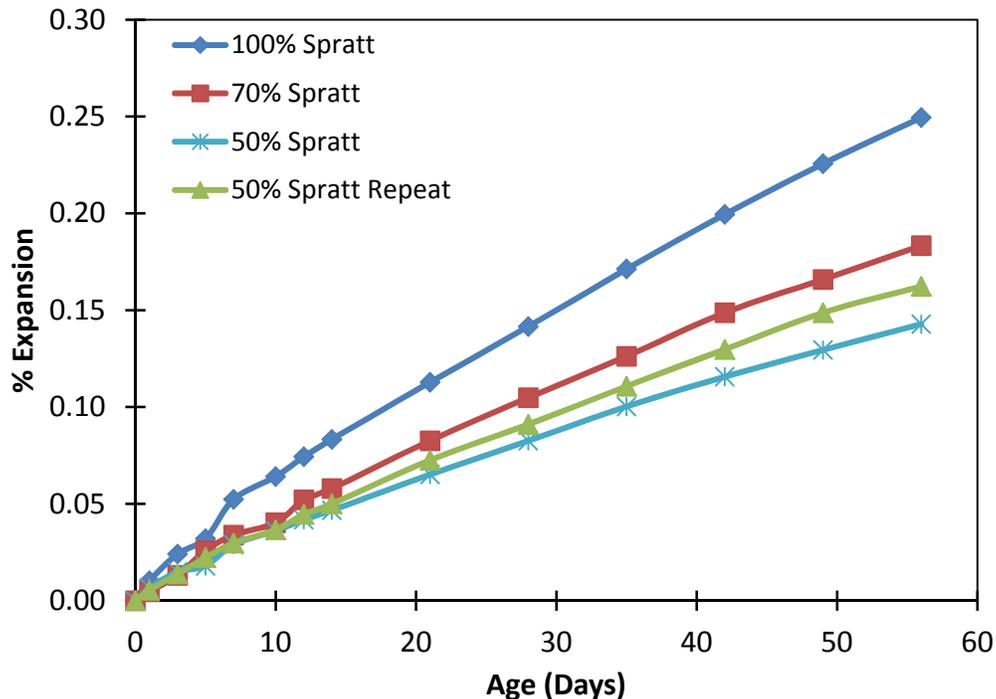


Figure 4.33 – Expansion of high replacement virgin Spratt aggregate with normal alkali PC

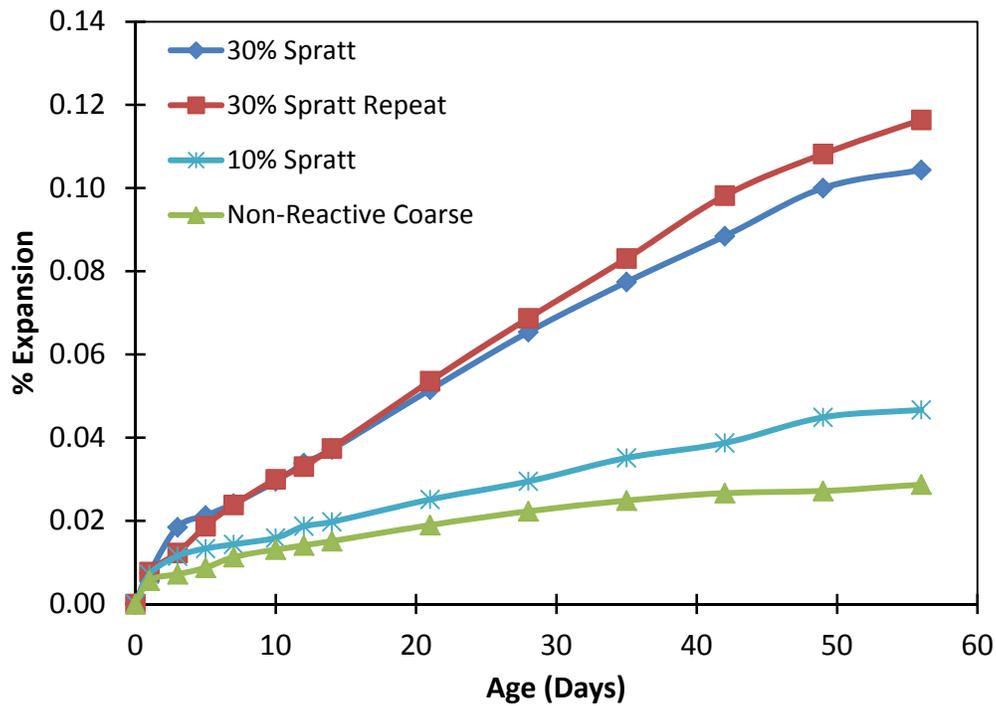


Figure 4.34 – Expansion of low replacement virgin Spratt aggregate with normal alkali PC

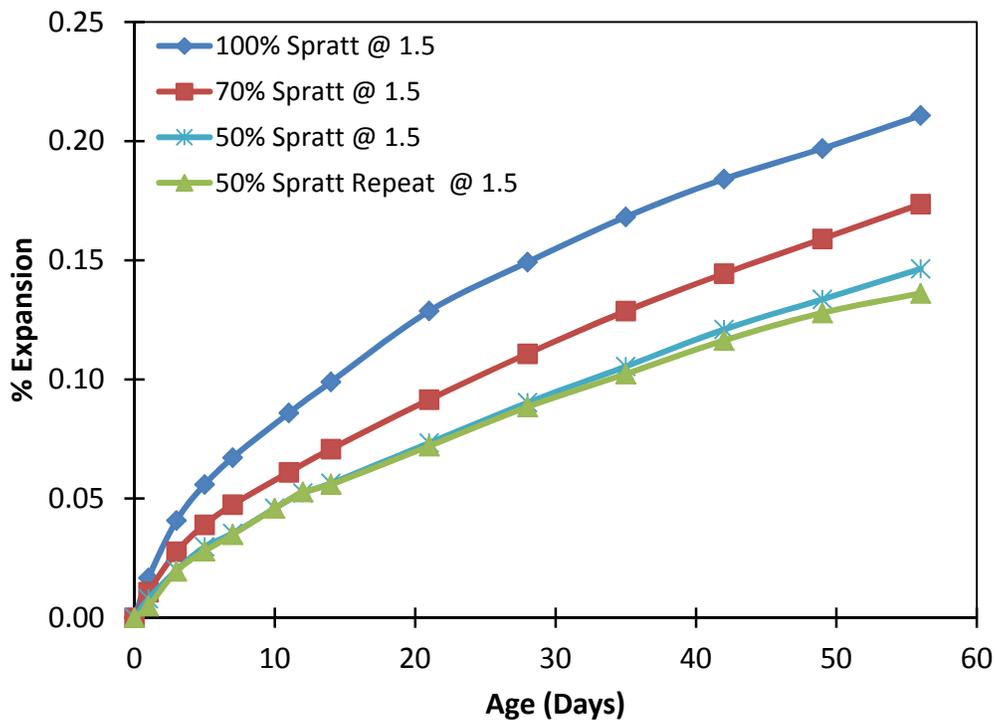


Figure 4.35 – Expansion of high replacement virgin Spratt aggregate with raised alkali PC

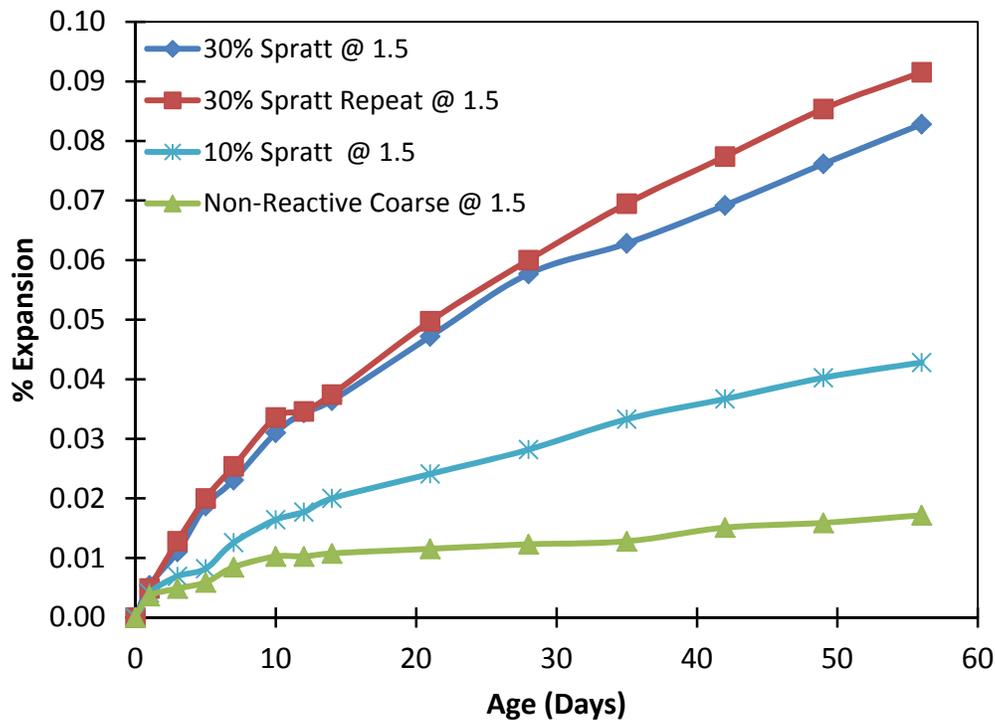


Figure 4.36 – Expansion of low replacement virgin Spratt aggregate with raised alkali PC

4.2.2.2 –Variation due to Alkali content in Concrete Microbar Test Results

To evaluate the effect of cement alkali concentration, batches of microbars were made using the standard cement with alkali of approximately 1% and others with the alkali raised to 1.5% Na_2O_e (@ 1.5). Specimens were made with Spratt comprising 100%, 70%, 50%, 30%, 10% and 0% of the total aggregate, with the remainder being non-reactive coarse. Repeat tests were conducted for 50% and 30% Spratt specimens. The variation of the normal and raised alkali specimens will be compared to the requirement of 8.3% of the mean value for allowable variation found in the ASTM C1260 test since there is no published standard for the CMBT.

Figure 4.37 shows some variation between 100% Spratt and 100% Spratt @ 1.5 specimens. The discrepancy at 28 days age between 100% Spratt and 100% Spratt @ 1.5 specimens was 0.0077% and the allowable variation is 0.0121% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is within the allowed range. However, the results of Grattan-Bellew 2003, using the same test method as

the 100% Spratt @ 1.5 specimens, yielded expansion results nearly double those of this test program and clearly well outside of even the multi-laboratory variation requirements (G.B. 2003). Figure 4.38 shows some variation between 70% Spratt and 70% Spratt @ 1.5 specimens. The variation at 28 days age between 70% Spratt and 70% Spratt @ 1.5 specimens was 0.0059% and the allowable variation is 0.0090% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is within the allowed range.

Figure 4.39 shows some variation between each of the 50% Spratt and 50% Spratt @ 1.5 specimens. The discrepancy at 28 days age between highest and lowest of the 50% Spratt and 50% Spratt @ 1.5 specimens was 0.0084% and the allowable variation is 0.0073% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the most remote specimens is not within the allowed range. However, excluding the 50% Spratt, the remaining specimens do fall within the required range. Figure 4.40 shows some variation between each of the 30% Spratt and 30% Spratt @ 1.5 specimens. The discrepancy at 28 days age between highest and lowest of the 30% Spratt and 30% Spratt @ 1.5 specimens was 0.0110% and the allowable variation is 0.0052% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the most remote specimens is not within the allowed range. However, the allowable range will be more sensitive due to the reduced expansion and is likely more responsible for the variation.

Figure 4.41 shows some variation between 10% Spratt and 10% Spratt @ 1.5 specimens. The discrepancy at 28 days age between 10% Spratt and 10% Spratt @ 1.5 specimens was 0.0013% and the allowable variation is 0.0024% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is within the allowed range. Figure 4.42 shows some variation between Non-Reactive and Non-Reactive @ 1.5 specimens. The discrepancy at 28 days age between Non-Reactive and Non-Reactive @ 1.5 specimens was 0.0100% and the allowable variation is 0.0014% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the most remote specimens is not within the allowed range. The miniscule expansion of these

particular specimens does make the variation less important since the variance will not cause a change in the pass/fail result. These results will be further discussed in Section 4.2.4.

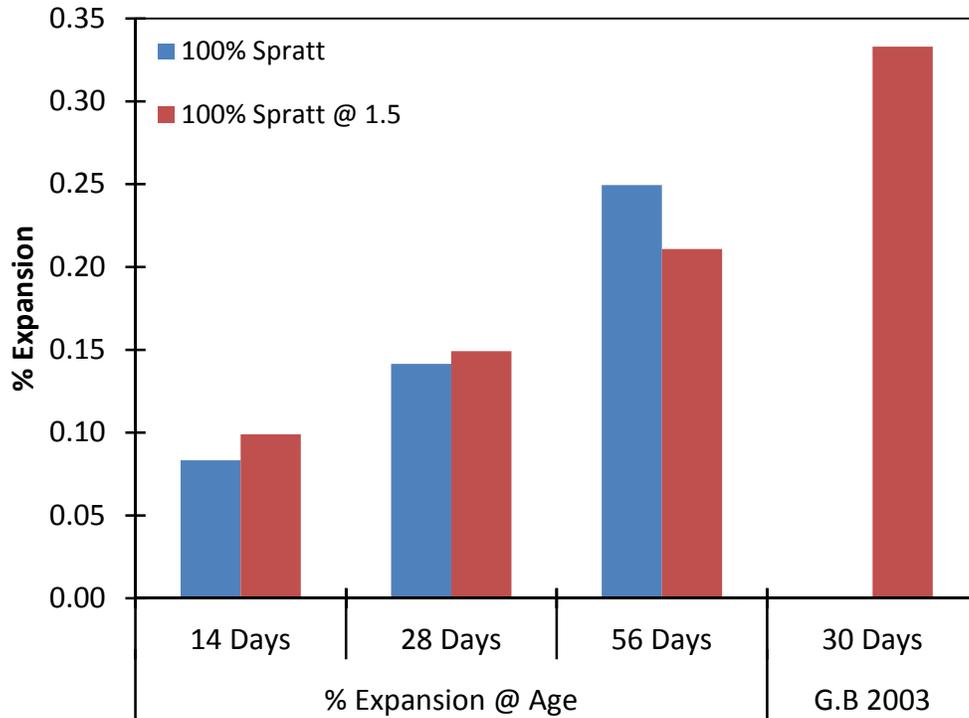


Figure 4.37 – Expansion of 100% virgin Spratt aggregate

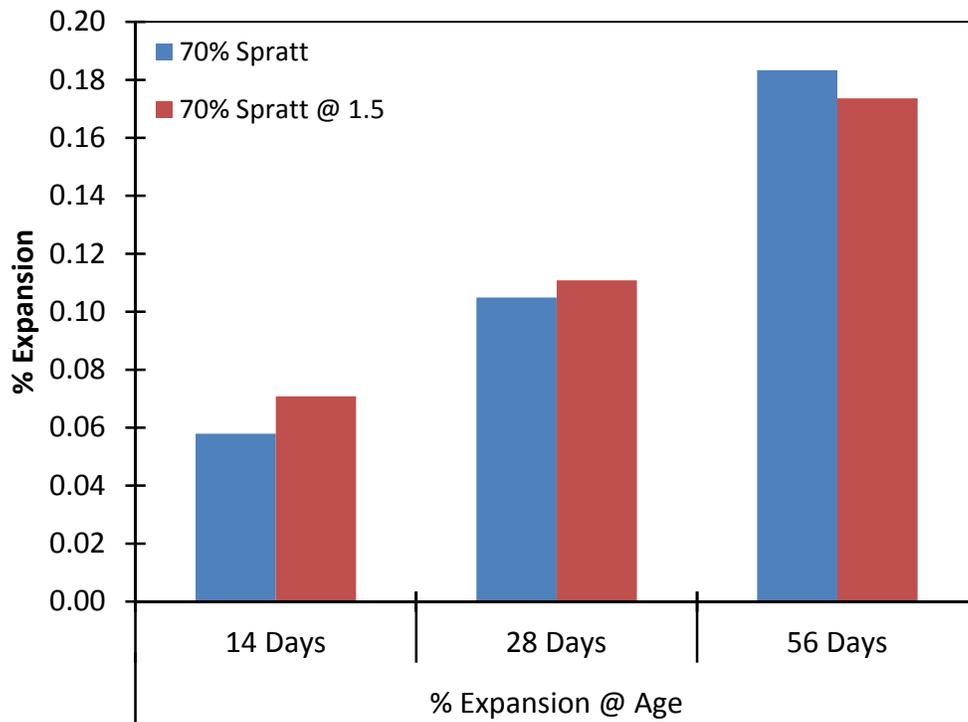


Figure 4.38 – Expansion of 70% virgin Spratt aggregate

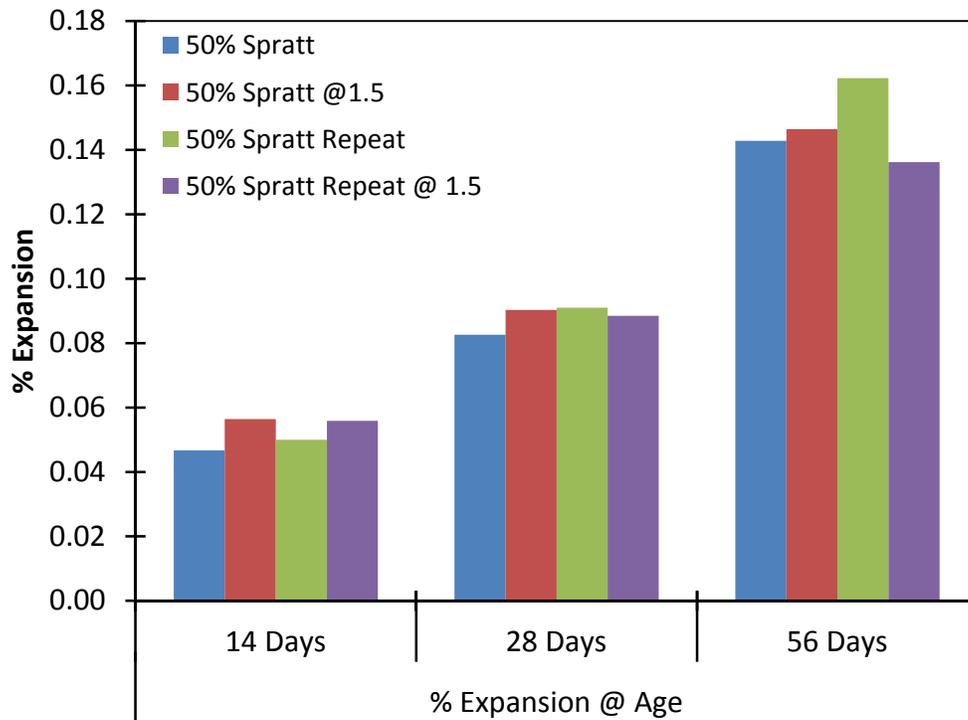


Figure 4.39 – Expansion of 50% virgin Spratt aggregate

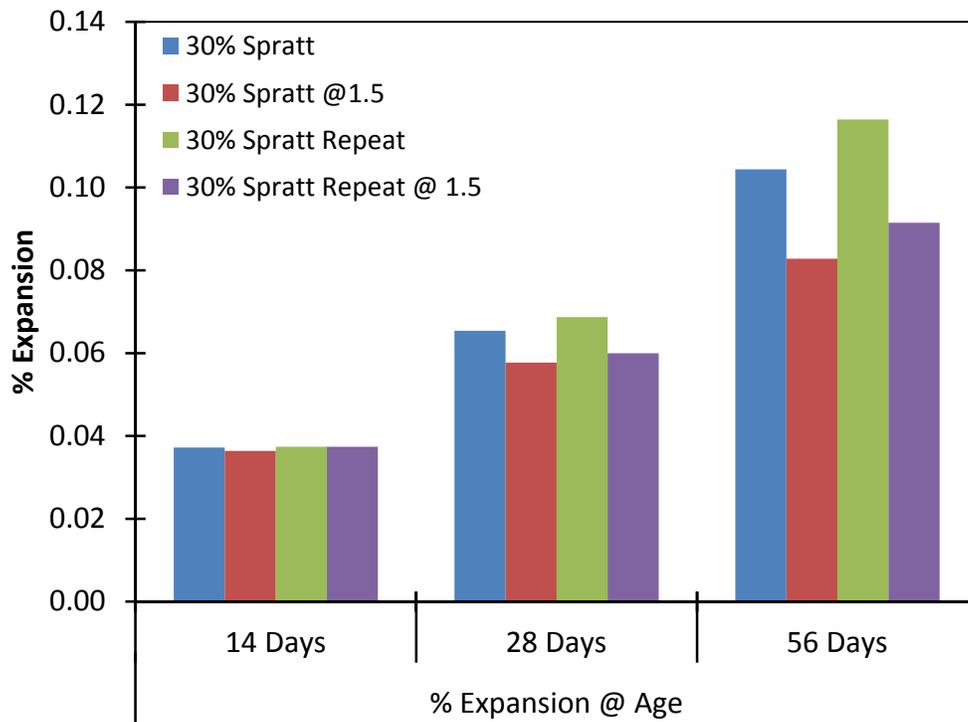


Figure 4.40 – Expansion of 30% virgin Spratt aggregate

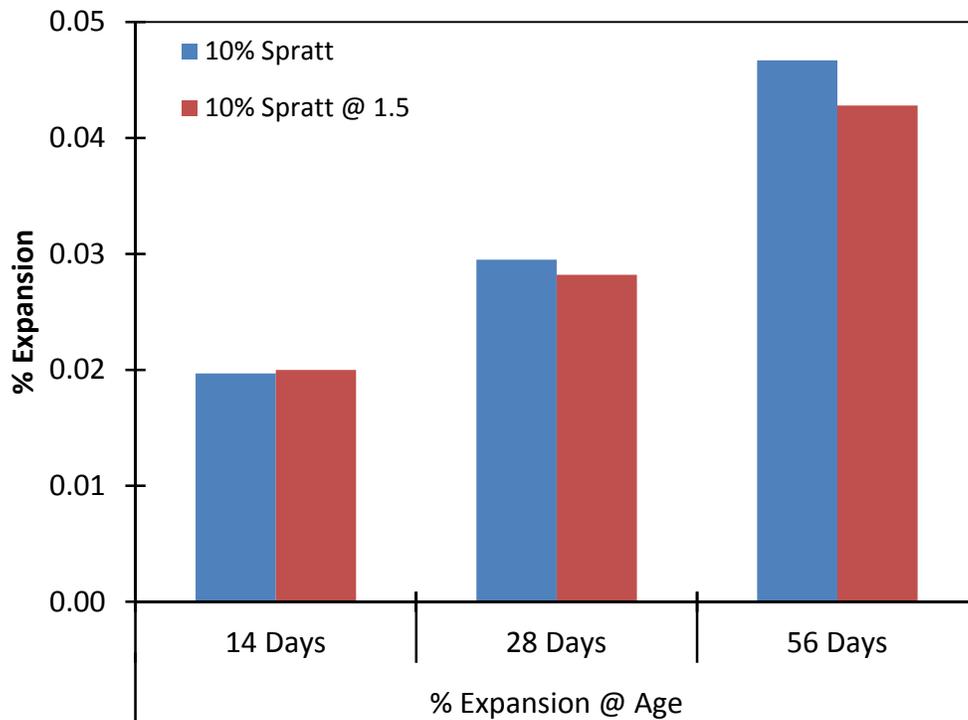


Figure 4.41 – Expansion of 10% virgin Spratt aggregate

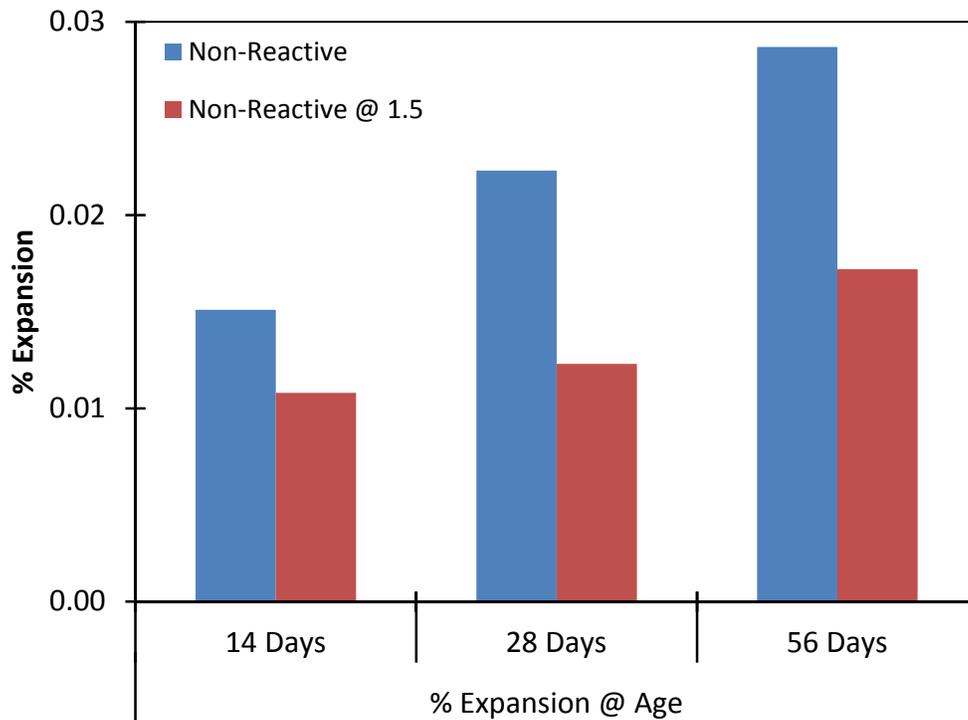


Figure 4.42 – Expansion of Non-Reactive aggregate

4.2.2.3 –Expansion of Virgin Spratt with SCM Concrete Microbar Test Results

As was discussed in Section 2.1.3.4 the increased paste content of the CMBT creates an overabundance of SCM if normal replacements are used. It was shown that based on the ratio of SCM to reactive aggregate; the CMBT has more than double the ratio of either the CPT or AMBT. To evaluate the veracity of this hypothesis, tests were conducted with 100% Spratt aggregate and various SCM's. The SCM's were used at normal replacement rates and at a modified replacement rate (EQ.) using a factor of 0.425, which represents the average of the SCM/reactive aggregate ratio for the CPT and AMBT. The SCM's used were GGBFS (Slag), Class C Fly Ash (HCFA) and Class F Fly Ash (LCFA), chemical analysis of the SCM's can be found in Table 3.8 in Section 3.6

The % expansion of the CMBT test specimens at 14, 28 and 56 days, as well as the pass or fail of the 0.1% expansion criteria at 28 days is shown in Table 4.18. Specimens that fail are likely to cause deleterious expansion if used in concrete. Figure 4.43 and Figure 4.44 clearly show that the

variation is most pronounced in the SCM blends that were expected to be effective in mitigating ASR expansion. The HCFA and Slag blends showed very little change in the expansion at 28 days even though the replacement of SCM was reduced by nearly 60%. The LCFA blends show a very large variation in expansions, 124% and 186% for 25% and 30% LCFA respectively. The results also indicate opposing pass/fail results. These results will be further discussed in Section 4.2.4.

Table 4.18 – Expansion of virgin Spratt with SCM

| <i>RCA Designation</i> | <i>% Expansion @ Age</i> | | | <i>Pass/Fail @ 28d</i> |
|------------------------|--------------------------|----------------|----------------|------------------------|
| | <i>14 Days</i> | <i>28 Days</i> | <i>56 Days</i> | |
| 30% HCFA | 0.0897 | 0.1372 | 0.2128 | Fail |
| 30% EQ. HCFA | 0.0969 | 0.1500 | 0.2464 | Fail |
| 30% Slag | 0.0626 | 0.1049 | 0.1954 | Fail |
| 30% EQ. Slag | 0.0700 | 0.1182 | 0.2054 | Fail |
| 25% LCFA | 0.0262 | 0.0531 | 0.1097 | Pass |
| 25% EQ. LCFA | 0.0731 | 0.1192 | 0.2044 | Fail |
| 30% LCFA | 0.0203 | 0.0390 | 0.0849 | Pass |
| 30% EQ. LCFA | 0.0638 | 0.1115 | 0.1844 | Fail |

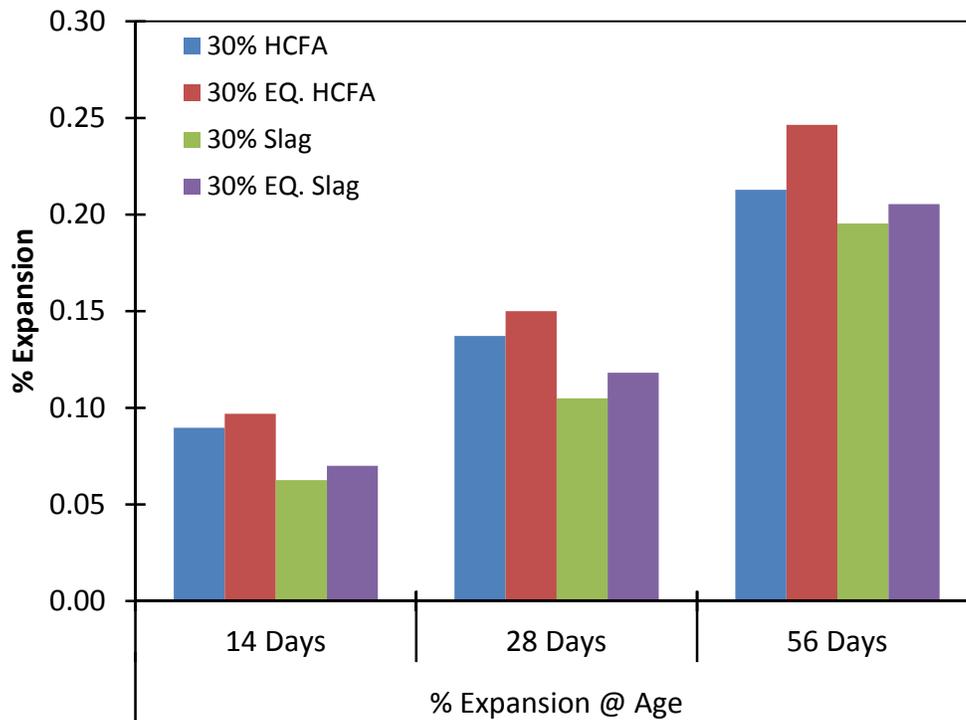


Figure 4.43 – Variation in expansion due to modified replacement SCM for HCFA and Slag

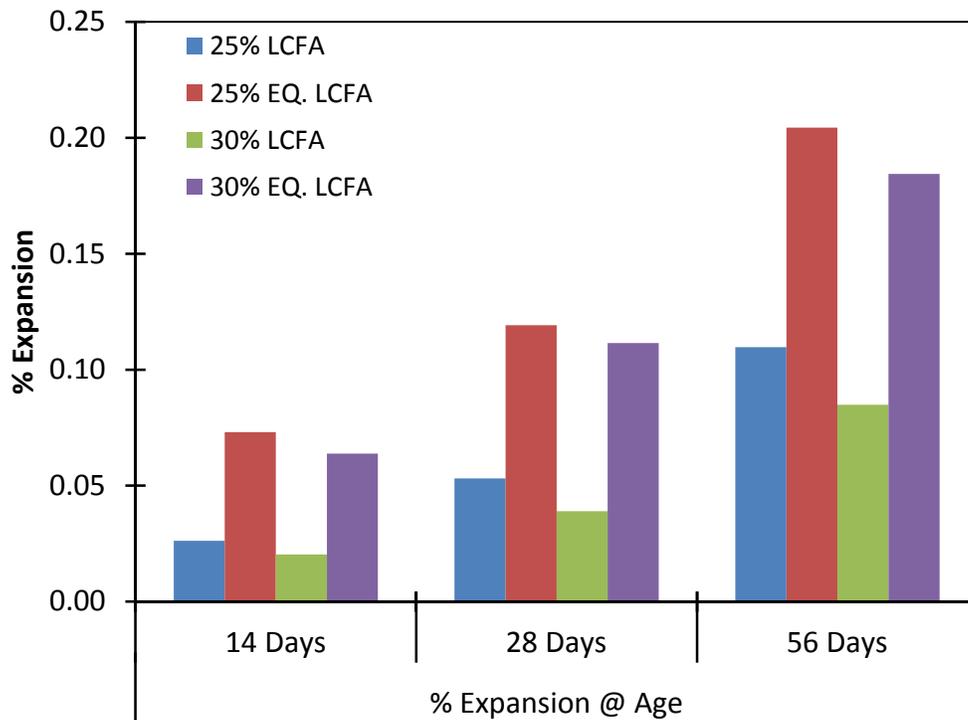


Figure 4.44 – Variation in expansion due to modified replacement SCM for LCFA

4.2.2.4 – Comparison of Concrete Microbar Test Results to CPT Results

Using an existing database of CPT results allowed for the comparison of expansion in Spratt CMBT specimens to the expansion of reference Spratt CPT specimens. For this comparison, the expansion and age results were factored to equivalent units. Age was expressed as a percentage of the limit age and expansion as a percentage of the expansion limit. For the CPT the limits were 0.04% expansion at 1 year, and for CMBT the limits were 0.1% expansion at 28 days. CPT results were available for 100%, 70% and 50% Spratt aggregate. The CPT results are shown as a line representing the expansion at 1 year.

The % expansion graph of the CMBT test specimens to an age of 56 days, representing 200% of the limit age, is shown in Figures 4.45, 4.46 and 4.47 compared to the 1 year CPT expansion. Figure 4.45 shows the difference in the expansion of the CPT at the limit age in comparison to the CMBT tests for 100% Spratt. The average expansion of both normal and raised alkali Spratt CMBT tests is 145% of the allowable expansion at 28 days and the expansion of Spratt CPT

specimens is 504% of the allowable expansion at 1 year. However, the results both indicate that a plain concrete made with 100% Spratt aggregate is likely to cause deleterious expansion. Figure 4.46 shows the difference in the expansion of the CPT at the limit age in comparison to the CMBT tests for 70% Spratt. The average expansion of both normal and raised alkali Spratt CMBT tests is 108% of the allowable expansion at 28 days and the expansion of Spratt CPT specimens is 368% of the allowable expansion at 1 year. However, the results both indicate that a plain concrete made with 70% Spratt aggregate is likely to cause deleterious expansion. Figure 4.47 shows the difference in the expansion of the CPT at the limit age in comparison to the CMBT tests for 50% Spratt. The average expansion of both normal and raised alkali Spratt CMBT tests is 86% of the allowable expansion at 28 days and the expansion of Spratt CPT specimens is 347% of the allowable expansion at 1 year. The CMBT indicates that a plain concrete made with 50% Spratt aggregate is not likely to cause deleterious expansion yet the CPT clearly indicates the opposite. The overall results indicate the CMBT is underestimating the expansion of Spratt aggregate compared to the CPT. This result will be further discussed in Section 4.2.4.

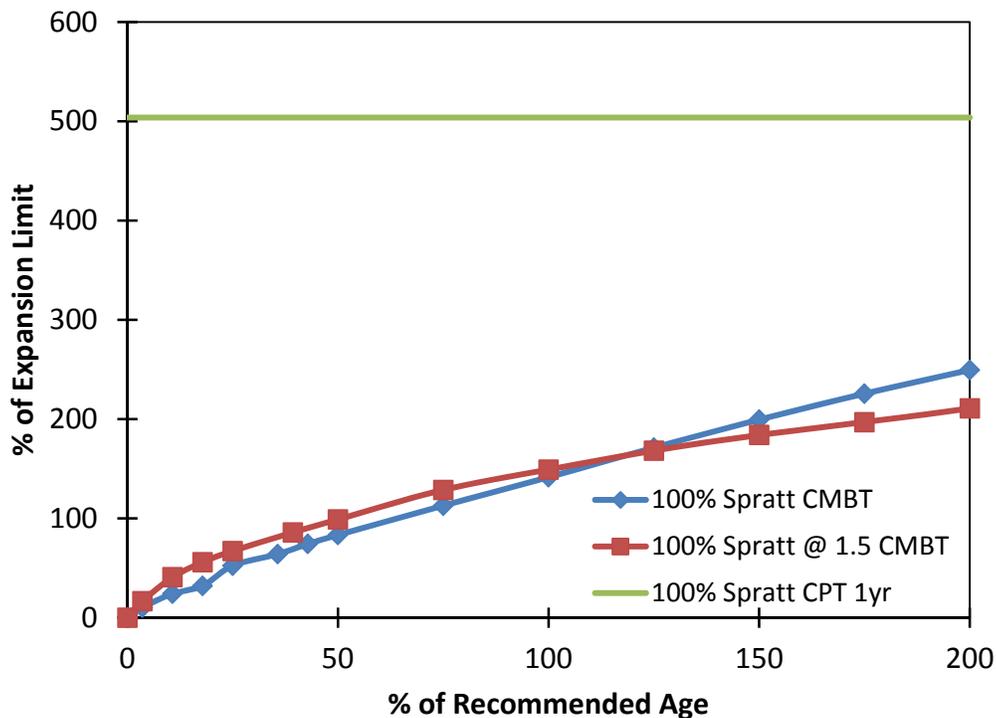


Figure 4.45 – Expansion of 100% virgin Spratt aggregate in CPT and CMBT

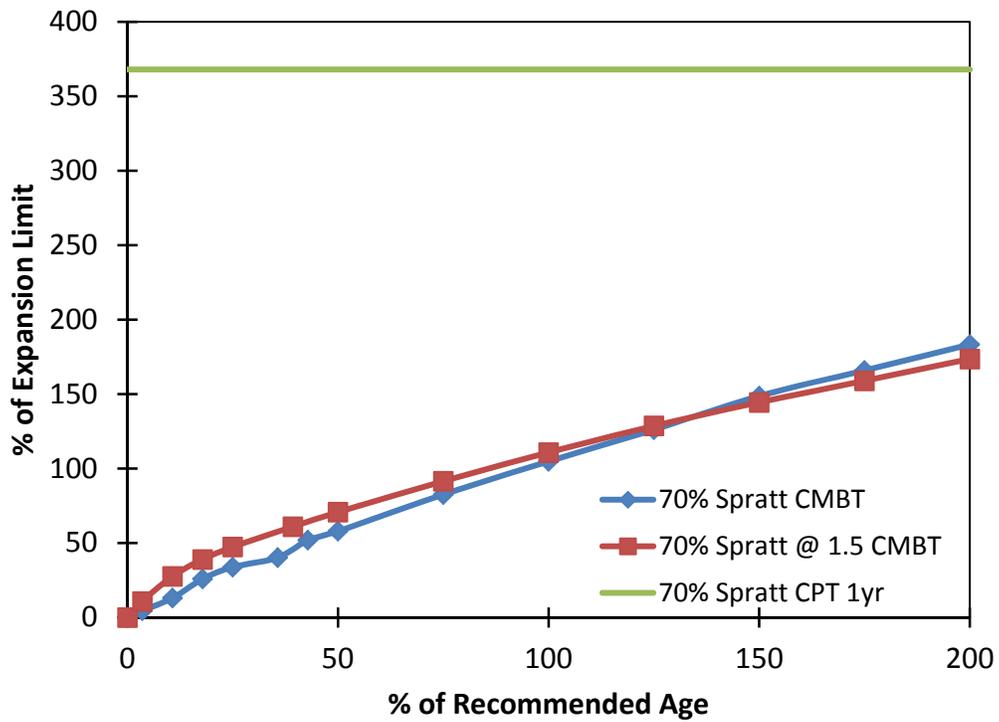


Figure 4.46 – Expansion of 70% virgin Spratt aggregate in CPT and CMBT

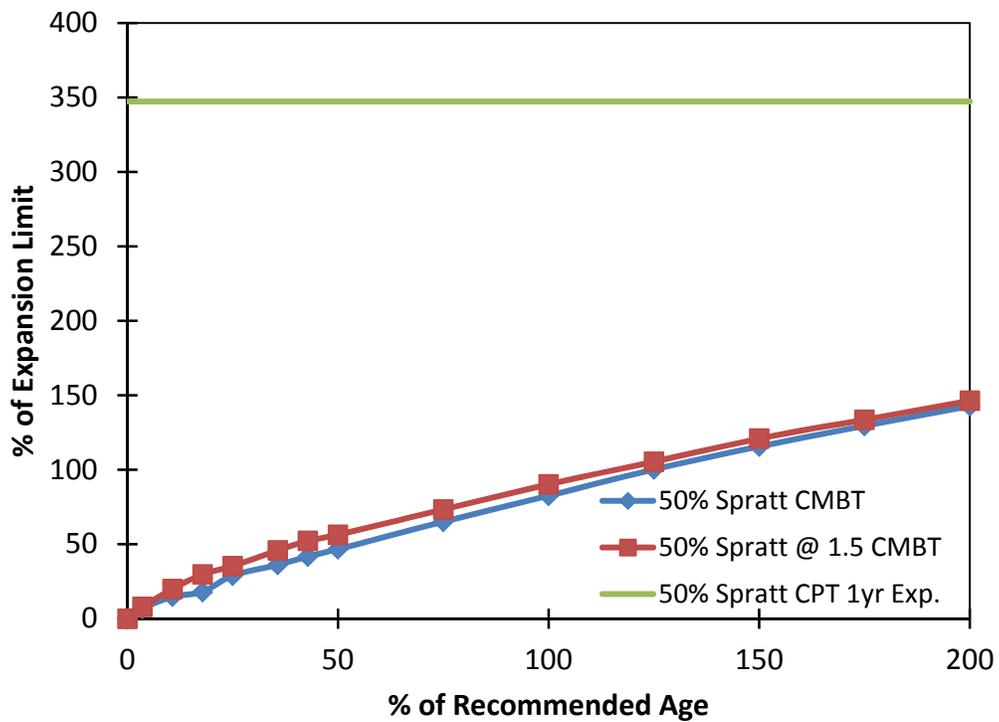


Figure 4.47 – Expansion of 50% virgin Spratt aggregate in CPT and CMBT

4.2.3 – Recycled Concrete Aggregate Concrete Microbar Test Results

4.2.3.1 – CMBT Results of RCA from Ottawa Test Blocks

The exact gradation of aggregate selected for use in the CMBT may result in some variation between tests. Selecting a finer grade of RCA using 13.2mm – 9.5mm and 9.5mm – 4.75mm (5-10) as opposed a coarser grade of RCA using 20mm – 13.2mm and 13.2mm – 9.5mm (10-14) created a more easily placed batch due to the 40mm mould size. For this phase of testing, the fine, (5–10) and coarse (10–14) specimens were used for testing. Corrections for RCA absorption were made using the same absorption values as in Sections 4.1.2 and 4.1.3.

The % expansion graph of the CMBT test specimens to an age of 56 days is shown in Figure 4.48 and Figure 4.49. The % expansion of the CMBT test specimens at 14, 28 and 56 days, as well as the pass or fail of the 0.1% expansion criteria at 28 days is shown in Table 4.19 below. Specimens that fail are likely to cause deleterious expansion if used in plain concrete. The testing showed that regardless of the gradation used, the pass/fail criteria agreed. Unlike the AMBT, the CMBT indicates that Potsdam RCA is likely to cause expansion as would be expected due to its high reactivity in the CPT. These results will be further discussed in Section 4.2.4.

Table 4.19 – Expansion of RCA from Ottawa Test Blocks in CMBT

| <i>RCA Designation</i> | <i>% Expansion @ Age</i> | | | <i>Pass/Fail @ 28d</i> |
|------------------------|--------------------------|----------------|----------------|------------------------|
| | <i>14 Days</i> | <i>28 Days</i> | <i>56 Days</i> | |
| Alberta RCA 5-10 | 0.0685 | 0.1292 | 0.2200 | Fail |
| Alberta RCA 10-14 | 0.0610 | 0.1079 | 0.1890 | Fail |
| Bernier RCA 5-10 | 0.0485 | 0.0856 | 0.1549 | Pass |
| Bernier RCA 10-14 | 0.0390 | 0.0697 | 0.1338 | Pass |
| Potsdam RCA 5-10 | 0.0638 | 0.1205 | 0.2151 | Fail |
| Potsdam RCA 10-14 | 0.0556 | 0.1072 | 0.1915 | Fail |
| Springhill RCA 5-10 | 0.0792 | 0.1415 | 0.2372 | Pass |
| Springhill RCA 10-14 | 0.0610 | 0.1069 | 0.1823 | Pass |

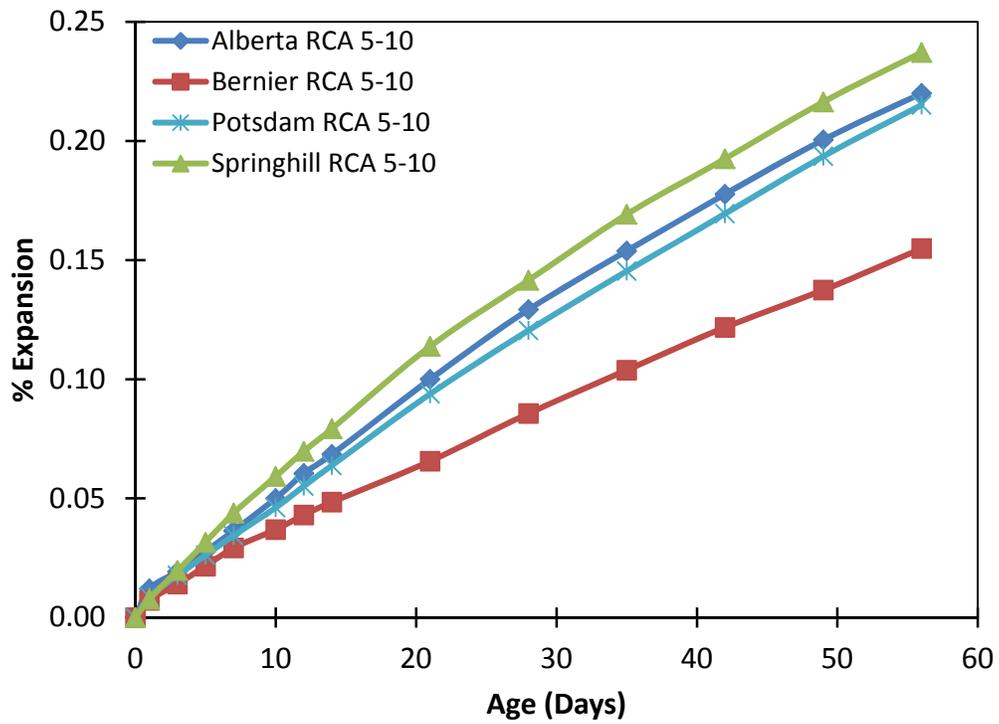


Figure 4.48 – Expansion of fine graded RCA from Ottawa Test Blocks in CMBT

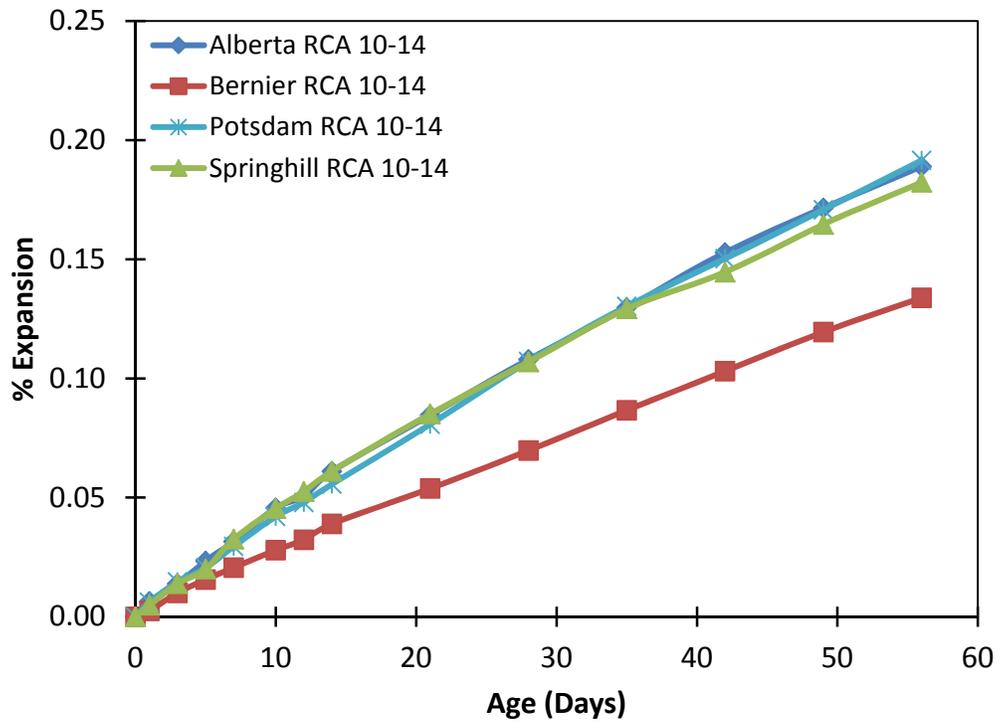


Figure 4.49 – Expansion of coarse graded ILS RCA in CMBT

4.2.3.2 – Variation due to Gradation of RCA from Ottawa Test Blocks CMBT Results

The fine, (5–10) and coarse (10–14) specimens were prepared for comparison. Corrections for RCA absorption were made using the same absorption values as in Sections 4.1.2 and 4.1.3. The variation of the coarse and fine specimens will be compared to the requirement of 8.3% of the mean value for allowable variation found in the ASTM C1260 test since there is no published standard for the CMBT.

Figure 4.50 shows some variation between fine and coarse Alberta RCA specimens. The discrepancy at 28 days age between coarse and fine specimens was 0.0213% and the allowable variation is 0.098% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is not within the allowed range. Figure 4.51 shows some variation between fine and coarse Bernier RCA specimens. The discrepancy at 28 days age between coarse and fine specimens was 0.0159% and the allowable variation is 0.064% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is not within the allowed range. The results of Grattan-Bellew 2003, (G.B. 2003) using the virgin Bernier aggregate, yielded expansion results more than double those of this test program. Further, these results are contradictory since the Grattan-Bellew expansion values indicate the Bernier aggregate is likely to cause expansion.

Figure 4.52 shows some variation between fine and coarse Potsdam RCA specimens. The discrepancy at 28 days age between coarse and fine specimens was 0.0133% and the allowable variation is 0.094% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is not within the allowed range. The results of Grattan-Bellew 2003, (G.B. 2003) using the virgin Potsdam aggregate, yielded expansion results slightly less than those of this test program and easily within the multi-laboratory variation requirements. Figure 4.53 shows some variation between fine and coarse Springhill RCA specimens. The discrepancy at 28 days age between coarse and fine specimens was 0.0346% and the allowable variation is 0.103% (8.3% of mean expansion) allowed by ASTM C1260 for single laboratory variation. Therefore the variation between the specimens is not within the allowed range. The results of Grattan-Bellew 2003, (G.B. 2003) using the virgin

Springhill aggregate, yielded expansion results similar to those of this test program and easily within the multi-laboratory variation requirements. The results show that the fine gradation will yield more expansion than the coarse gradation. These results will be further discussed in Section 4.2.4.

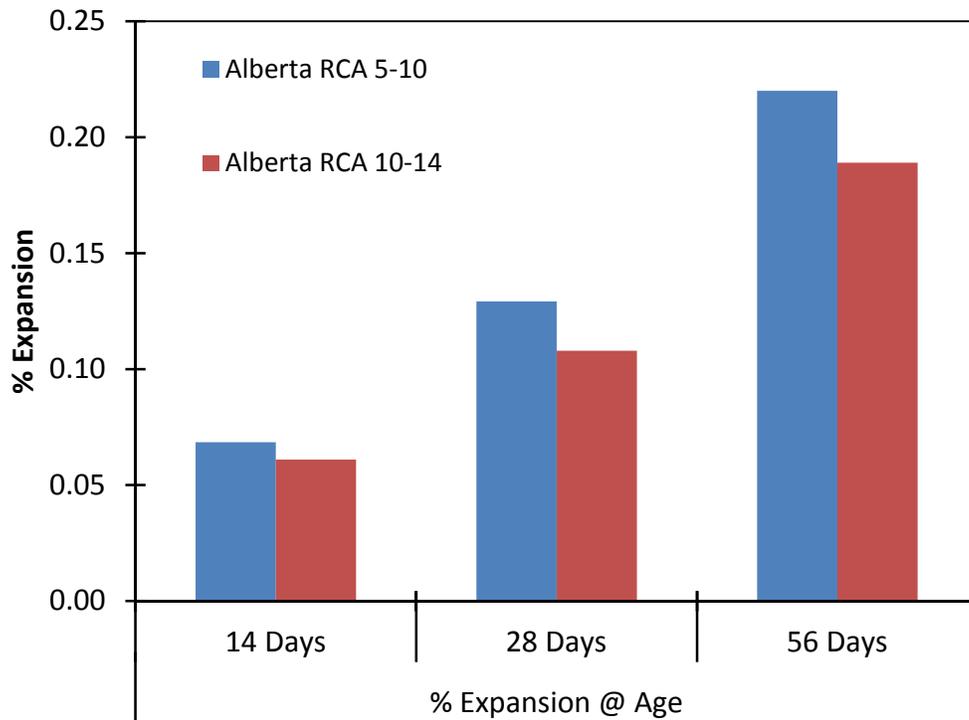


Figure 4.50 – Expansion of fine and coarse graded Alberta RCA in CMBT

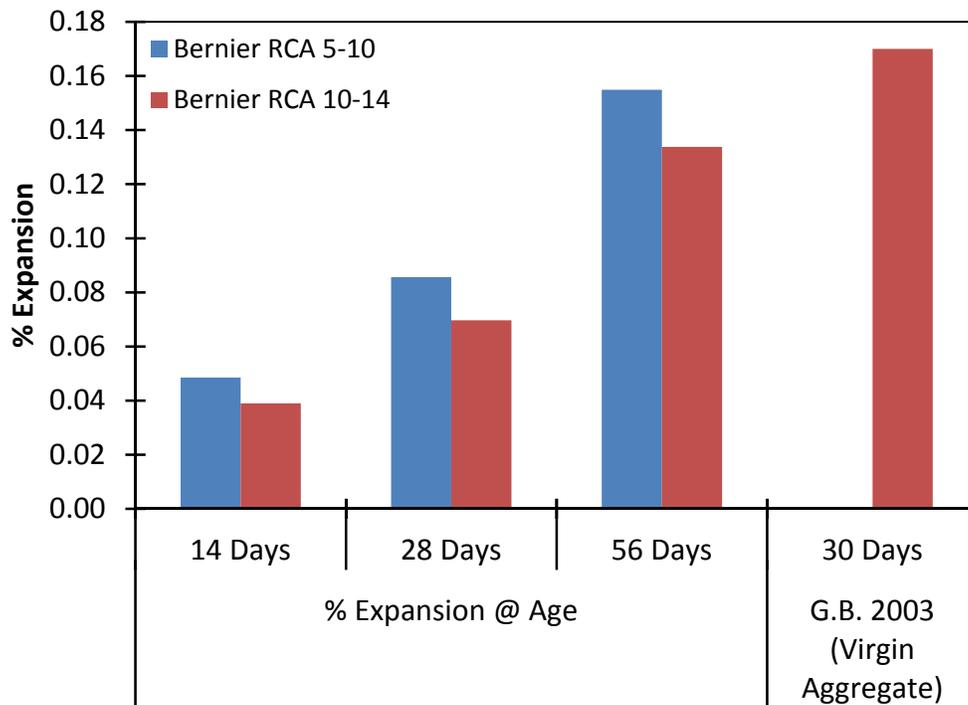


Figure 4.51 – Expansion of fine and coarse graded Bernier RCA in CMBT

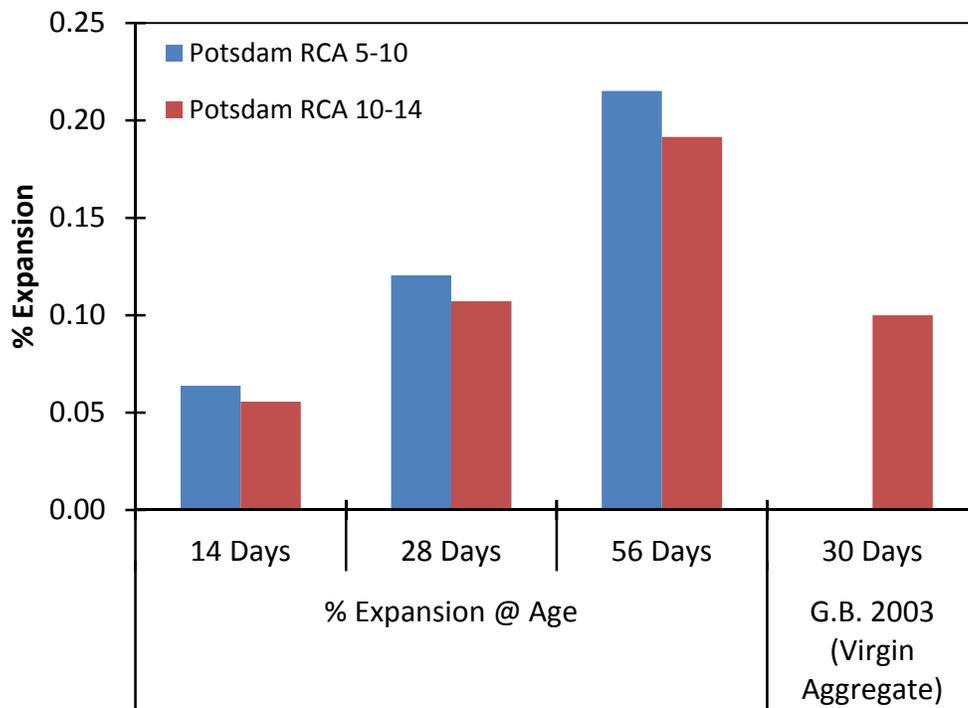


Figure 4.52 – Expansion of fine and coarse graded Potsdam RCA in CMBT

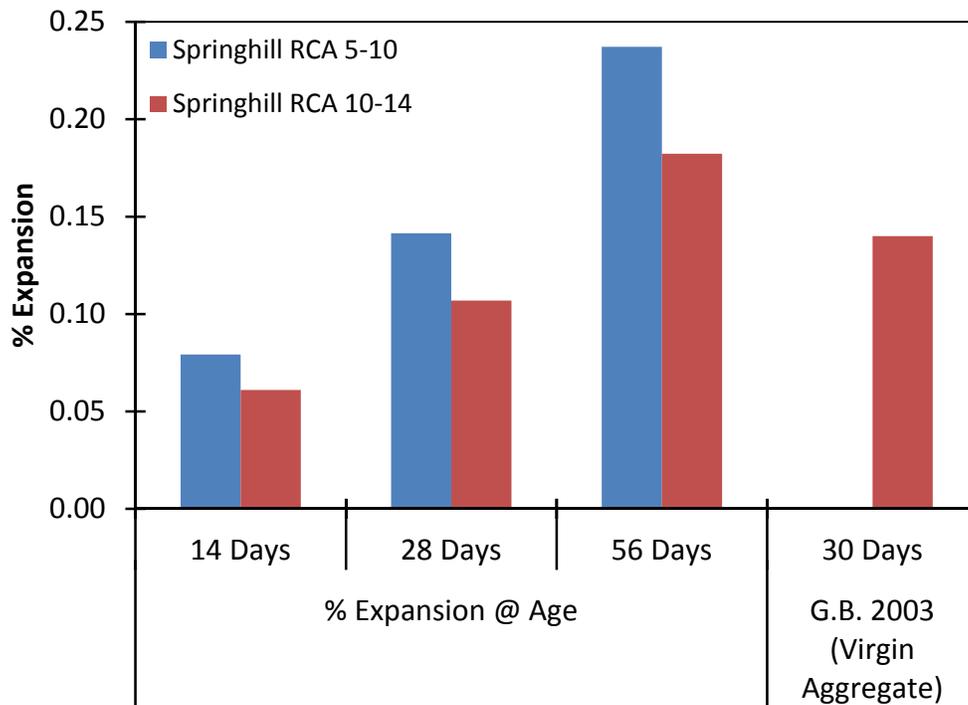


Figure 4.53 – Expansion of fine and coarse graded Springhill RCA in CMBT

4.2.3.3 – Variation between CMBT and AMBT Results of RCA from Ottawa Test Blocks

The results for the ILS RCA CMBT testing can be compared to the results found in Section 4.1 to evaluate the effectiveness of the CMBT in comparison to the AMBT. For this comparison, the expansion was presented at the limit age for each test. The limit age is 14 days for the AMBT and 28 days for the CMBT. Since the expansion limit is the same at the limit age, no modifications to the % expansion were required.

Figure 4.54 shows that Alberta RCA CMPT specimens are not comparable to the AMBT coarse results. The expansions of the (5-10) and (10-14) CMBT specimens are 59% and 66% lower respectively than that of the AMBT coarse specimens. They are more comparable to the AMBT fine results which are considered unreliable as discussed in Section 4.1.7. However, the overall results of the specimens all provide a valid screening of the RCA on the pass/fail result. Figure 4.55 shows that Bernier RCA CMPT specimens are not comparable to the AMBT coarse results. The expansions of the (5-10) and (10-14) CMBT specimens are 24% and 38% lower respectively

than that of the AMBT coarse specimens. They are more comparable to the AMBT fine results which are considered unreliable as discussed in Section 4.1.7. The overall results of the specimens do not provide a valid screening of the RCA on the pass/fail result since only the coarse AMBT indicates a failure.

Figure 4.56 shows that Potsdam RCA CMPT specimens are not comparable to the AMBT coarse results. The expansions of the (5-10) and (10-14) CMBT specimens are 70% and 51% higher respectively than that of the AMBT coarse specimens. The CMBT results do however indicate that the Potsdam RCA is likely to cause deleterious expansion in concrete which the AMBT was not able to do even though this was the expected result. Figure 4.57 shows that Springhill RCA CMPT specimens are not comparable to the AMBT coarse results. The expansions of the (5-10) and (10-14) CMBT specimens are 56% and 67% lower respectively than that of the AMBT coarse specimens. They are more comparable to the AMBT fine results which are considered unreliable as discussed in Section 4.1.7. However, the overall results of the specimens all provide a valid screening of the RCA on the pass/fail result. The results were varied in comparison of the ILS RCA CMBT and AMBT results. The results of the CMBT are not comparable to the AMBT coarse results in these scenarios but still provided reasonable results in pass/fail criteria. These results will be further discussed in Section 4.2.4.

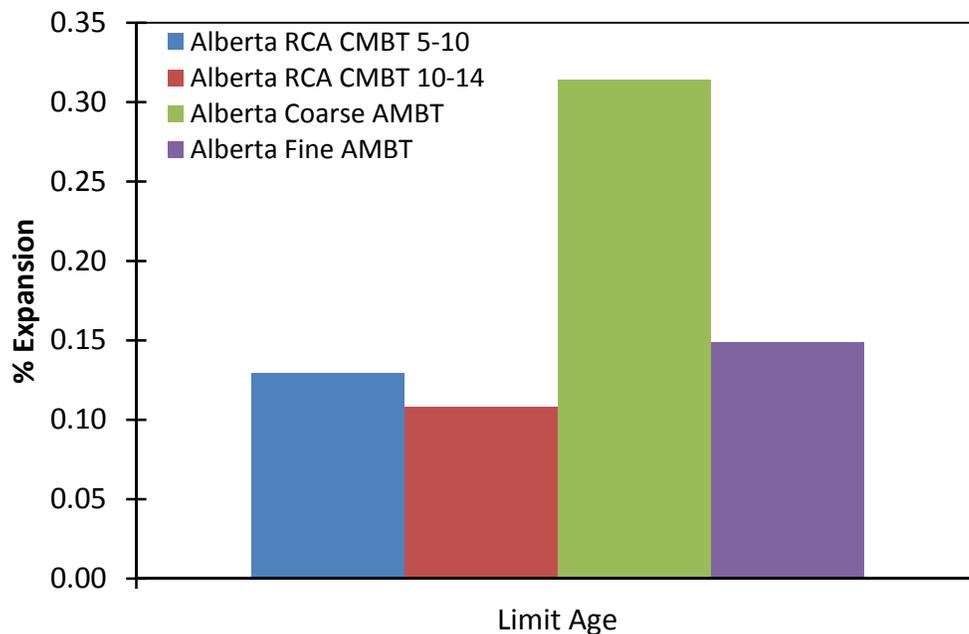


Figure 4.54 – Variation in expansion for Alberta RCA CMBT and AMBT

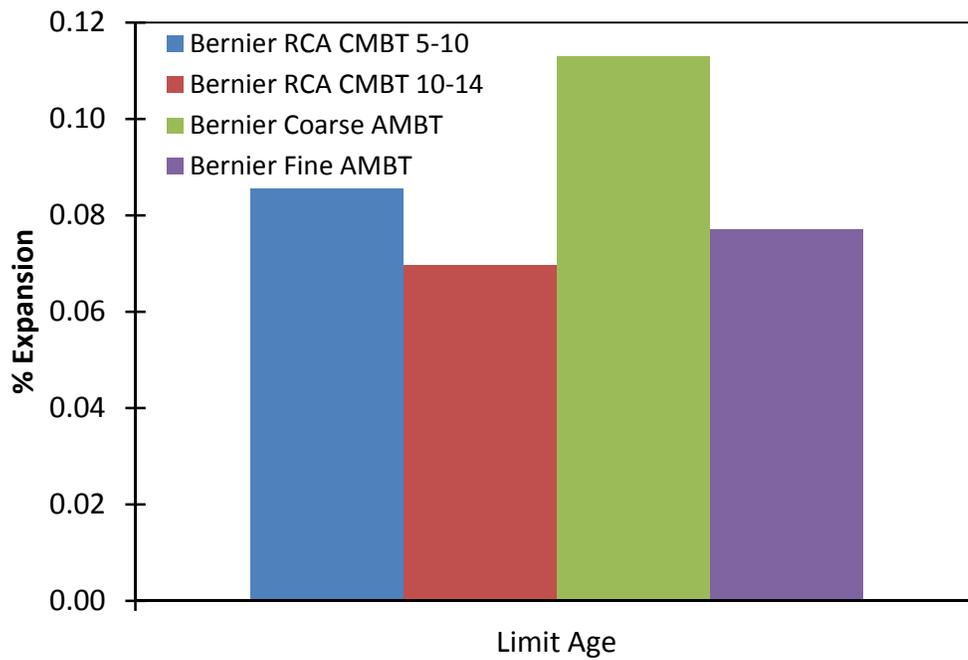


Figure 4.55 – Variation in expansion for Bernier RCA CMBT and AMBT

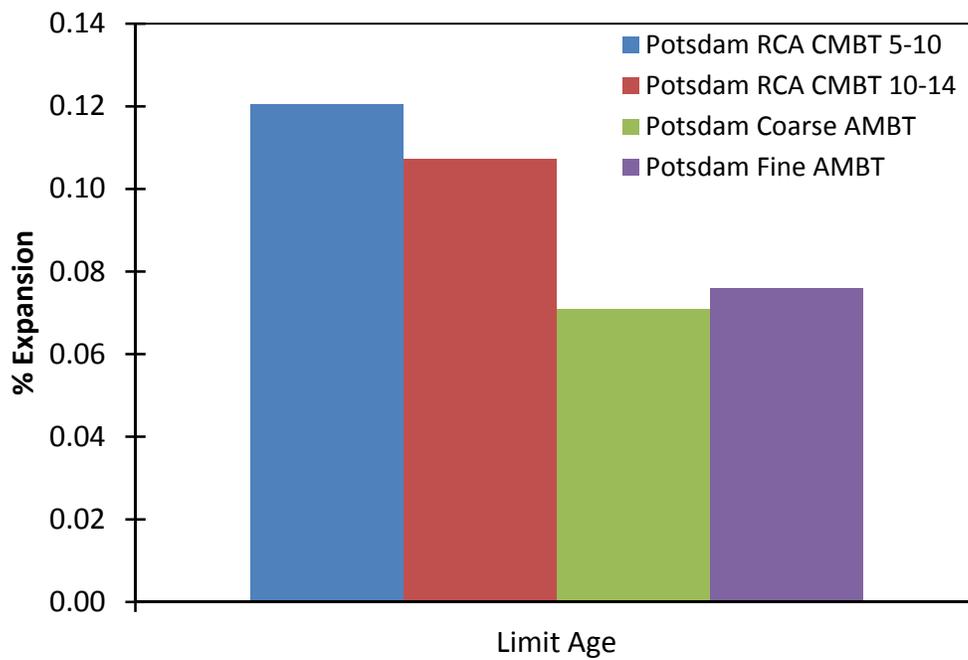


Figure 4.56 – Variation in expansion for Potsdam RCA CMBT and AMBT

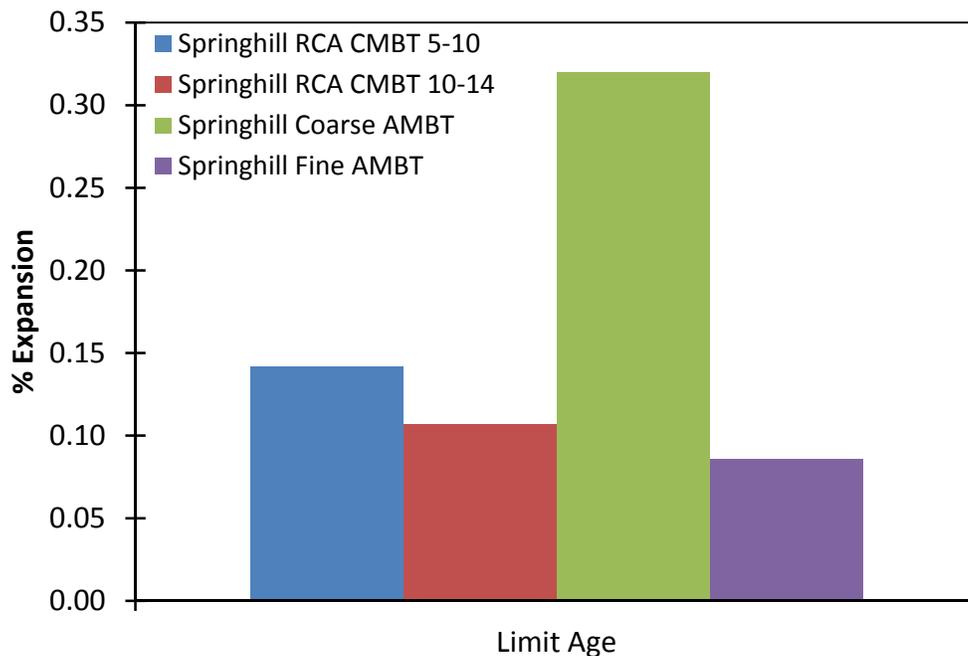


Figure 4.57 – Variation in expansion for Springhill RCA CMBT and AMBT

4.2.3.4 – 100% Spratt RCA CMBT Results

For this phase of the study, CMBT specimens were made using 100% Spratt RCA and ternary blends of cement. The ternary blends were selected to correlate to an existing database of CPT results. Absorption of the RCA was calculated as 5.13% using the procedure outlined in ASTM C128. The following SCM blends were tested; 20% LCFA & 30% Slag, 5% SF & 45% Slag, 5% SF & 30% LCFA, 5% SF & 20% LCFA, and 5% SF and 25% Slag. A repeat test of 5% SF & 20% LCFA was conducted with the alkali raised to 1.5%.

The % expansion graph of the CMBT test specimens to an age of 56 days is shown in Figure 4.58 and Figure 4.59. The % expansion of the CMBT test specimens at 14, 28 and 56 days, as well as the pass or fail of the 0.1% expansion criteria at 28 days is shown in Table 4.20. Specimens that fail are likely to cause deleterious expansion if used in concrete. The expansion results for 5% SF & 20% LCFA raised alkali with 100% Spratt RCA are not included in the

graphs since further investigation revealed that SF agglomerations had produced ASR expansion in the raised alkali specimens thus the results were omitted. The results all indicated that all of the selected SCM ternary blends would be effective in mitigating ASR expansion. However, the database of CPT results indicated that some of these blends should not be effective. These results will be further discussed in Section 4.2.4.

Table 4.20 – Expansion of 100% Spratt RCA with SCM in CMBT

| <i>RCA Designation</i> | <i>% Expansion @ Age</i> | | | <i>Pass/Fail @ 28d</i> |
|-----------------------------------|--------------------------|----------------|----------------|------------------------|
| | <i>14 Days</i> | <i>28 Days</i> | <i>56 Days</i> | |
| 20% LCFA & 30% Slag | 0.0241 | 0.0405 | 0.0695 | Pass |
| 5% SF & 45% Slag | 0.0256 | 0.0444 | 0.0833 | Pass |
| 5% SF & 30% LCFA | 0.0256 | 0.0446 | 0.0818 | Pass |
| 5% SF & 20% LCFA | 0.0328 | 0.0603 | 0.1149 | Pass |
| 5% SF & 25% Slag | 0.0490 | 0.0823 | 0.1541 | Pass |
| 5% SF & 20% LCFA Raised Alkali | 0.0582 | 0.1205 | 0.2197 | Fail |

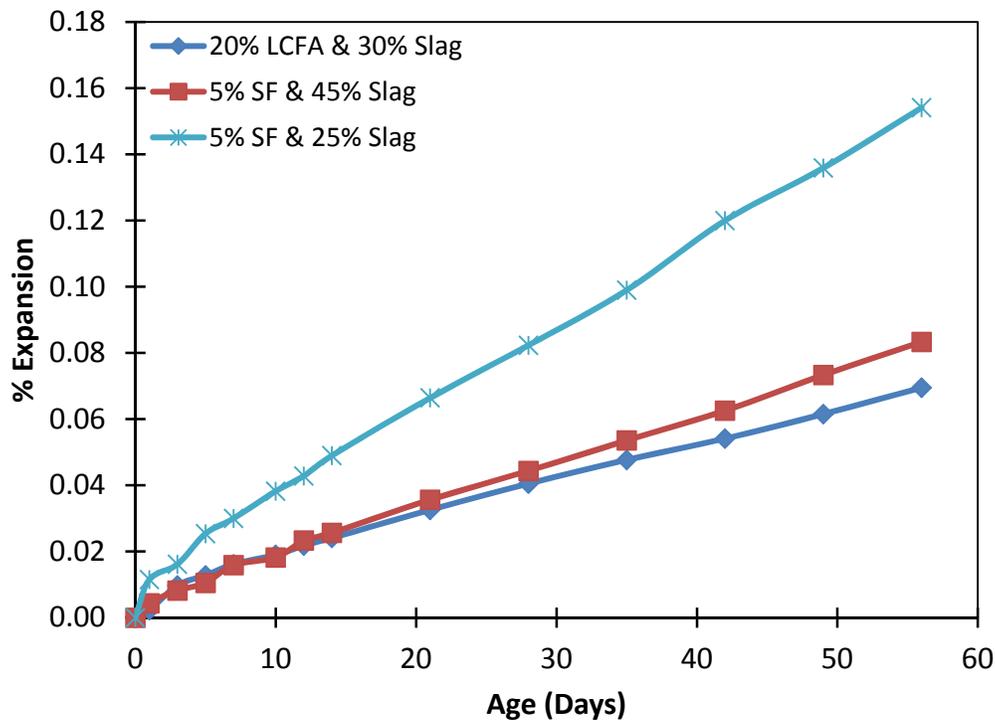


Figure 4.58 – Expansion of 100% Spratt RCA with SCM in CMBT

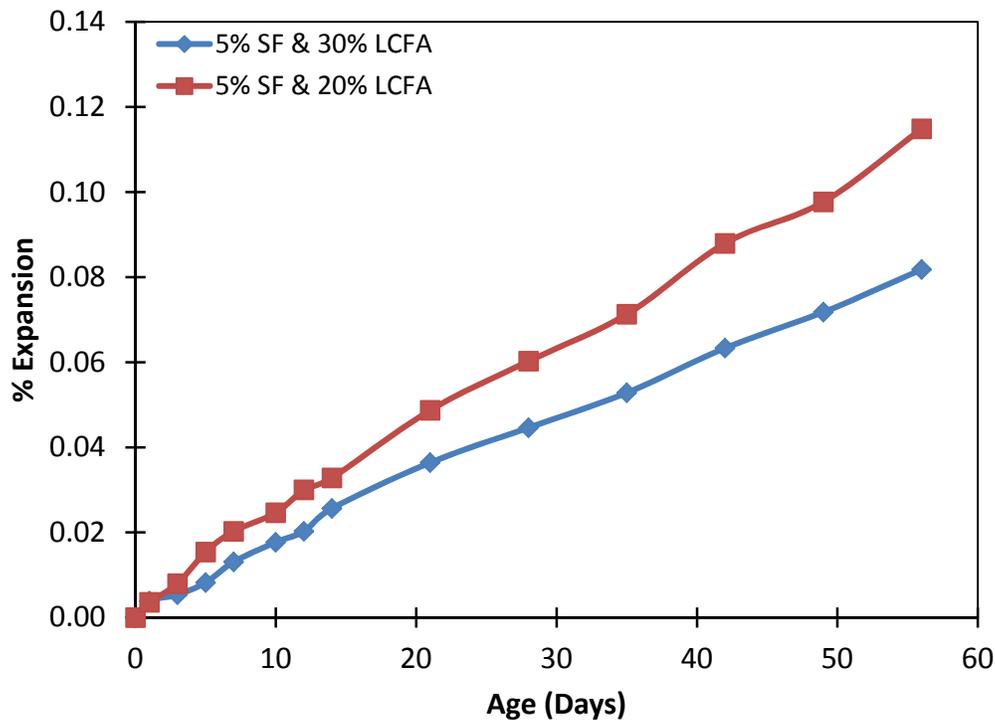


Figure 4.59 – Expansion of 100% Spratt RCA with SCM in CMBT

4.2.3.5 – Variation of 100% Spratt RCA CMBT and CPT Results

For this phase of the study, CMBT specimens were made using 100% Spratt RCA and ternary blends of cement. The ternary blends were selected to correlate to an existing database of CPT results. Absorption of the RCA was calculated as 5.13% using the procedure outlined in ASTM C128. The following SCM blends were tested; 20% LCFA & 30% Slag, 5% SF & 45% Slag, 5% SF & 30% LCFA, 5% SF & 20% LCFA, and 5% SF and 25% Slag. Upon analysis it became clear that as suggested, the CMBT results with SCM were underestimating the expansion results of the CPT.

Since the standard for using the CPT with SCM requires the limit age to be doubled to two years, it was hypothesized that the same would be applicable for CMBT with SCM to improve the correlation. The limit age for the CMBT in this phase of the study was increased to 56 days (Mod. Age). For this comparison, the expansion and age results were factored to equivalent units. Age was expressed as a percentage of the limit age and expansion as a percentage of the

expansion limit. For the CPT the limits were 0.04% expansion at 2 years, and for CMBT the limits were 0.1% expansion at 28 days for the standard and 0.1% expansion at 56 days for the modified age (Mod. Age) results. The CPT results are shown as a line representing the expansion at 2 years.

The % expansion graph of the CMBT test specimens to an age of 56 days, representing 200% of the standard limit age, is shown in Figures 4.60, 4.61, 4.62, 4.63 and 4.64 compared to the 2 year CPT expansion. The % expansion of the CMBT and CPT test specimens at 100% of the normal and modified limit age, as well as the pass or fail of the expansion limit at 100% of the limit age is shown in Table 4.21. Specimens that fail are likely to cause deleterious expansion if used in concrete. The results of the CPT indicate that a concrete made with 5% SF & 45% Slag and 100% Spratt RCA is likely to result in deleterious expansion but the CMBT does not. The results of the CPT and modified age CMBT indicate that a concrete made with 5% SF & 20% LCFA with 100% Spratt RCA is likely to result in deleterious expansion while the standard CMBT does not. The results of the CPT and modified age CMBT indicate that a concrete made with 5% SF & 25% Slag and 100% Spratt RCA is likely to result in deleterious expansion while the standard CMBT does not. Modifying the limit age of the CMBT when using SCM provides better correlation of results with the CPT. These results will be further discussed in Section 4.2.4.

Table 4.21 – Expansion of 100% Spratt RCA with SCM in CMBT

| <i>RCA Test Designation</i> | <i>CMBT Expansion % of Limit</i> | | <i>CPT Expansion % of Limit</i> | <i>Pass/Fail @ Limit Age (28/56/2)</i> |
|-----------------------------|--|-----------------------------------|---|--|
| | <i>Normal Limit 28d</i> | <i>Modified Limit 56d</i> | <i>Normal Limit 2y</i> | |
| 20% LCFA & 30% Slag | 40.5 | 69.5 | 88.7 | (P/P/P) |
| 5% SF & 45% Slag | 44.4 | 83.3 | 124 | (P/P/F) |
| 5% SF & 30% LCFA | 44.6 | 81.8 | 92.7 | (P/P/P) |
| 5% SF & 20% LCFA | 60.3 | 114.9 | 131 | (P/F/F) |
| 5% SF & 25% Slag | 82.3 | 154 | 181 | (P/F/F) |

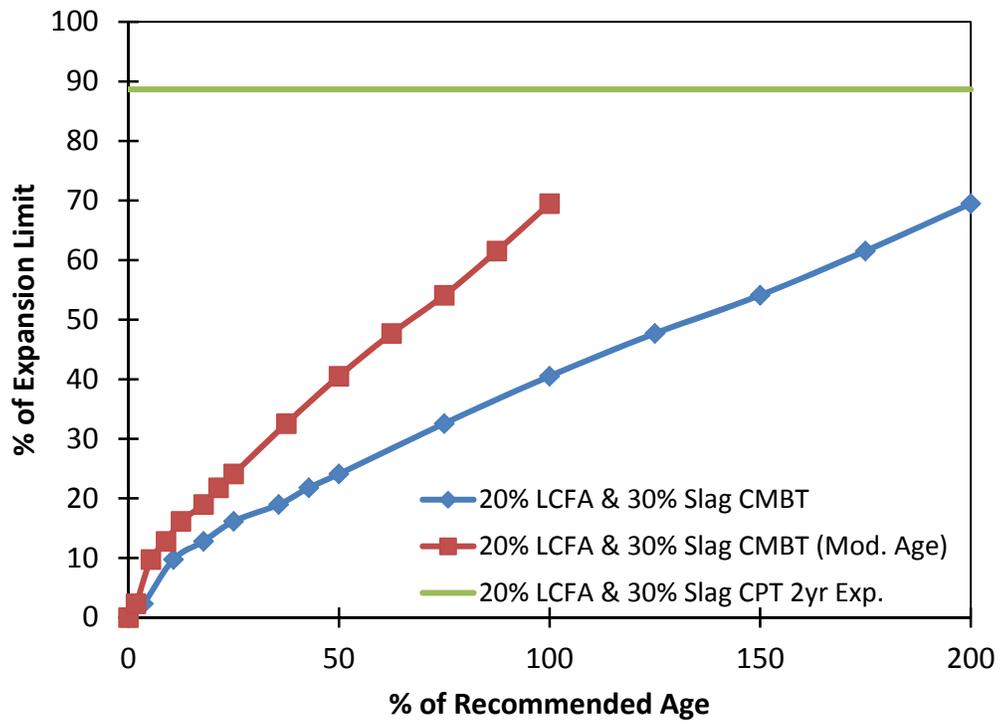


Figure 4.60 – Expansion of 100% Spratt RCA with 20% LCFA & 30% Slag in CMBT and CPT

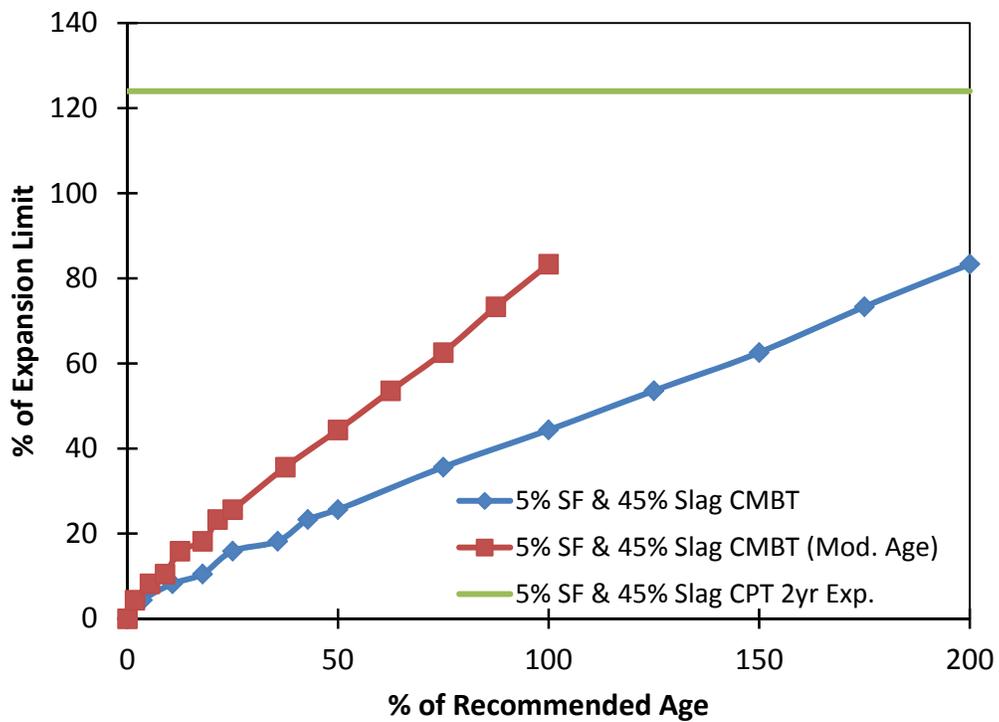


Figure 4.61 – Expansion of 100% Spratt RCA with 5% SF & 45% Slag in CMBT and CPT

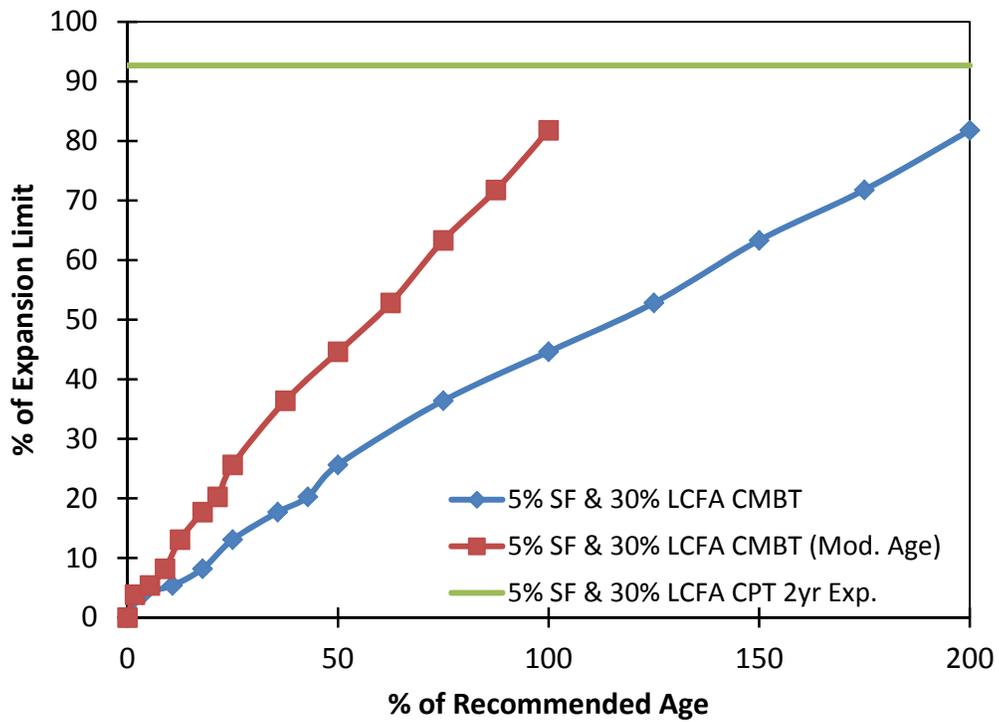


Figure 4.62 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in CMBT and CPT

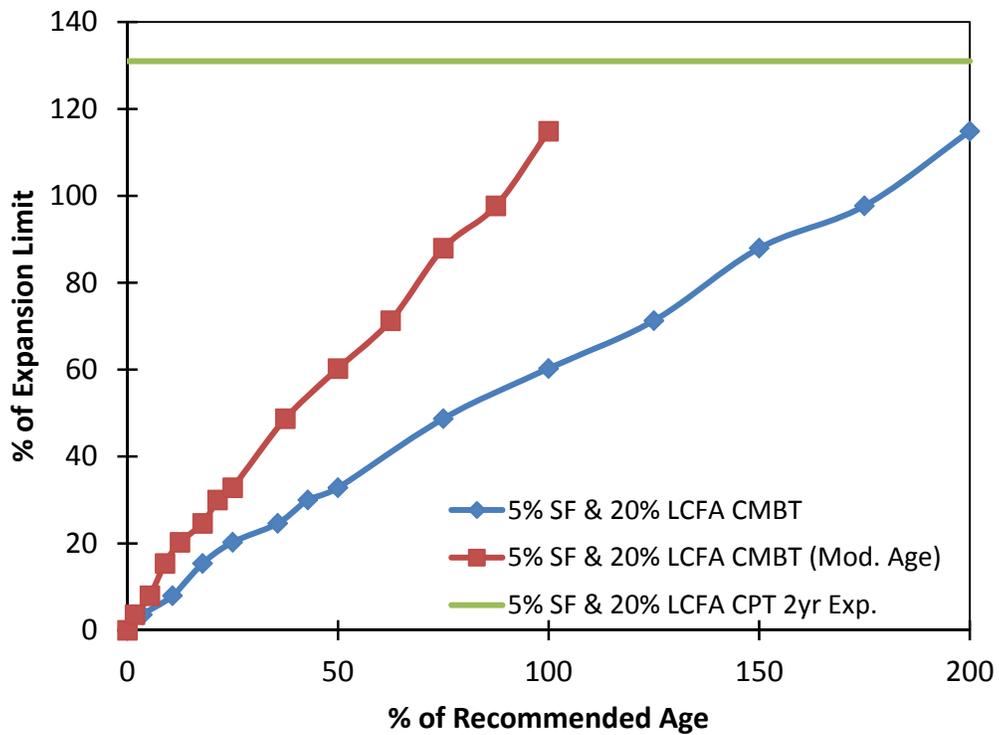


Figure 4.63 – Expansion of 100% Spratt RCA with 5% SF & 20% LCFA in CMBT and CPT

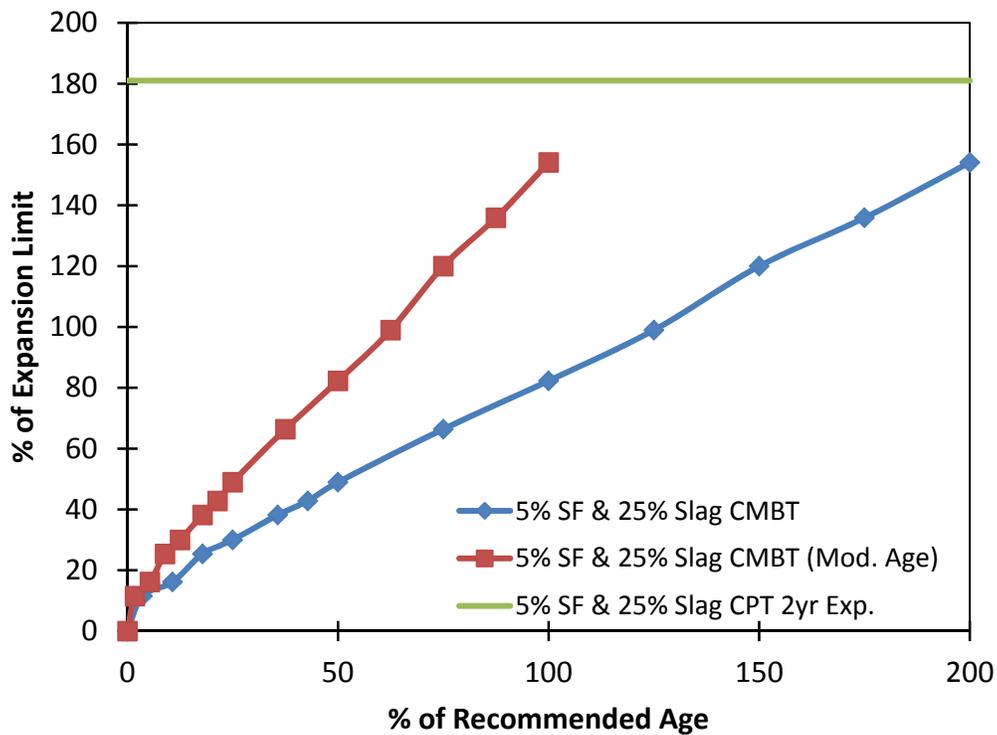


Figure 4.64 – Expansion of 100% Spratt RCA with 5% SF & 25% Slag in CMBT and CPT

4.2.3.6 – 70% Spratt RCA CMBT Results

For this phase of the study, CMBT specimens were made using 70% Spratt RCA with 30% non-reactive coarse aggregate and binary blends of cement. The binary blends were selected to correlate to an existing database of CPT results. Absorption of the RCA was calculated as 5.13% using the procedure outlined in ASTM C128. A set of control specimens made with cement and 70% Spratt RCA with 30% non-reactive coarse were created. Binary blends of 25% LCFA and 50% Slag with 70% Spratt RCA with 30% non-reactive coarse were also made. A repeat test of the control was conducted with the alkali raised to 1.5%.

The % expansion graph of the CMBT test specimens to an age of 56 days is shown in Figure 4.65. The % expansion of the CMBT test specimens at 14, 28 and 56 days, as well as the pass or fail of the 0.1% expansion criteria at 28 days is shown in Table 4.22. Specimens that fail are likely to cause deleterious expansion if used in concrete. The database of CPT results indicated

that some of these batches should not be effective. These results will be further discussed in Section 4.2.4.

Table 4.22 – Expansion of 70% Spratt RCA with SCM in CMBT

| <i>RCA Designation</i> | <i>% Expansion @ Age</i> | | | <i>Pass/Fail @ 28d</i> |
|------------------------------|--------------------------|----------------|----------------|------------------------|
| | <i>14 Days</i> | <i>28 Days</i> | <i>56 Days</i> | |
| 70% Spratt RCA | 0.0485 | 0.0859 | 0.1503 | Pass |
| 70% Spratt RCA @ 1.5 | 0.0572 | 0.0987 | 0.1656 | Pass |
| 70% Spratt RCA with 25% LCFA | 0.0333 | 0.0523 | 0.0931 | Pass |
| 70% Spratt RCA with 50% Slag | 0.0323 | 0.0546 | 0.1006 | Pass |

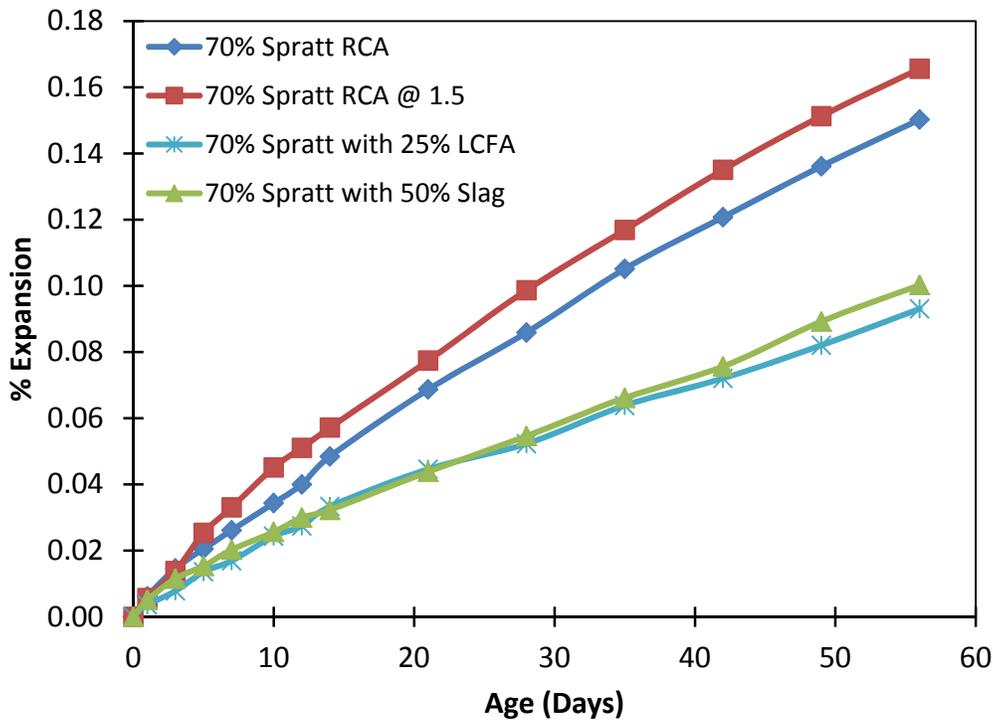


Figure 4.65 – Expansion of 70% Spratt RCA with SCM in CMBT

4.2.3.7 – Variation of 70% Spratt RCA CMBT and CPT Results

For this phase of the study, CMBT specimens were made using 70% Spratt RCA with 30% non-reactive coarse aggregate and binary blends of cement. The binary blends were selected to correlate to an existing database of CPT results. Absorption of the RCA was calculated as 5.13% using the procedure outlined in ASTM C128. A set of control specimens made with cement and

70% Spratt RCA with 30% non-reactive coarse were created. Binary blends of 25% LCFA and 50% Slag with 70% Spratt RCA with 30% non-reactive coarse were also made. A repeat test of the control was conducted with the alkali raised to 1.5%. Upon analysis it became clear that as suggested, the CMBT results with SCM were underestimating the expansion results of the CPT.

Since the standard for using the CPT with SCM requires the limit age to be doubled to two years, it was hypothesized that the same would be required for CMBT with SCM to improve the correlation. The limit age for the CMBT in this phase of the study was increased to 56 days (Mod. Age) when SCM was used. For this comparison, the expansion and age results were factored to equivalent units. Age was expressed as a percentage of the limit age and expansion as a percentage of the expansion limit. For the CPT the limits were 0.04% expansion at 2 years (1 year for control), and for CMBT the limits were 0.1% expansion at 28 days for the standard and 0.1% expansion at 56 days for the modified age (Mod. Age) results. The CPT results are shown as a line representing the expansion at 2 years (1 year for control). Since there is no precedent for increasing the limit age for specimens without SCM the age is not modified for 70% Spratt RCA with 30% non-reactive coarse.

The % expansion graph of the CMBT test specimens to an age of 56 days, representing 200% of the standard limit age, is shown in Figures 4.66, 4.67 and 4.68 compared to the 2 year (1 year for control) CPT expansion. The % expansion of the CMBT and CPT test specimens at 100% of the normal and modified limit age, as well as the pass or fail of the expansion limit at 100% of the limit age is shown in Table 4.23. Specimens that fail are likely to cause deleterious expansion if used in concrete. The CPT results indicate that a plain concrete made with 70% Spratt RCA is likely to result in deleterious expansion while the CMBT results do not. The results all indicate that a concrete made with 70% Spratt RCA with 25% LCFA is not likely to result in deleterious expansion. The results of the CMBT at normal age and the CPT indicate that a concrete made with 70% Spratt RCA with 50% Slag RCA is not likely to result in deleterious expansion but the modified age result is barely exceeding the limit. Modifying the limit age of the CMBT when using SCM provides better correlation of results with the CPT. These results will be further discussed in Section 4.2.4.

Table 4.23 – Expansion of 70% Spratt RCA with SCM in CMBT and CPT

| <i>RCA Test Designation</i> | <i>CMBT Expansion % of Limit</i> | | <i>CPT Expansion % of Limit</i> | <i>Pass/Fail @ Limit Age (28/56/2)</i> |
|------------------------------|--|-----------------------------------|---|--|
| | <i>Normal Limit 28d</i> | <i>Modified Limit 56d</i> | <i>Normal Limit 2y</i> | |
| 70% Spratt RCA | 85.9 | - | 243 | (P/-/F) |
| 70% Spratt RCA @ 1.5 | 98.7 | - | 243 | (P/-/F) |
| 70% Spratt RCA with 25% LCFA | 52.3 | 93.1 | 86 | (P/P/P) |
| 70% Spratt RCA with 50% Slag | 54.6 | 100.3 | 84.7 | (P/F/P) |

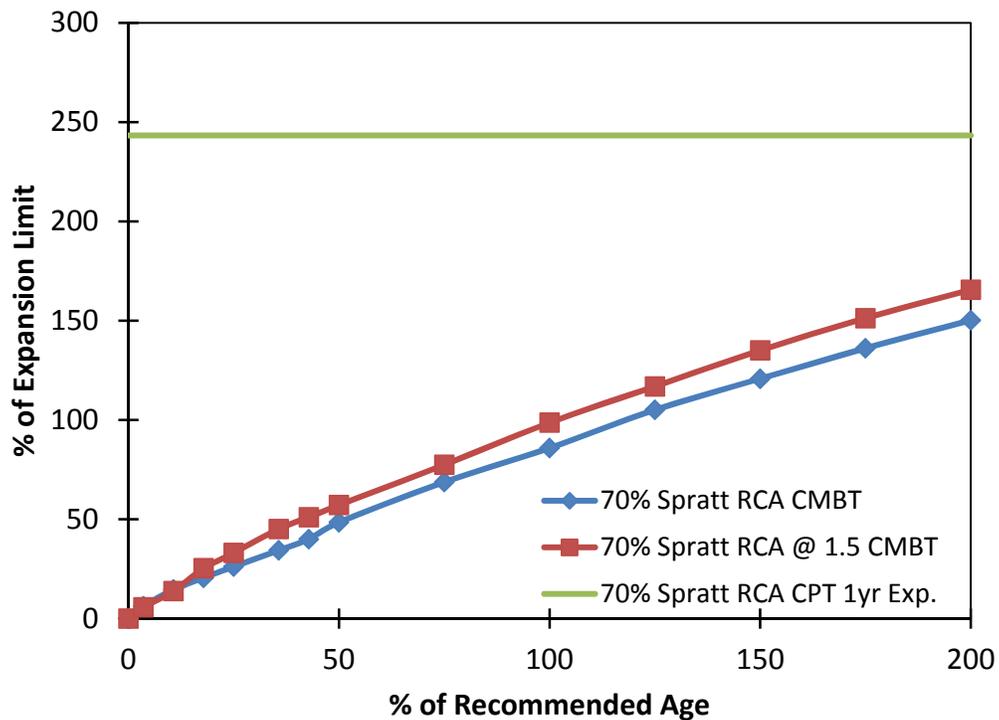


Figure 4.66 – Expansion of 70% Spratt RCA in CMBT and CPT

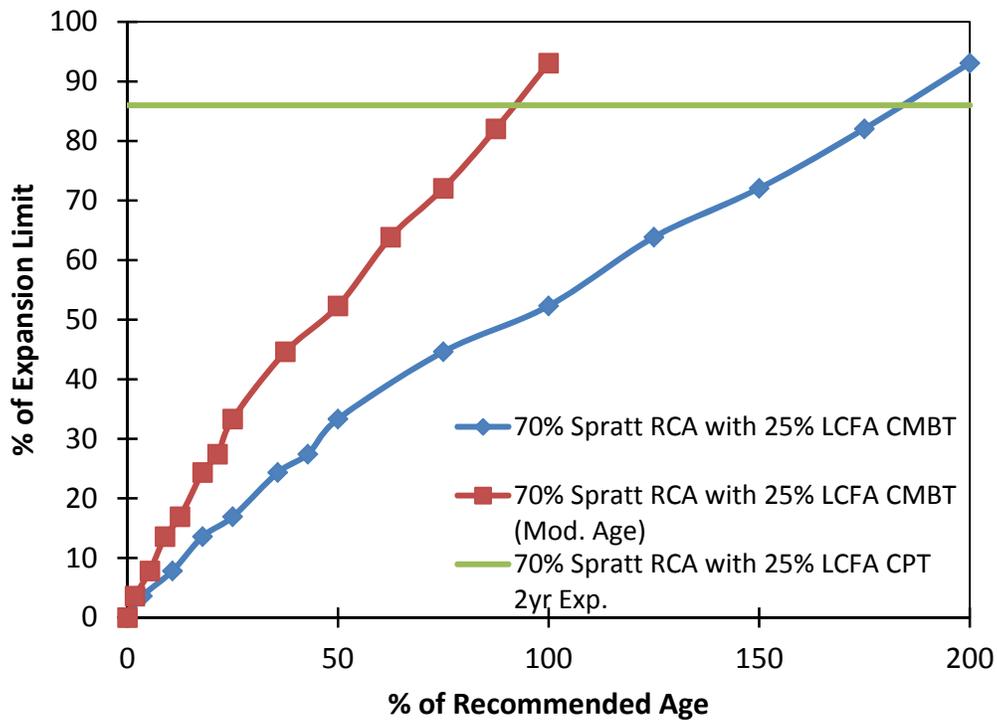


Figure 4.67 – Expansion of 70% Spratt RCA with 25% LCFA in CMBT and CPT

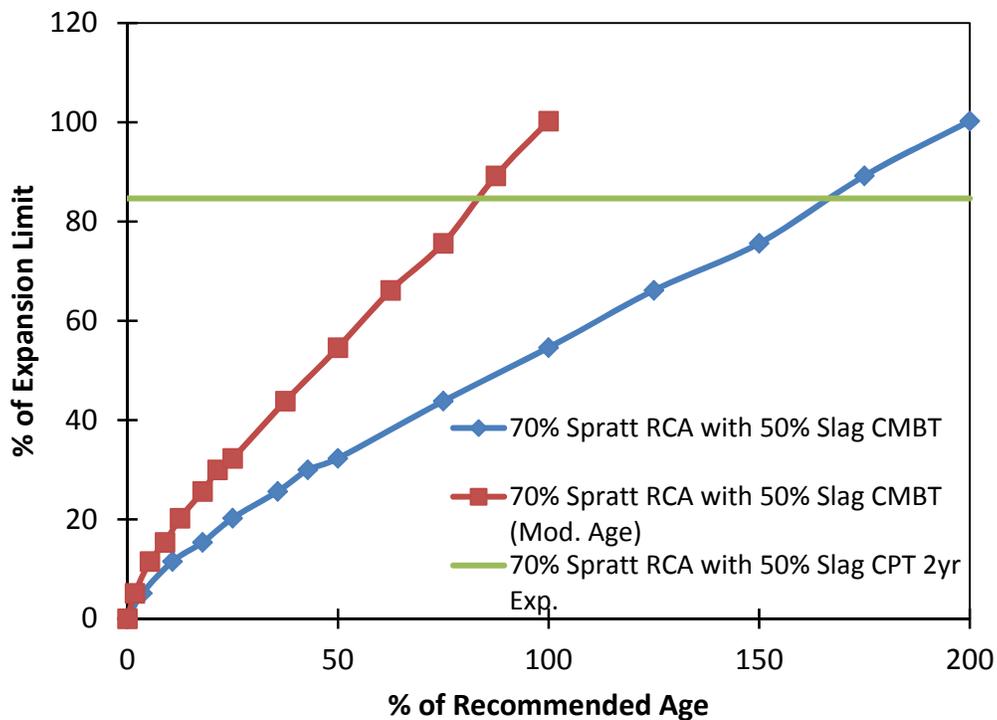


Figure 4.68 – Expansion of 70% Spratt RCA with 50% Slag in CMBT and CPT

4.2.3.8 – Variation of CMBT, AMBT and CPT Results

For this phase of the study, AMBT specimens were made using 100% Spratt RCA & 70% Spratt RCA with 30% non-reactive coarse aggregate and binary & ternary blends of cement. The batches were selected to correlate to selected CMBT results. Absorption of the RCA was calculated as 5.13% using the procedure outlined in ASTM C128. The AMBT specimens were tested by the modified ASTM C1260 test outlined in Section 3.2. The selected specimens were 70% Spratt RCA control, 70% Spratt RCA with 25% LCFA and 100% Spratt RCA with 5% SF & 30% LCFA. Upon analysis it became clear that as suggested, the CMBT results with SCM were underestimating the expansion results of the CPT.

Since the standard for using the CPT with SCM requires the limit age to be doubled to two years, it was hypothesized that the same would be required for CMBT to improve the correlation. The same procedure was followed for the AMBT to determine if a similar correlation existed. The limit age for the CMBT and the AMBT in this phase of the study was increased to 56 & 28 days respectively (Mod. Age). For this comparison, the expansion and age results were factored to equivalent units. Age was expressed as a percentage of the limit age and expansion as a percentage of the expansion limit. For the CPT the limits were 0.04% expansion at 2 years (1 year for control), and for CMBT and AMBT the limits were 0.1% expansion at 28 and 14 days respectively for the standard and 0.1% expansion at 56 & 28 days respectively for the modified age (Mod. Age) results. The CPT results are shown as a line representing the expansion at 2 years (1 year for control).

The % expansion graph of the AMBT test specimens to an age of 28 days, representing 200% of the standard limit age, is shown in Figures 4.69, 4.70, 4.71 and 4.72 compared to the % expansion graph of the AMBT test specimens to an age of 56 days, representing 200% of the standard limit age, and 2 year (1 year for control) CPT expansion. The % expansion of the CMBT and CPT test specimens at 100% of the normal and modified limit age, as well as the pass or fail of the expansion limit at 100% of the limit age is shown in Table 4.24. Specimens that fail are likely to cause deleterious expansion if used in concrete. The CPT and AMBT results indicate that a plain concrete made with 70% Spratt RCA is likely to result in deleterious

expansion while the CMBT results do not. The results indicate that a concrete made with 70% Spratt RCA with 25% LCFA is not likely to result in deleterious expansion except for the modified age AMBT specimens. The results indicate that a concrete made with 70% Spratt RCA with 25% LCFA is not likely to result in deleterious expansion except for the modified age AMBT specimens. The CMBT results using RCA with no SCM underestimate the expansion of when compared to the AMBT and CPT to the extent of disagreeing on the pass/fail criteria. Modifying the limit age of the CMBT and AMBT when using SCM provides better correlation of results with the CPT. But in the case of the AMBT, the overall pass/fail result becomes questionable. These results will be further discussed in Section 4.2.4.

Table 4.24 – Expansion of Spratt RCA with SCM in CMBT, AMBT and CPT

| <i>RCA Test Designation</i> | <i>CMBT Expansion % of Limit</i> | | <i>AMBT Expansion % of Limit</i> | | <i>CPT Expansion % of Limit</i> | <i>Pass/Fail @ Limit Age (28/56/14/28/2)</i> |
|--|--|-----------------------------------|--|-----------------------------------|---|---|
| | <i>Normal Limit 28d</i> | <i>Modified Limit 56d</i> | <i>Normal Limit 14d</i> | <i>Modified Limit 28d</i> | <i>Normal Limit 2y</i> | |
| 70% Spratt RCA | 85.9 | - | 278 | - | 243 | (P/-/F/-/F) |
| 70% Spratt RCA @ 1.5 CMBT | 98.7 | - | 278 | - | 243 | (P/-/F/-/F) |
| 70% Spratt RCA with 25% LCFA | 44.6 | 93.1 | 47.7 | 103 | 86 | (P/P/P/F/P) |
| 100% Spratt RCA with 5% SF & 30% LCFA | 52.3 | 81.8 | 37.4 | 101 | 92.7 | (P/P/P/P/F/P) |

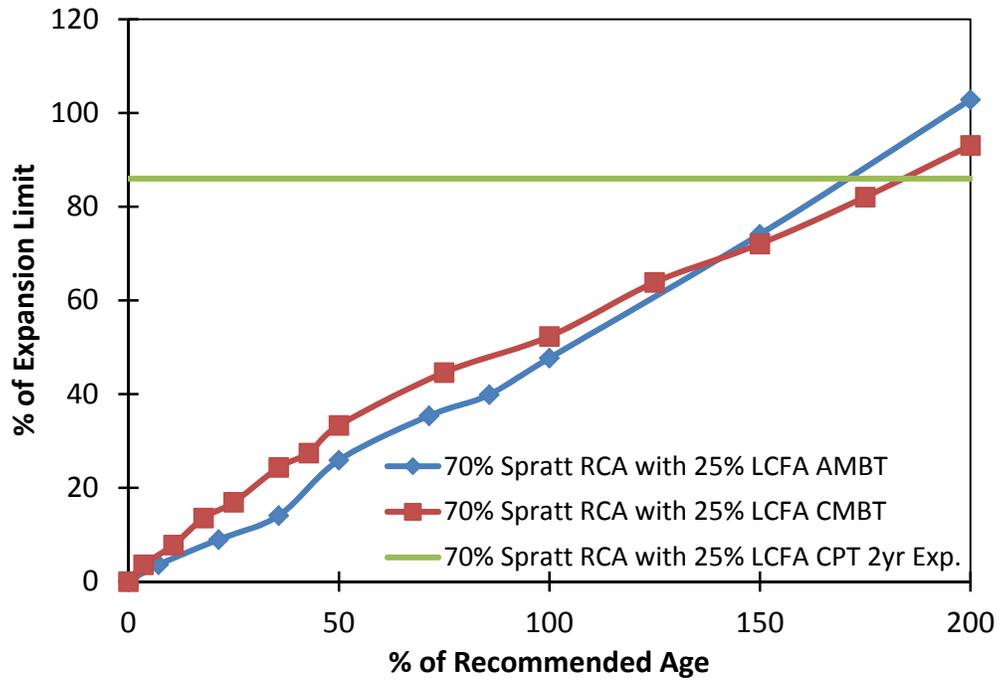


Figure 4.69 – Expansion of 70% Spratt RCA with 25% LCFA in AMBT, CMBT and CPT

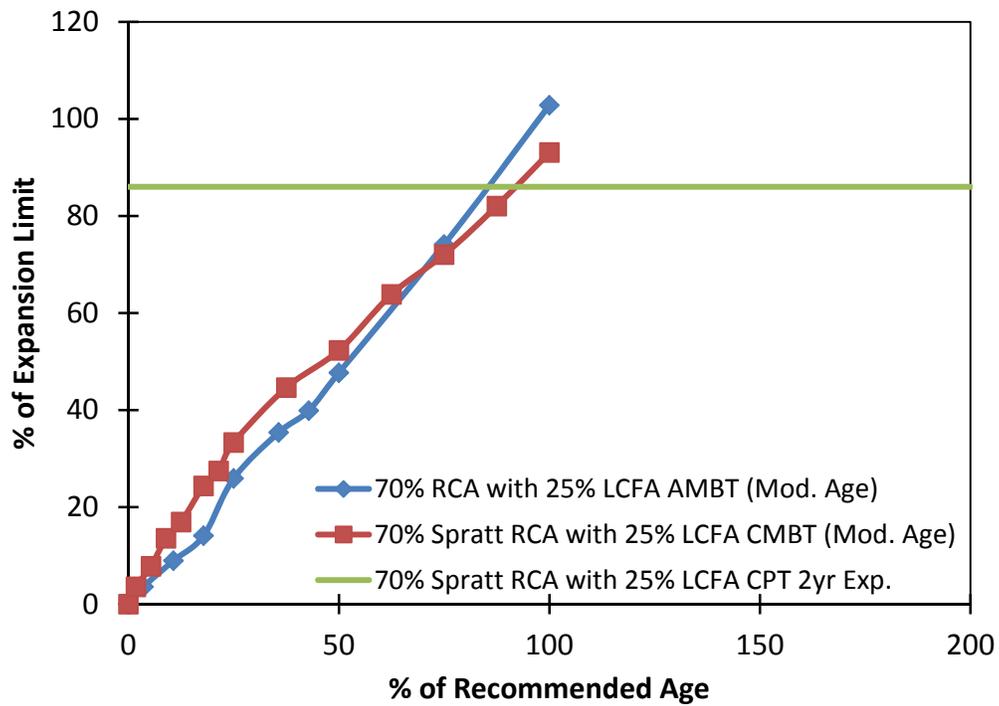


Figure 4.70 – Expansion of 70% Spratt RCA with 25% LCFA in AMBT, CMBT and CPT

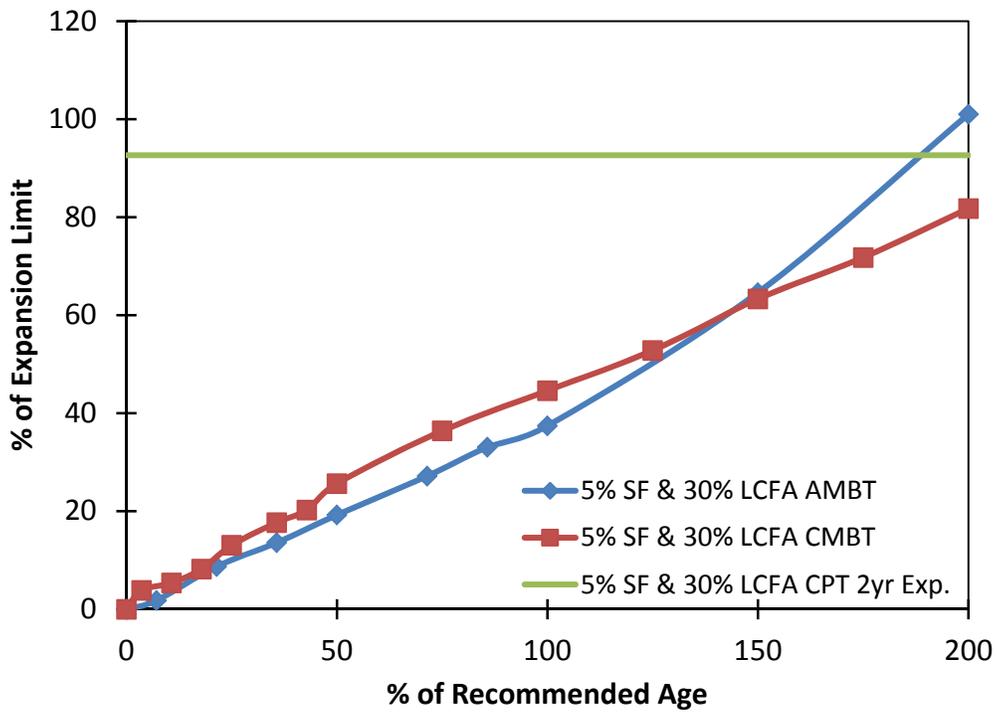


Figure 4.71 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in AMBT, CMBT and CPT

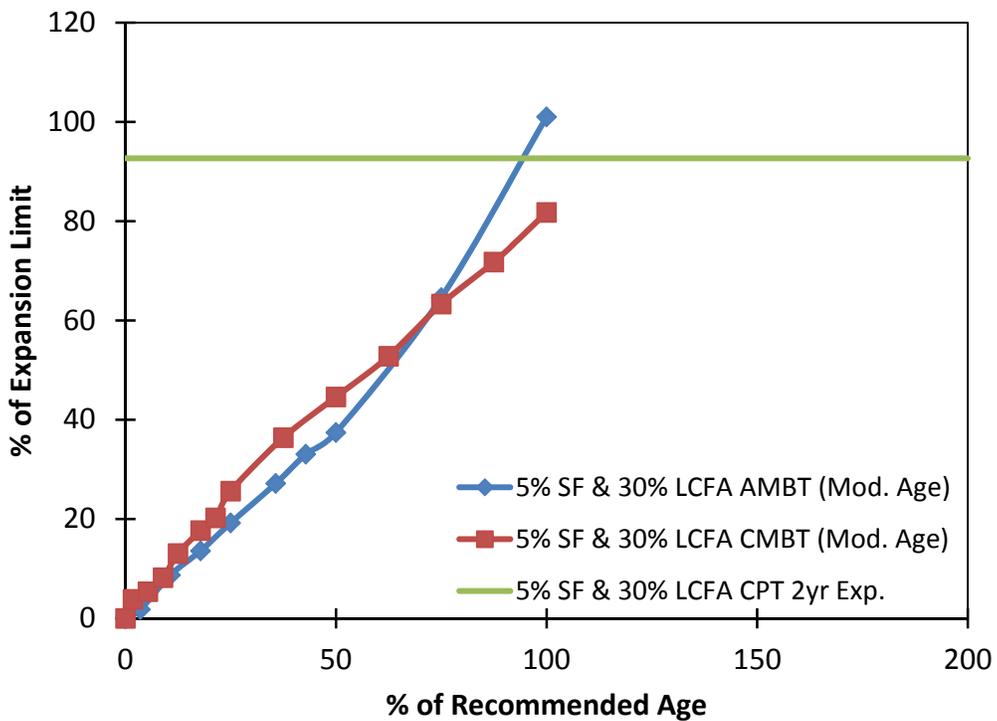


Figure 4.72 – Expansion of 100% Spratt RCA with 5% SF & 30% LCFA in AMBT, CMBT and CPT

4.2.4 – Discussion of CMBT Test Results

A concern of the CMBT as has been discussed previously is the paste volume compared to aggregate in the sample. This can affect many of the testing variables foremost of which is the alkali content in the mix itself. The CPT uses specimens with the cement alkali raised to 1.5% to ensure consistent test results and adequate supply of alkali. The CMBT is more sensitive to changes in alkali since the ratio of cement to aggregate is so high. Thus raising the alkali in the CMBT would result in significantly greater alkali available in the bar itself. However, the CMBT like the AMBT relies on external alkalis supplied by the solution to react. The trend seen in Section 4.2.2.2 shows that with raised alkali, the more reactive specimens ie. those with more than 50% Spratt, showed higher early expansion but reduced late expansion when compared to the standard alkali content. This indicates that in the early stages, the internal alkali sustains the reaction until the external alkali penetrates the specimens. The trend in the figures in Section 4.2.2.1 shows a reduction in the rate of expansion between 3 and 5 days. This may represent the age at which the external alkalis begin to supply the primary alkali to continue the reaction. It may also be an indication that the early expansion has created a gel structure that reduces the penetration of the alkali to sustain the ASR. Regardless, at the limit age of 28 days, the variation between expansion is generally within the required single laboratory variation suggested for the ASTM C1260 test. This indicates that for obtaining 28 day results for reactive aggregates, raising the alkali to 1.5% will not result in significant changes in expansion.

For the specimens prepared with less reactive aggregates, less than 50% Spratt, the reduced expansion creates larger discrepancies since the average values are reduced. For the different aggregate blends tested, representing reactive to unreactive aggregates, the alkali content will not create significant variation to the overall pass/fail results. The results of Section 4.2.2.4 clearly showed that neither normal nor raised alkali could provide a comparable expansion to the CPT. Comparing the CMBT results of virgin Spratt aggregate to existing CPT results showed that CMBT greatly underestimates the expansion of plain Spratt aggregate, however the result may also be attributable to the variation of quarried Spratt aggregate since the original Spratt CPT tests were performed.

The results of Section 4.2.2.3 support the argument that testing SCM with the standard CMBT test may result in underestimated expansion results. It was shown that reducing the SCM content to match the SCM to reactive aggregate ratio of the CPT and AMBT created variation in the expansion results. The variation was small for blends of SCM that failed the expansion criteria under normal conditions. The results remained in agreement on the pass/fail criteria. The variation was significantly larger for blends of SCM that passed the expansion criteria under normal conditions. The variation was large enough to cause the blends of SCM that passed the criteria to fail when the SCM content was reduced. The greatest concern in this result is that the largest variations seem to manifest for SCM blends that seemed to be extremely effective. The resultant blend of the modified SCM content may not be perfectly representative of the blend found in the CPT and AMBT thus the results may over exaggerate this issue. However, the results clearly indicate that effective SCM's may greatly underestimate the expansion of concrete if tested with the standard CMBT.

The results in Section 4.2.3.2 indicate that selecting a smaller grade of RCA will result in larger expansion. This is beneficial since the size of the CMBT moulds makes the aggregate sizing critical. Using the a 13.2mm nominal max, as in the 5-10 specimens, allows the batches to be placed more easily and ensuring a more consistent placement of the particles. Using a 20mm nominal max, as in the 10-14 specimens means that the aggregates must be carefully positioned to fit within the mould dimensions and a less consistent placement since the voids that must be filled are larger. This leads to one possibility as to why the larger gradation produces lower expansion, that the total volume of aggregate is less and there are more paste filled zones to accommodate the expansive gel. Another possibility is due to the material characteristics. The larger RCA particles have undergone less fracturing and breakdown than the smaller particles. This could lead to a larger volume of adhered paste which may mitigate the ingress of alkali from the solution the specimens rest in. The larger volume of paste and the increased voids may also simply lead to a reduced total available reactive aggregate content.

The results in Section 4.2.3.3 indicated that the CMBT provided lower than expected expansion results. In general the results compared to the AMBT provided reasonable correlation on the pass/fail results. However, the magnitude of expansion did not correlate well to the crushed

coarse AMBT results. The CMBT specimens did not agree with the pass/fail evaluation for Bernier RCA where the AMBT indicated that deleterious expansion was likely. However, the virgin Bernier aggregate was also shown to be the least reactive in CPT testing. The opposite occurred for the Potsdam RCA CMBT specimens which indicated that deleterious expansion was likely where the AMBT did not. This is a positive result since it was expected that the Potsdam RCA would be very reactive but did not expand in AMBT testing. The CMBT was somewhat effective in evaluating the reactivity of RCA but as was shown for virgin Spratt, the results seem to underestimate the expansion.

The results in Sections 4.2.3.5 and 4.2.3.7 indicate that the variation in expansion between the CMBT and CPT for evaluating mitigating SCM can be remedied. The results of the CMBT at 28 days greatly underestimate the potential expansion of all the tested SCM blends. However, when the results are compared at 56 days, there is a much closer correlation between the CMBT and CPT results. This was postulated because when testing for the mitigating effect of SCM in the CPT the expansion limit age is doubled to two years. Using the same adjustment for the CMBT and raising the expansion limit age to 56 days lead to much improved correlations. In fact, the adjustment remedied two of the three cases where the overall pass/fail criteria were in disagreement.

These results were compared to AMBT results in Section 4.2.3.8 where it was found that a similar trend occurred. When the limit age of the AMBT was raised to 28 days, the results were very comparable to both CPT and CMBT results. However, the overall pass/fail criteria was exceeded and the AMBT specimens no longer agreed with the CPT and CMBT. Due to the smaller size of the AMBT test specimens, the increased test duration may allow overexpansion as ASR gel induces micro-cracking which increases the permeability. This argument is supported by Figure 4.70 and Figure 4.72, which show an increase in the rate of expansion after 14 days, 50% of the modified limit age, for AMBT compared to the CMBT. This does not occur in the CMBT because the increased specimen size increases the volume of cracking that must occur to compromise the larger specimens.

4.3 – Results and Analysis of the Analytical Supporting Tests

4.3.1 – Scope of Analytical Supporting Tests

This focus of this section of the study was to provide supporting results for AMBT and CMBT testing. The testing selected for this was porosity testing, RCPT and alkali leaching test as described by Shehata and Thomas, 2006. These investigations were meant to provide supporting arguments for specific results. The materials used in this testing were identical to those in the previous test sections with the exception of the Ottawa sand. This was standard ASTM graded silica sand that was selected for the AMBT specimens.

The porosity and RCPT used the same test specimens and followed the procedure outlined in Section 3.4. The specimens allowed for comparison of the porosity and permeability of mixes made according to the CPT, AMBT and CMBT test specifications. They also allowed for direct comparison of the porosity and permeability of individual specimens. The porosity and RCPT results provide insight into the mechanism by which the CPT, AMBT and CMBT work and what variables are likely to affect the results. Three specimens were made for each test and the average results were presented.

The alkali leaching test was conducted using the same materials previously used in the study. This testing provided results on the alkali binding capacity of the SCM's to be analysed with the expansion results. The testing compared the binding capacity of SCM in artificial pore solution, the alkali release of plain concrete and RCA in artificial pore solution, and the net effect of SCM and RCA at full and 70% RCA dilution in artificial pore solution. The paste specimens were prepared and tested according to the procedure in Section 3.5

4.3.2 – Porosity and RCPT Results

The porosity and RCPT specimens were batched according to their respective test procedures but instead of placed in prism moulds, were placed in 100mm cylinder moulds according to the

procedure in Section 3.4.5. The cylinders were all cured for 1 day in the moulds at 23°C in 100% RH before being demoulded and cut into 50mm thick specimens. The 50mm thick specimens were then aged in the method according to the procedure shown below in Table 4.25. CPT, AMBT and CMBT specimens were made using Spratt aggregate of the correct gradation. Three variables were tested for all test types, control Spratt, 25% LCFA Spratt and 23°C cured control. The CMBT specimens also included a reduced LCFA specimen (25% EQ.) that supports the testing seen in Section 4.2.2.3. The AMBT specimens also included specimens made from Ottawa Sand repeating the standard test variables above. All of the specimens exhibited good workability and were easily placed and compacted. Upon demoulding, there were no significant surface voids observable on the specimens.

Table 4.25 – Curing details of CMBT, CPT and AMBT test specimens

| Test Specimen | | Specimen Preparation Processes | |
|---------------|---------------------|--|-----------------------------------|
| | | Conditioning | Curing |
| CPT | Spratt | 7 days @ 23°C 100% RH | 28 days @ 38°C 100% RH |
| | 25% LCFA | 7 days @ 23°C 100% RH | 28 days @ 38°C 100% RH |
| | Spratt @ 23°C | 35 days @ 23°C 100% RH | |
| AMBT | Spratt | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| | Spratt 25% LCFA | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| | Ottawa @ 23°C | 9 days @ 23°C 100% RH | |
| | Ottawa | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| | Ottawa 25% LCFA | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| CMBT | Spratt | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| | Spratt @ 23°C | 9 days @ 23°C 100% RH | |
| | Spratt 25% LCFA | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |
| | Spratt EQ. 25% LCFA | 1 days @ 23°C 100% RH & 1 Day @ 80°C Immersed in Water | 7 Days @ 80°C Immersed in 1N NaOH |

The porosity and permeability of the specimens are shown in Table 4.2. The results shown in red in Table 4.26 indicate RCPT results where the test was stopped automatically due to the extremely high permeability of the specimens. The results demonstrate that the controlling mode

of reaction for the CMBT and AMBT is very different than that of the CPT. The porosity of the CMBT and AMBT is clearly related to the permeability while the porosity of the CPT had no discernable effect on the permeability. These results will be further discussed in Section 4.3.4.

Table 4.26 – Porosity and permeability of CMBT, CPT and AMBT test specimens

| Test Specimen | | Average Result | |
|---------------|---------------------|----------------|-------|
| | | Porosity (%) | RCPT |
| CPT | Spratt | 14.12 | 2241 |
| | 25% LCFA | 14.23 | 272 |
| | Spratt @ 23°C | 14.39 | 2270 |
| AMBT | Spratt | 20.01 | 9361 |
| | Spratt 25% LCFA | 15.61 | 454 |
| | Ottawa @ 23°C | 17.37 | 8933 |
| | Ottawa | 20.66 | 13000 |
| | Ottawa 25% LCFA | 14.46 | 486 |
| CMBT | Spratt | 16.85 | 7547 |
| | Spratt @ 23°C | 18.20 | 5482 |
| | Spratt 25% LCFA | 14.57 | 473 |
| | Spratt EQ. 25% LCFA | 15.73 | 1968 |

4.3.3 – Alkali Leaching Test Results

The flame photometer analysis uses photo-sensors to detect colour changes in a flame caused by the presence of dissolved ions. This apparatus provides an extremely accurate assay of the concentration of dissolved ions in a given solution to 0.2ppm. Using the correction procedure outlined in Appendix F, the change in Na_2O_e as a percent of cementitious materials for each solution was calculated and presented. A positive value indicates a release of alkali by the test specimen, while a negative result indicates a binding of alkali by the test specimen. The artificial pore solution was 0.25N NaOH for all test specimens and the concentration of Na^+ and K^+ ions in the solution were analyzed. Due to the limited samples and concentrations investigated, only the general trends will be discussed.

The results in Figures 4.73, 4.74, 7.75 and 4.76, show the net change in alkali content in Na_2O_e as a percent of cementitious materials. Figure 4.73 shows the change in alkali of specimens made

with only plain PC paste, RCA or both combined. The results indicate that plain PC paste will release some alkali to the system as would be expected. The RCA results however show a clear discrepancy, adding a full volume of RCA seems to bind some of the alkali from the system while using a diluted volume of 70% of the RCA will release a significant amount of alkali. The use of RCA with plain paste creates a nearly net zero change in concentration which implies that the RCA binds some alkali from the system. This is contradicting to the results of the sample with 70% RCA, which shows the RCA to release significant amounts of alkalis to the solution. The author recommends repeating the whole testing program with more than three specimens per sample to confirm the results in the manner suggested in Section 5.3.1.

Figure 4.74 shows the change in alkali of specimens made with paste containing blends of SCM. These results more consistently indicate that SCM will bind alkali from the system. It should be noted that the solution contains only sodium ions, with no potassium. The study of Shehata and Thomas 2006 has both Na^+ and K^+ ions. This explains why the values obtained here are not comparable to those in Shehata and Thomas' work. These results show that the ternary blend of 20/30 LCFA/Slag binds the most alkali as is supported by its excellent performance in CPT testing. Figure 4.75 shows the change in alkali of specimens made with paste containing blends of SCM and RCA. The best alkali binding is again shown by the 20/30 blend with the reduced binding suggesting that excess alkali is released from the RCA. This is also suggested by the net increase in alkali seen with the other specimens again suggesting that the RCA release alkali. Figure 4.76 shows the change in alkali of specimens made with paste containing blends of SCM and diluted 70% RCA. These results seem to contradict the results of the SCM and 100% RCA specimens since the overall results indicate a net zero change or slight decrease in alkali concentration. This indicates that the diluted 70% RCA is actually binding some alkali compared to the 100% RCA. These results will be further discussed in Section 4.3.4.

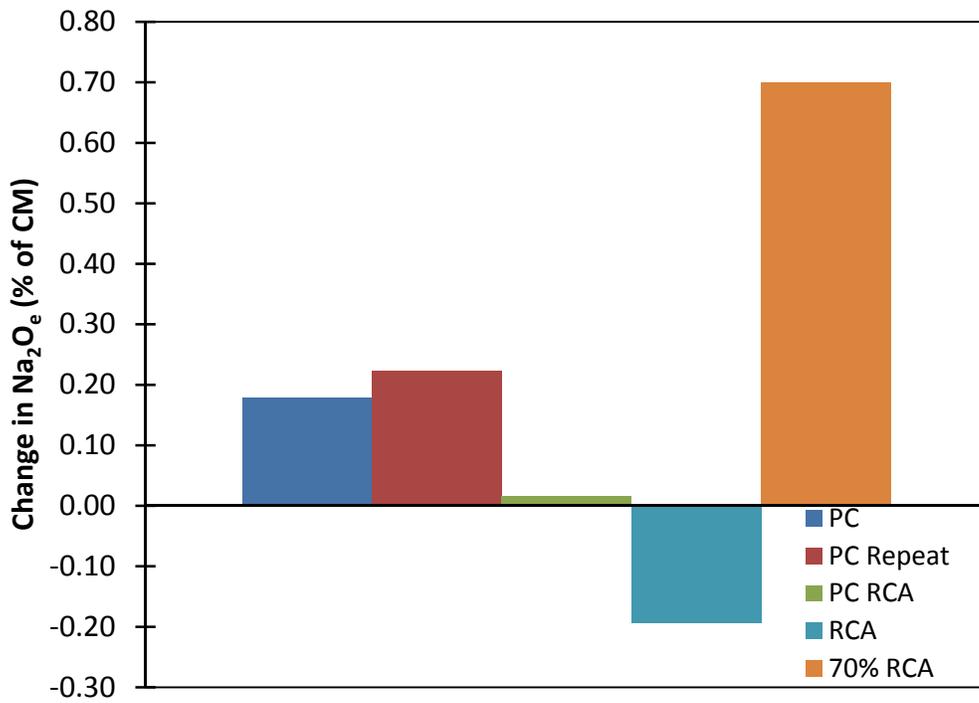


Figure 4.73 – Alkali concentration of plain cement paste and RCA specimens

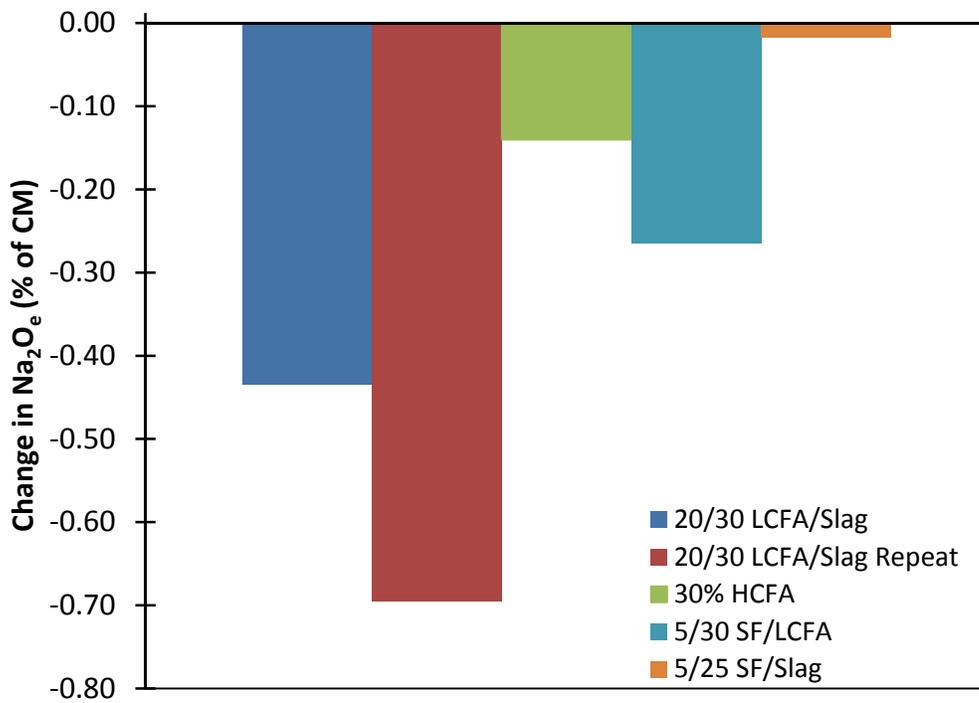


Figure 4.74 – Alkali concentration of SCM paste specimens

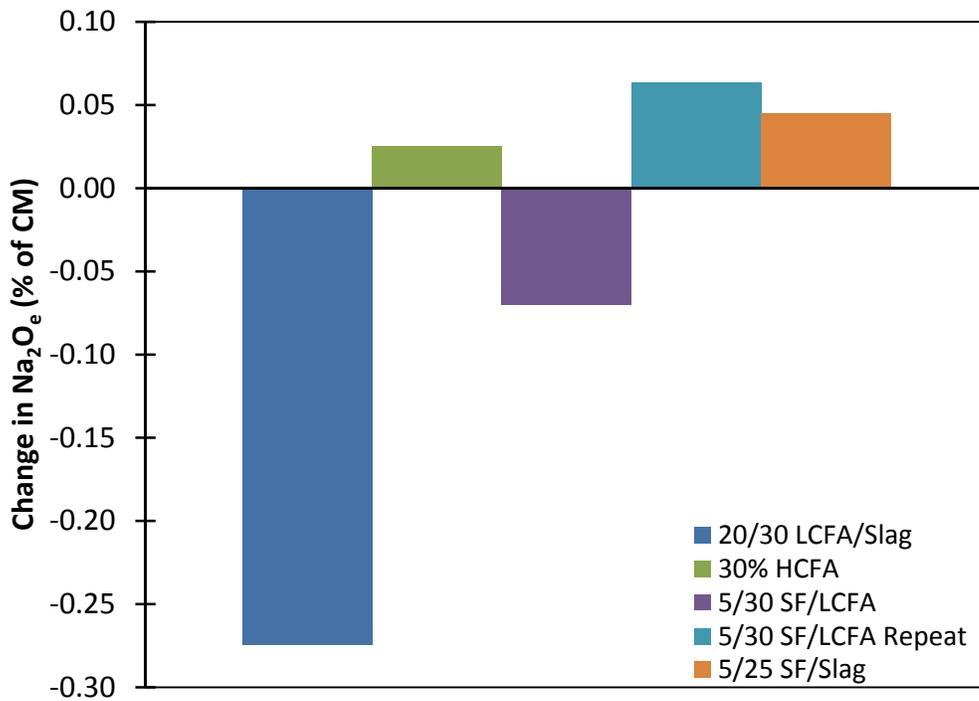


Figure 4.75 – Alkali concentration of SCM paste and RCA specimens

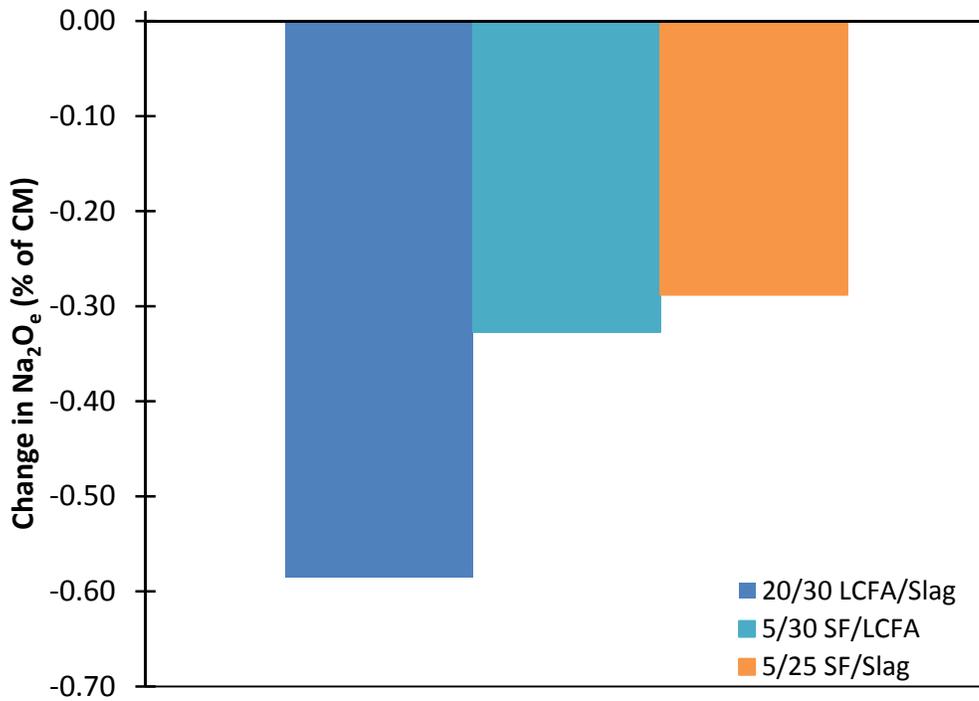


Figure 4.76 – Alkali concentration of SCM paste and 70% RCA specimens

4.3.4 – Discussion of Analytical Support Testing Results

The discussion of CMBT test results in Section 4.2.4 suggested that the alkali content within the bar of the CMBT and AMBT were not critical and did not significantly affect the test results. The Porosity and RCPT testing results in Section 4.3.2 support this suggestion. It was shown that the CPT test specimens maintained a consistent porosity even though the permeability by RCPT greatly varied. The addition of 25% LCFA created no variation in the average porosity but created a very impermeable mix. This indicates that the changes in the CPT specimens when using SCM create microstructural changes that reduce the permeability. This is likely a change in void connectivity and pore size rather than in overall void content. The CMBT and AMBT however showed significant variation in porosity depending on the mix. Comparing the specimens cured in the 80°C NaOH solution to those cured in the 23°C 100% RH chamber showed that the porosity is not completely a by-product of an ASR reaction causing cracking. The overall results indicate that for CMBT and AMBT specimens, a larger porosity will result in a higher permeability. This indicates that the ASR is controlled by the ingress of Alkali from the solution. This also means that the CMBT and AMBT are the most comparable tests. The results utilizing fly ash support that porosity is the controlling factor. LCFA will create a more refined microstructure and in the CMBT and AMBT this also meant a less porous structure which led to a direct reduction in permeability. However, this creates a discrepancy between the CMBT, AMBT and CPT. The effectiveness of SCM found by reduction in expansion of CMBT and AMBT specimens only evaluates one of the suggested modes by which SCM mitigates ASR. Since the alkali in the test is supplied in excess by the external solution, CMBT and AMBT testing only models expansion reductions caused by the reduced propagation of alkali and water in the system. The CPT is more representative of the actual ASR expansion and thus how individual SCM properties cause different modes of expansion reduction.

The Alkali Leaching test results in Section 4.3.3 were affected by insufficient data since only one or two specimens were prepared for each sample type. Due to the homogeneity of the paste specimens this is a recommended procedure to mitigate errors due to material. However, the general trends were evaluated and presented due to the anomalous results found when using RCA. The results without RCA seemed to provide reasonable results that follow trends seen in

previous research. However the RCA results were extremely variable and it is suggested that they would have invalidated the results regardless of the number of repeat tests available. The nature of RCA makes it far more sensitive to testing such as this. The two main constituents of RCA will likely have differing effects on the solution alkali concentration. The residual paste is likely to release alkali to the system just as in new paste but reactive aggregate in the RCA may cause the opposite result. The reactive aggregate may be able to utilize the alkali in the solution to create more ASR gel products. The ASR gel will bind the alkali and thus reduce the apparent concentration. This would mean that the composition of each individual RCA particle will have an effect on the concentration. For example, an RCA composed mainly of residual paste is likely to increase the alkali concentration of the solution while a particle composed mainly of reactive aggregate may reduce the concentration. Since the sample size was so small for the test, the results using RCA were much more sensitive to the individual RCA particle's composition and thus increased the overall variability in the test. This postulate explains the results seen in the testing in Section 4.3.3.

5 – Summary of Results, Conclusions and Recommendations for Future Research

5.1 – Accelerated Mortar Bar Testing

The AMBT testing program was conducted to evaluate the single and multi-laboratory variability of RCA as well the individual testing procedures that could affect the testing results. These factors included; as delivered gradation, absorption corrections, method of crushing and washing.

5.1.1 – Conclusions for AMBT using RCA

1. The material to be tested should be delivered to the testing lab in the same condition as it will be used in the field. This means that a coarse RCA with a 20mm nominal max size should be delivered for testing in that same gradation.
2. Using the coarse aggregate to prepare AMBT specimens yields results that are likely to produce repeatable results that meet ASTM C1260 single and multi-laboratory requirements.
3. Using crusher's fines from the same RCA processing will yield more variable results that are not likely to produce repeatable results that meet ASTM C1260 single laboratory requirements. It should also be noted that crusher's fines produces much less expansion than the coarse RCA
4. RCA that must be prepared for AMBT testing should be crushed in one large batch that is blended to produce the most consistent results. Crushing individual batched increases the variability and the specimens are not likely to meet ASTM C1260 single laboratory requirements.
5. RCA should be crushed using an apparatus that utilizes a fixed aperture within crusher to ensure all particles are crushed to a certain size before exiting the machine. Without this fixed size, only the weakest particles will be broken leading to an overabundance of paste in the crushed particles.

6. Determining the correct absorption for the RCA will allow for more consistent expansion results. Varying the absorption will change the expansion but overestimating the absorption causes a smaller variation than underestimating the absorption.
7. Washing RCA prior to testing should be avoided since it decreases the expansion results but if necessary, all comparable samples should be washed in the same way since washing will change the expansion results.

5.2 – Concrete Microbar Testing

The primary goal of the CMBT program was to evaluate the validity of the CMBT in evaluating the reactivity of RCA and the mitigation of SCM. The CMBT testing program evaluated the effect of cement alkali content and perceived overabundance of SCM on the expansion of Spratt Aggregate. Testing also evaluated the CMBT effectiveness in screening reactive RCA in comparison to the AMBT. Further testing compared the CMBT, CPT and AMBT in evaluating the mitigating effect of SCM.

5.2.1 – Conclusions for CMBT with Virgin Spratt Aggregate

1. The effect of alkali supplied by cement or raised by the addition of NaOH provided negligible change in the expansion of specimens at 28 days.
2. Aggregate blends with a greater reactive aggregate content that were tested with raised alkali showed greater expansion at early ages but decreased expansion at late ages.
3. The expansion results of the CMBT greatly underestimate the expansion when compared with CPT specimens.
4. Modifying the SCM content to reflect the same SCM to reactive aggregate ratio found in the AMBT and CPT tests will result in significant changes in the expansion of CMBT specimens with SCM that are effective in mitigating the expansion at the normal replacement levels.

5.2.2 – Conclusions for CMBT using RCA

1. Using a finer gradation of 5-10mm RCA will result in higher expansion and produce a more workable mix than the larger 10-14mm RCA for all tested RCA types.
2. The CMBT using RCA underestimated the expansion when compared to the reactive AMBT test specimens. The CMBT indicated a failing result with an RCA that is shown to provide a passing AMBT result despite its highly expansive CPT results. However, the virgin aggregate used in this RCA represents a special case where the aggregates passed the AMBT but failed the CPT. This is because in crushing the aggregates to prepare the AMBT samples, the reactive constituents of this aggregate is lost. Hence, the CMBT is, in fact, a more effective test than AMBT in evaluating this type of aggregate or RCA.
3. Extending the expansion limit age to 56 days for the CMBT when using SCM provides a closer correlation to the expansion result at 2 years for the CPT using SCM.

5.3 – Analytical Support Testing

The analytical support test program was devised to provide results that support the analysis of the AMBT and CMBT programs. Testing was conducted to evaluate the porosity and permeability of AMBT, CMBT and CPT. Further testing was conducted to evaluate the changes in alkali concentration within the AMBT and CPT test specimens.

5.3.1 – Conclusions for Analytical Support Testing

1. The CMBT and AMBT are highly sensitive to changes in porosity which will directly affect the expansion results due to the increased permeability. Creating a sufficiently workable mix and proper compaction techniques will prevent placement voids from affecting the overall porosity and thus the expansion results.

2. Since the abundance of alkali in the system from the solution reduces mitigation effect caused by alkali binding, the CMBT and AMBT tests may evaluate the mitigating effect of SCM differently than the CPT.
3. Modifying the SCM content in the CMBT to represent the SCM to reactive aggregate ratio found in the AMBT and CPT does not provide acceptable expansion results for the following reasons;
 - a. The proposed modification is based on alkali binding capacity which is of lower importance in the CMBT compared to the CPT (owing to the abundant supply of alkalis in case of CMBT).
 - b. The SCM replacement (as partial replacement of cement) is no longer equivalent to that in concrete.
4. Alkali leaching test specimens containing RCA require a greater volume than what is used in this thesis to allow the inclusion of sufficient RCA in the sample. This is needed to mitigate the inherent variability of individual particles.

5.4 – Conclusions for Accelerated Test Methods for RCA

This thesis can provide some guidance in terms of utilizing accelerated test methods to evaluate the alkali silica reactivity of RCA. The research clearly shows that a modified procedure to prepare AMBT specimens will provide results sufficient to reject a source of RCA due to the level of ASR. However, the AMBT test cannot be used to accept a source of RCA with acceptable certainty. The following is a summary of the required modifications to the AMBT when testing RCA.

1. Coarse aggregate must be crushed using an apparatus with a fixed aperture size to ensure consistent crushing of paste and aggregate particles.
2. An addition of water equal to the absorption of the RCA to be tested must be added to the standard water content in the AMBT mix.
3. The RCA and water must be blended in a sealed container for 30 minutes prior to mixing to allow for absorption by the RCA and ensure the correct workability is obtained.

This thesis has shown that the CMBT is a promising test to evaluate ASR in RCA. At this time, significant research is still required to determine an expansion limit that provides acceptable pass/fail screening of RCA samples. Further research may show that the CMBT is the ideal alternative to screen RCA made with aggregate types known to provide false passing results in the AMBT. However, this thesis has clearly shown that the CMBT may potentially be an ideal test for pre-evaluating the efficacy of SCM in mitigating ASR. Using 56 days as the limit age for CMBT with SCM is recommended to improve the correlation. Further research is critical in evaluating this finding. At this time it is believed that the 56 day limit age results should provide results sufficient to exclude failing SCM blends. This would allow for a selection of SCM blends that will be effective to be prepared using the CPT to confirm the results.

5.5 – Recommendations for Future Research

In Section 5.1.1, Conclusion #7 indicates that washing of RCA prior to use in the AMBT will affect the expansion results. The washing is assumed to leach alkalis from the adhered paste and the resulting reduction in alkali in the system produces lower expansion. However, in Section 5.3.1, Conclusion #2 indicates that the AMBT relies on external alkali from the solution to produce expansion. Future research should be conducted to support this discrepancy. The author recommends a short AMBT program that compares unwashed RCA, washed RCA and washed RCA with raised alkali. Comparing the washed RCA and washed RCA with raised alkali with the unwashed RCA expansion will evaluate if the alkali leaching resulted in the change in expansion.

In Section 5.2.2, Conclusion #2 indicated that the CMBT provided a result that indicated an RCA was likely to cause deleterious expansion for an RCA that is known to produce a false passing result in the AMBT. Future research should be conducted to evaluate whether the CMBT can provide a better evaluation of aggregates and RCA types that yield false passing results in the AMBT. It is known that some aggregates do not react once they have been crushed. Since the

CMBT does not require fine crushing of the aggregates it may potentially provide a better screening for these misleading aggregates.

In Section 5.2.2, Conclusion #3 indicates that the 56 day expansion results of CMBT specimens made with SCM provide a better correlation with the 2 year CPT expansion results. Future research should be conducted to support this finding. Since the AMBT 14 day results using SCM, most of the time, underestimate the expansion of a given SCM blend, the stronger correlation of results indicates that the CMBT results could be a better alternative. It was suggested in this study that perhaps extending the AMBT testing age limit could provide a similar correlation. The results showed that in excess of 14 days, the rate of expansion in the AMBT begins to increase. The rate of expansion after 28 days for the CMBT is more constant. A full test program for CMBT specimens correlating to known CPT specimens should be conducted for all available results to ensure this is not limited to the RCA used in this test.

In Section 5.3.1, Conclusion #3 suggests that the manner in which SCM mitigates expansion in the CMBT and AMBT is not representative of the CPT. The CPT will also evaluate mitigation by reducing available alkali in the specimen caused by alkali binding by the SCM. Since the CMBT and AMBT are less able to evaluate this, particularly when the test period is extended, the mitigation is based only on the reduction in permeability and thus the prevention of alkali reaching the reactive aggregate in the specimen. Future research should be conducted to isolate the variables of the manner of mitigating. CPT and CMBT specimens should be created using polymer admixture. Polymer admixture would greatly reduce the permeability of the specimens and therefore provide a comparable result since that is the only manner of mitigation that would be evaluated in both the CMBT and CPT. This may also provide an indication of the importance of alkali binding in mitigating ASR with SCM.

Appendix A – Test Mix Designs

| Mix | RCA (g) | NR Sand (g) | Cement (g) | Water (g) | Absorption (g) |
|--------------------|---------|-------------|------------|-----------|----------------|
| 100% Alberta | 990 | | 440 | 206.8 | 65.9 |
| 50% Alberta | 495 | 495 | 440 | 206.8 | 33.0 |
| 50% Alberta 2 | 495 | 495 | 440 | 206.8 | 33.0 |
| 25% Alberta | 247.5 | 742.5 | 440 | 206.8 | 16.5 |
| 25% Alberta 2 | 247.5 | 742.5 | 440 | 206.8 | 16.5 |
| 100% Bernier | 990 | | 440 | 206.8 | 61.2 |
| 50% Bernier | 495 | 495 | 440 | 206.8 | 30.6 |
| 50% Bernier 2 | 495 | 495 | 440 | 206.8 | 30.6 |
| 25% Bernier | 247.5 | 742.5 | 440 | 206.8 | 15.3 |
| 100% Potsdam | 990 | | 440 | 206.8 | 41.8 |
| 50% Potsdam | 495 | 495 | 440 | 206.8 | 20.9 |
| 25% Potsdam | 247.5 | 742.5 | 440 | 206.8 | 10.4 |
| 100% Springhill | 990 | | 440 | 206.8 | 77.0 |
| 100% Springhill 2 | 990 | | 440 | 206.8 | 77.0 |
| 100% Springhill SC | 990 | | 440 | 206.8 | 77.0 |
| 50% Springhill | 495 | 495 | 440 | 206.8 | 38.5 |
| 25% Springhill | 247.5 | 742.5 | 440 | 206.8 | 19.3 |

Table A.1 – Interlab RCA crushed coarse AMBT mix designs

| Mix | RCA (g) | NR Sand (g) | Cement (g) | Water (g) | Absorption (g) |
|-------------------|---------|-------------|------------|-----------|----------------|
| 100% Alberta | 990 | | 440 | 206.8 | 65.9 |
| 50% Alberta | 495 | 495 | 440 | 206.8 | 33.0 |
| 50% Alberta 2 | 495 | 495 | 440 | 206.8 | 33.0 |
| 25% Alberta | 247.5 | 742.5 | 440 | 206.8 | 16.5 |
| 25% Alberta 2 | 247.5 | 742.5 | 440 | 206.8 | 16.5 |
| 100% Bernier | 990 | | 440 | 206.8 | 61.2 |
| 50% Bernier | 495 | 495 | 440 | 206.8 | 30.6 |
| 50% Bernier 2 | 495 | 495 | 440 | 206.8 | 30.6 |
| 25% Bernier | 247.5 | 742.5 | 440 | 206.8 | 15.3 |
| 100% Potsdam | 990 | | 440 | 206.8 | 41.8 |
| 50% Potsdam | 495 | 495 | 440 | 206.8 | 20.9 |
| 25% Potsdam | 247.5 | 742.5 | 440 | 206.8 | 10.4 |
| 100% Springhill | 990 | | 440 | 206.8 | 77.0 |
| 100% Springhill 2 | 990 | | 440 | 206.8 | 77.0 |
| 50% Springhill | 495 | 495 | 440 | 206.8 | 38.5 |
| 25% Springhill | 247.5 | 742.5 | 440 | 206.8 | 19.3 |

Table A.2 – Interlab RCA crusher's fines AMBT mix designs

| Mix | Aggregate (g) | NR Coarse (g) | Cement (g) | Water (g) | Absorption (g) |
|-------------------|---------------|---------------|------------|-----------|----------------|
| Spratt Control | 1620 | 0 | 1620 | 522 | 16.2 |
| 70% Spratt | 1134 | 486 | 1620 | 522 | 16.2 |
| 50% Spratt | 810 | 810 | 1620 | 522 | 16.2 |
| 50% Spratt Repeat | 810 | 810 | 1620 | 522 | 16.2 |
| 30% Spratt | 486 | 1134 | 1620 | 522 | 16.2 |
| 30% Spratt Repeat | 486 | 1134 | 1620 | 522 | 16.2 |
| 10% Spratt | 162 | 1458 | 1620 | 522 | 16.2 |
| NR Control | 0 | 1620 | 1620 | 522 | 16.2 |

Table A.3 – Virgin Spratt CMBT mix designs

| Mix | Aggregate (g) | Cement (g) | HCFA (g) | LCFA (g) | Slag (g) | Water (g) | Absorption (g) |
|------------------|---------------|------------|----------|----------|----------|-----------|----------------|
| 30% HCFA | 1620 | 1134 | 486 | | | 522 | 16.2 |
| 30% Slag | 1620 | 1134 | | | 486 | 522 | 16.2 |
| 25% LCFA | 1620 | 1215 | | 405 | | 522 | 16.2 |
| 30% LCFA | 1620 | 1134 | | 486 | | 522 | 16.2 |
| 30% HCFA * 0.425 | 1620 | 1413 | 207 | | | 522 | 16.2 |
| 30% Slag * 0.425 | 1620 | 1413 | | | 207 | 522 | 16.2 |
| 25% LCFA * 0.425 | 1620 | 1448 | | 172 | | 522 | 16.2 |
| 30% LCFA * 0.425 | 1620 | 1413 | | 207 | | 522 | 16.2 |

Table A.4 – Virgin Spratt with modified SCM CMBT mix designs

| Mix | RCA (g) | Cement (g) | Water (g) | Absorption (g) |
|------------------|---------|------------|-----------|----------------|
| Alberta 5-10 | 1620 | 1620 | 522 | 107.9 |
| Bernier 5-10 | 1620 | 1620 | 522 | 100.1 |
| Potsdam 5-10 | 1620 | 1620 | 522 | 68.4 |
| Springhill 5-10 | 1620 | 1620 | 522 | 126.0 |
| Alberta 10-14 | 1620 | 1620 | 522 | 107.9 |
| Bernier 10-14 | 1620 | 1620 | 522 | 100.1 |
| Potsdam 10-14 | 1620 | 1620 | 522 | 68.4 |
| Springhill 10-14 | 1620 | 1620 | 522 | 126.0 |

Table A.5 – Interlab RCA CMBT mix designs

| Mix | RCA (g) | NR Coarse (g) | Cement (g) | Slag (g) | LCFA (g) | Silica Fume (g) | Water (g) | Absorption (g) |
|----------------|---------|---------------|------------|----------|----------|-----------------|-----------|----------------|
| 70/30 Control | 1134 | 486 | 1620 | | | | 522.0 | 63.0 |
| 70/30 25% FA | 1134 | 486 | 1215 | | 405 | | 522.0 | 63.0 |
| 70/30 50% Slag | 1134 | 486 | 810 | 810 | | | 522.0 | 63.0 |
| 20/30 FA/Slag | 1620 | | 810 | 486 | 324 | | 522.0 | 83.1 |
| 5/45 SF/Slag | 1620 | | 810 | 729 | | 81 | 522.0 | 83.1 |
| 5/30 SF/FA | 1620 | | 1053 | | 486 | 81 | 522.0 | 83.1 |
| 5/20 SF/FA | 1620 | | 1215 | | 324 | 81 | 522.0 | 83.1 |
| 5/25 SF/Slag | 1620 | | 1134 | 405 | | 81 | 522.0 | 83.1 |

Table A.6 – Spratt RCA with SCM CMBT mix designs

| Mix | RCA (g) | NR Coarse (g) | Cement (g) | LCFA (g) | Silica Fume (g) | Water (g) | Absorption (g) |
|---------------|---------|---------------|------------|----------|-----------------|-----------|----------------|
| 70/30 Control | 693 | 297 | 440 | | | 206.8 | 25 |
| 70/30 25% FA | 693 | 297 | 330 | 110 | | 206.8 | 25 |
| 5/30 SF/FA | 990 | | 286 | 132 | 22 | 206.8 | 33 |

Table A.7 – Spratt RCA with SCM AMBT mix designs

| Mix | Aggregate (g) | Cement (g) | LCFA (g) | Water (g) |
|-----------------|---------------|------------|----------|-----------|
| Ottawa | 2828.6 | 1257.1 | | 590.9 |
| Ottawa 25% LCFA | 2828.6 | 942.9 | 314.3 | 590.9 |
| Spratt | 2828.6 | 1257.1 | | 590.9 |
| Spratt 25% LCFA | 2828.6 | 942.9 | 314.3 | 590.9 |

Table A.8 – Porosity/RCPT representing AMBT mix designs

| Mix | Aggregate (g) | Cement (g) | LCFA (g) | Water (g) |
|---------------------|---------------|------------|----------|-----------|
| Spratt | 2000 | 2000 | | 590.9 |
| Spratt 25% LCFA | 2000 | 1500 | 500 | 590.9 |
| Spratt 25% EQ. LCFA | 2000 | 1787.5 | 212.5 | 590.9 |

Table A.9 – Porosity/RCPT representing CMBT mix designs

| Mix | Coarse (kg) | NR Sand (kg) | Cement (kg) | LCFA (kg) | Water (kg) |
|-----------------|-------------|--------------|-------------|-----------|------------|
| Spratt | 15.273 | 10.182 | 6.3 | | 2.745 |
| Spratt 25% LCFA | 15.273 | 10.182 | 4.725 | 1.575 | 2.745 |

Table A.10 – Porosity/RCPT representing CPT mix designs

Appendix B – AMBT Test Program Results

| Date | Age | 100% Potsdam Coarse RCA | | | | | | | | | | COV |
|-----------|-----|-------------------------|--------|-------|----------------|----------------|----------------|------------------|--------|--------|--------|-------|
| | | Bar 1 | Bar 2 | Bar 3 | % Change Bar 1 | % Change Bar 2 | % Change Bar 3 | % Change Average | | | | |
| 05-Aug-10 | 0 | -0.010 | -0.160 | 0.204 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | - |
| 06-Aug-10 | 1 | 0.010 | -0.142 | 0.220 | 0.0075 | 0.0068 | 0.0060 | 0.0068 | 0.0068 | 0.0068 | 0.0068 | 0.111 |
| 08-Aug-10 | 3 | 0.022 | -0.122 | 0.236 | 0.0121 | 0.0143 | 0.0121 | 0.0121 | 0.0128 | 0.0128 | 0.0128 | 0.102 |
| 10-Aug-10 | 5 | 0.068 | -0.080 | 0.286 | 0.0294 | 0.0302 | 0.0309 | 0.0302 | 0.0302 | 0.0302 | 0.0302 | 0.025 |
| 12-Aug-10 | 7 | 0.090 | -0.060 | 0.304 | 0.0377 | 0.0377 | 0.0377 | 0.0377 | 0.0377 | 0.0377 | 0.0377 | 0.000 |
| 15-Aug-10 | 10 | 0.134 | -0.012 | 0.348 | 0.0543 | 0.0558 | 0.0543 | 0.0543 | 0.0548 | 0.0548 | 0.0548 | 0.016 |
| 17-Aug-10 | 12 | 0.160 | 0.010 | 0.370 | 0.0642 | 0.0642 | 0.0626 | 0.0626 | 0.0636 | 0.0636 | 0.0636 | 0.014 |
| 19-Aug-10 | 14 | 0.184 | 0.030 | 0.400 | 0.0732 | 0.0717 | 0.0740 | 0.0740 | 0.0730 | 0.0730 | 0.0730 | 0.016 |
| 22-Aug-10 | 17 | 0.222 | 0.066 | 0.428 | 0.0875 | 0.0853 | 0.0845 | 0.0845 | 0.0858 | 0.0858 | 0.0858 | 0.018 |
| 26-Aug-10 | 21 | 0.268 | 0.110 | 0.484 | 0.1049 | 0.1019 | 0.1057 | 0.1057 | 0.1042 | 0.1042 | 0.1042 | 0.019 |
| 29-Aug-10 | 24 | 0.304 | 0.146 | 0.522 | 0.1185 | 0.1155 | 0.1200 | 0.1200 | 0.1180 | 0.1180 | 0.1180 | 0.020 |
| 02-Sep-10 | 28 | 0.326 | 0.184 | 0.550 | 0.1268 | 0.1298 | 0.1306 | 0.1306 | 0.1291 | 0.1291 | 0.1291 | 0.015 |

Table B.1 – Sample of data worksheet for recording AMBT expansion results

| 100% Alberta | | 100% Bernier | | 100% Potsdam | | 100% Springhill | |
|--------------|------------------|--------------|------------------|--------------|------------------|-----------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0113 | 1 | 0.0116 | 1 | 0.0068 | 1 | 0.0121 |
| 3 | 0.0689 | 3 | 0.0357 | 3 | 0.0128 | 3 | 0.0745 |
| 5 | 0.1379 | 5 | 0.0712 | 5 | 0.0302 | 5 | 0.1628 |
| 7 | 0.2020 | 7 | 0.0943 | 7 | 0.0377 | 7 | 0.2297 |
| 10 | 0.2848 | 10 | 0.1094 | 10 | 0.0548 | 10 | 0.2953 |
| 12 | 0.3208 | 12 | 0.1204 | 12 | 0.0636 | 12 | 0.3291 |
| 14 | 0.3384 | 14 | 0.1318 | 14 | 0.0730 | 14 | 0.3565 |
| 17 | 0.3942 | 17 | 0.1421 | 17 | 0.0858 | 17 | 0.3912 |
| 21 | 0.4365 | 21 | 0.1499 | 21 | 0.1042 | 21 | 0.4262 |
| 24 | 0.4613 | 24 | 0.1530 | 24 | 0.1180 | 24 | 0.4460 |
| 28 | 0.4906 | 28 | 0.1605 | 28 | 0.1291 | 28 | 0.4669 |

| 50% Alberta | | 50% Bernier | | 50% Potsdam | | 100% Springhill Repeat | |
|-------------|------------------|-------------|------------------|-------------|------------------|------------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0093 | 1 | 0.0040 | 1 | 0.0055 | 1 | 0.0083 |
| 3 | 0.0629 | 3 | 0.0161 | 3 | 0.0088 | 3 | 0.0805 |
| 5 | 0.1328 | 5 | 0.0337 | 5 | 0.0229 | 5 | 0.1537 |
| 7 | 0.1952 | 7 | 0.0493 | 7 | 0.0309 | 7 | 0.2297 |
| 10 | 0.2672 | 10 | 0.0644 | 10 | 0.0463 | 10 | 0.3049 |
| 12 | 0.2921 | 12 | 0.0737 | 12 | 0.0556 | 12 | 0.3442 |
| 14 | 0.3157 | 14 | 0.0833 | 14 | 0.0664 | 14 | 0.3733 |
| 17 | 0.3535 | 17 | 0.0918 | 17 | 0.0767 | 17 | 0.4146 |
| 21 | 0.3842 | 21 | 0.1031 | 21 | 0.0964 | 21 | 0.4521 |
| 24 | 0.4035 | 24 | 0.1099 | 24 | 0.1074 | 24 | 0.4747 |
| 28 | 0.4274 | 28 | 0.1187 | 28 | 0.1223 | 28 | 0.5001 |

| 50% Alberta Repeat | | 50% Bernier Repeat | | 25% Potsdam | | 100% Springhill S.Crushing | |
|--------------------|------------------|--------------------|------------------|-------------|------------------|----------------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0043 | 1 | 0.0015 | 1 | 0.0101 | 1 | 0.0138 |
| 3 | 0.0553 | 3 | 0.0111 | 3 | 0.0088 | 3 | 0.0830 |
| 5 | 0.1278 | 5 | 0.0264 | 5 | 0.0199 | 5 | 0.1882 |
| 7 | 0.1912 | 7 | 0.0493 | 7 | 0.0279 | 7 | 0.2631 |
| 10 | 0.2531 | 10 | 0.0624 | 10 | 0.0430 | 10 | 0.3391 |
| 12 | 0.2878 | 12 | 0.0707 | 12 | 0.0536 | 12 | 0.3826 |
| 14 | 0.3079 | 14 | 0.0805 | 14 | 0.0652 | 14 | 0.4153 |
| 17 | 0.3391 | 17 | 0.0906 | 17 | 0.0762 | 17 | 0.4581 |
| 21 | 0.3733 | 21 | 0.1034 | 21 | 0.0941 | 21 | 0.5009 |
| 24 | 0.3902 | 24 | 0.1107 | 24 | 0.1059 | 24 | 0.5240 |
| 28 | 0.4116 | 28 | 0.1192 | 28 | 0.1220 | 28 | 0.5530 |

| 25% Alberta | |
|-------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0088 |
| 3 | 0.0335 |
| 5 | 0.0870 |
| 7 | 0.1389 |
| 10 | 0.1904 |
| 12 | 0.2131 |
| 14 | 0.2312 |
| 17 | 0.2526 |
| 21 | 0.2840 |
| 24 | 0.2931 |
| 28 | 0.3155 |

| 25% Bernier | |
|-------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0028 |
| 3 | 0.0096 |
| 5 | 0.0226 |
| 7 | 0.0430 |
| 10 | 0.0538 |
| 12 | 0.0647 |
| 14 | 0.0737 |
| 17 | 0.0870 |
| 21 | 0.1029 |
| 24 | 0.1117 |
| 28 | 0.1253 |

| 50% Springhill | |
|----------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0050 |
| 3 | 0.0576 |
| 5 | 0.1260 |
| 7 | 0.1829 |
| 10 | 0.2481 |
| 12 | 0.2755 |
| 14 | 0.2996 |
| 17 | 0.3321 |
| 21 | 0.3615 |
| 24 | 0.3819 |
| 28 | 0.4033 |

| 25% Alberta Repeat | |
|--------------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0231 |
| 3 | 0.0337 |
| 5 | 0.0916 |
| 7 | 0.1406 |
| 10 | 0.1935 |
| 12 | 0.2158 |
| 14 | 0.2362 |
| 17 | 0.2543 |
| 21 | 0.2843 |
| 24 | 0.3019 |
| 28 | 0.3215 |

| 25% Springhill | |
|----------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0003 |
| 3 | 0.0478 |
| 5 | 0.0825 |
| 7 | 0.1311 |
| 10 | 0.1761 |
| 12 | 0.1987 |
| 14 | 0.2204 |
| 17 | 0.2440 |
| 21 | 0.2717 |
| 24 | 0.2891 |
| 28 | 0.3064 |

Table B.2 – Interlab RCA crushed coarse average expansion results

| 100% Alberta | | 100% Bernier | | 100% Potsdam | | 100% Springhill | |
|--------------|------------------|--------------|------------------|--------------|------------------|-----------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0116 | 1 | 0.0184 | 1 | 0.0035 | 1 | 0.0050 |
| 3 | 0.0267 | 3 | 0.0372 | 3 | 0.0121 | 3 | 0.0118 |
| 5 | 0.0415 | 5 | 0.0543 | 5 | 0.0184 | 5 | 0.0181 |
| 7 | 0.0606 | 7 | 0.0684 | 7 | 0.0370 | 7 | 0.0206 |
| 10 | 0.1057 | 10 | 0.0858 | 10 | 0.0506 | 10 | 0.0357 |
| 12 | 0.1364 | 12 | 0.0875 | 12 | 0.0634 | 12 | 0.0428 |
| 14 | 0.1655 | 14 | 0.0938 | 14 | 0.0725 | 14 | 0.0523 |
| 17 | 0.2081 | 17 | 0.0933 | 17 | 0.0848 | 17 | 0.0616 |
| 21 | 0.2468 | 21 | 0.1019 | 21 | 0.1019 | 21 | 0.0752 |
| 24 | 0.2699 | 24 | 0.1029 | 24 | 0.1130 | 24 | 0.0833 |
| 28 | 0.2820 | 28 | 0.1079 | 28 | 0.1313 | 28 | 0.0958 |

| 50% Alberta | | 50% Bernier | | 50% Potsdam | | 100% Springhill Repeat | |
|-------------|------------------|-------------|------------------|-------------|------------------|------------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0126 | 1 | 0.0005 | 1 | 0.0005 | 1 | 0.0151 |
| 3 | 0.0194 | 3 | 0.0081 | 3 | 0.0111 | 3 | 0.0249 |
| 5 | 0.0415 | 5 | 0.0136 | 5 | 0.0249 | 5 | 0.0460 |
| 7 | 0.0659 | 7 | 0.0201 | 7 | 0.0408 | 7 | 0.0604 |
| 10 | 0.1117 | 10 | 0.0317 | 10 | 0.0553 | 10 | 0.0873 |
| 12 | 0.1292 | 12 | 0.0382 | 12 | 0.0702 | 12 | 0.1001 |
| 14 | 0.1494 | 14 | 0.0445 | 14 | 0.0800 | 14 | 0.1072 |
| 17 | 0.1670 | 17 | 0.0513 | 17 | 0.0916 | 17 | 0.1210 |
| 21 | 0.1899 | 21 | 0.0619 | 21 | 0.1049 | 21 | 0.1343 |
| 24 | 0.2073 | 24 | 0.0672 | 24 | 0.1160 | 24 | 0.1409 |
| 28 | 0.2204 | 28 | 0.0797 | 28 | 0.1338 | 28 | 0.1535 |

| 50% Alberta Repeat | | 50% Bernier Repeat | | 25% Potsdam | | 50% Springhill | |
|--------------------|------------------|--------------------|------------------|-------------|------------------|----------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0078 | 1 | 0.0033 | 1 | -0.0023 | 1 | 0.0103 |
| 3 | 0.0214 | 3 | 0.0083 | 3 | 0.0085 | 3 | 0.0146 |
| 5 | 0.0307 | 5 | 0.0136 | 5 | 0.0211 | 5 | 0.0390 |
| 7 | 0.0518 | 7 | 0.0179 | 7 | 0.0357 | 7 | 0.0564 |
| 10 | 0.0823 | 10 | 0.0282 | 10 | 0.0536 | 10 | 0.0946 |
| 12 | 0.1089 | 12 | 0.0332 | 12 | 0.0669 | 12 | 0.1104 |
| 14 | 0.1308 | 14 | 0.0400 | 14 | 0.0785 | 14 | 0.1238 |
| 17 | 0.1628 | 17 | 0.0435 | 17 | 0.0921 | 17 | 0.1411 |
| 21 | 0.1909 | 21 | 0.0541 | 21 | 0.1072 | 21 | 0.1547 |
| 24 | 0.2096 | 24 | 0.0584 | 24 | 0.1200 | 24 | 0.1670 |
| 28 | 0.2204 | 28 | 0.0682 | 28 | 0.1361 | 28 | 0.1826 |

| 25% Alberta | |
|-------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0050 |
| 3 | 0.0239 |
| 5 | 0.0375 |
| 7 | 0.0647 |
| 10 | 0.0845 |
| 12 | 0.0938 |
| 14 | 0.1077 |
| 17 | 0.1228 |
| 21 | 0.1303 |
| 24 | 0.1411 |
| 28 | 0.1535 |

| 25% Bernier | |
|-------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0179 |
| 3 | 0.0282 |
| 5 | 0.0440 |
| 7 | 0.0581 |
| 10 | 0.0747 |
| 12 | 0.0780 |
| 14 | 0.0843 |
| 17 | 0.0860 |
| 21 | 0.0953 |
| 24 | 0.1026 |
| 28 | 0.1074 |

| 25% Springhill | |
|----------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | -0.0015 |
| 3 | 0.0126 |
| 5 | 0.0231 |
| 7 | 0.0397 |
| 10 | 0.0732 |
| 12 | 0.0865 |
| 14 | 0.0994 |
| 17 | 0.1190 |
| 21 | 0.1369 |
| 24 | 0.1469 |
| 28 | 0.1663 |

| 25% Alberta Repeat | |
|--------------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0050 |
| 3 | 0.0199 |
| 5 | 0.0340 |
| 7 | 0.0629 |
| 10 | 0.0936 |
| 12 | 0.1069 |
| 14 | 0.1208 |
| 17 | 0.1394 |
| 21 | 0.1585 |
| 24 | 0.1683 |
| 28 | 0.1786 |

Table B.3 – Interlab RCA crusher’s fines average expansion results

| Laval Control | | Laval Washed | |
|---------------|------------------|--------------|------------------|
| Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0105 | 1 | 0.0085 |
| 3 | 0.0623 | 3 | 0.0410 |
| 5 | 0.1213 | 5 | 0.0764 |
| 7 | 0.1579 | 7 | 0.1085 |
| 10 | 0.2038 | 10 | 0.1485 |
| 12 | 0.2167 | 12 | 0.1685 |
| 14 | 0.2297 | 14 | 0.1836 |
| 21 | 0.2672 | 21 | 0.2159 |
| 28 | 0.2823 | 28 | 0.2382 |

| Laval Reduced Water | | Laval Compressive Crushing | |
|---------------------|------------------|----------------------------|------------------|
| Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0146 | 1 | 0.0072 |
| 3 | 0.0715 | 3 | 0.0326 |
| 5 | 0.1390 | 5 | 0.0559 |
| 7 | 0.1828 | 7 | 0.0762 |
| 10 | 0.2292 | 10 | 0.1008 |
| 12 | 0.2472 | 12 | 0.1105 |
| 14 | 0.2618 | 14 | 0.1213 |
| 21 | 0.2995 | 21 | 0.1436 |
| 28 | 0.3195 | 28 | 0.1562 |

| Laval Increased Water | |
|-----------------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0138 |
| 3 | 0.0613 |
| 5 | 0.1162 |
| 7 | 0.1536 |
| 10 | 0.1915 |
| 12 | 0.2067 |
| 14 | 0.2192 |
| 21 | 0.2500 |
| 28 | 0.2674 |

Table B.4 – Laval RCA average expansion results

Appendix C – CMBT Test Program Results

| Date | Age | Spratt Control | | | Bar 3 | % Change Bar 1 | % Change Bar 2 | % Change Bar 3 | % Change Average | COV | Temp |
|-----------|-----|----------------|-------|-------|--------|----------------|----------------|----------------|------------------|------|------|
| | | Bar 1 | Bar 2 | Bar 3 | | | | | | | |
| 20-Dec-10 | 0 | 5.288 | 5.294 | 5.500 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | - | - | - |
| 21-Dec-10 | 1 | 5.316 | 5.320 | 5.526 | 0.0108 | 0.0100 | 0.0100 | 0.0103 | 0.043 | 80.2 | 80.2 |
| 23-Dec-10 | 3 | 5.354 | 5.352 | 5.564 | 0.0254 | 0.0223 | 0.0246 | 0.0241 | 0.066 | 80.4 | 80.4 |
| 24-Dec-10 | 4 | 5.376 | 5.374 | 5.582 | 0.0338 | 0.0308 | 0.0315 | 0.0321 | 0.050 | 80.6 | 80.6 |
| 27-Dec-10 | 7 | 5.430 | 5.424 | 5.636 | 0.0546 | 0.0500 | 0.0523 | 0.0523 | 0.044 | 80.2 | 80.2 |
| 30-Dec-10 | 10 | 5.460 | 5.454 | 5.668 | 0.0662 | 0.0615 | 0.0646 | 0.0641 | 0.037 | 80.4 | 80.4 |
| 01-Jan-11 | 12 | 5.486 | 5.480 | 5.696 | 0.0762 | 0.0715 | 0.0754 | 0.0744 | 0.033 | 80.6 | 80.6 |
| 03-Jan-11 | 14 | 5.506 | 5.500 | 5.726 | 0.0838 | 0.0792 | 0.0869 | 0.0833 | 0.046 | 80.5 | 80.5 |
| 10-Jan-11 | 21 | 5.588 | 5.576 | 5.798 | 0.1154 | 0.1085 | 0.1146 | 0.1128 | 0.034 | 80.6 | 80.6 |
| 17-Jan-11 | 28 | 5.664 | 5.648 | 5.874 | 0.1446 | 0.1362 | 0.1438 | 0.1415 | 0.033 | 80.4 | 80.4 |
| 24-Jan-11 | 35 | 5.744 | 5.718 | 5.956 | 0.1754 | 0.1631 | 0.1754 | 0.1713 | 0.041 | 80.5 | 80.5 |
| 31-Jan-11 | 42 | 5.824 | 5.780 | 6.034 | 0.2062 | 0.1869 | 0.2054 | 0.1995 | 0.055 | 80.5 | 80.5 |
| 07-Feb-11 | 49 | 5.900 | 5.836 | 6.106 | 0.2354 | 0.2085 | 0.2331 | 0.2256 | 0.066 | 80.3 | 80.3 |
| 14-Feb-11 | 56 | 5.966 | 5.890 | 6.172 | 0.2608 | 0.2292 | 0.2585 | 0.2495 | 0.070 | 80.6 | 80.6 |

Table C.1 – Sample of data worksheet for recording CMBT expansion results

| 100% Spratt | | 50% Spratt | | 30% Spratt | | 10% Spratt | |
|-------------|------------------|------------|------------------|------------|------------------|------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0103 | 1 | 0.0067 | 1 | 0.0074 | 1 | 0.0072 |
| 3 | 0.0241 | 3 | 0.0149 | 3 | 0.0185 | 3 | 0.0115 |
| 5 | 0.0321 | 5 | 0.0179 | 5 | 0.0213 | 5 | 0.0133 |
| 7 | 0.0523 | 7 | 0.0290 | 7 | 0.0241 | 7 | 0.0144 |
| 10 | 0.0641 | 10 | 0.0362 | 10 | 0.0295 | 10 | 0.0159 |
| 12 | 0.0744 | 12 | 0.0418 | 12 | 0.0338 | 12 | 0.0187 |
| 14 | 0.0833 | 14 | 0.0467 | 14 | 0.0372 | 14 | 0.0197 |
| 21 | 0.1128 | 21 | 0.0651 | 21 | 0.0515 | 21 | 0.0251 |
| 28 | 0.1415 | 28 | 0.0826 | 28 | 0.0654 | 28 | 0.0295 |
| 35 | 0.1713 | 35 | 0.1003 | 35 | 0.0774 | 35 | 0.0351 |
| 42 | 0.1995 | 42 | 0.1156 | 42 | 0.0885 | 42 | 0.0387 |
| 49 | 0.2256 | 49 | 0.1295 | 49 | 0.1000 | 49 | 0.0449 |
| 56 | 0.2495 | 56 | 0.1428 | 56 | 0.1044 | 56 | 0.0467 |

| 70% Spratt | | 50% Spratt Repeat | | 30% Spratt Repeat | | Non-Reactive Coarse | |
|------------|------------------|-------------------|------------------|-------------------|------------------|---------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0046 | 1 | 0.0054 | 1 | 0.0077 | 1 | 0.0056 |
| 3 | 0.0131 | 3 | 0.0138 | 3 | 0.0123 | 3 | 0.0072 |
| 5 | 0.0259 | 5 | 0.0223 | 5 | 0.0187 | 5 | 0.0087 |
| 7 | 0.0338 | 7 | 0.0297 | 7 | 0.0238 | 7 | 0.0113 |
| 10 | 0.0403 | 10 | 0.0367 | 10 | 0.0300 | 10 | 0.0131 |
| 12 | 0.0521 | 12 | 0.0446 | 12 | 0.0331 | 12 | 0.0141 |
| 14 | 0.0579 | 14 | 0.0500 | 14 | 0.0374 | 14 | 0.0151 |
| 21 | 0.0826 | 21 | 0.0726 | 21 | 0.0536 | 21 | 0.0190 |
| 28 | 0.1049 | 28 | 0.0910 | 28 | 0.0687 | 28 | 0.0223 |
| 35 | 0.1262 | 35 | 0.1108 | 35 | 0.0831 | 35 | 0.0249 |
| 42 | 0.1487 | 42 | 0.1297 | 42 | 0.0982 | 42 | 0.0267 |
| 49 | 0.1659 | 49 | 0.1487 | 49 | 0.1082 | 49 | 0.0272 |
| 56 | 0.1833 | 56 | 0.1623 | 56 | 0.1164 | 56 | 0.0287 |

Table C.2 – Virgin Spratt aggregate with normal alkali average expansion results

| 100% Spratt @ 1.5 | | 50% Spratt @ 1.5 | | 30% Spratt @ 1.5 | | 10% Spratt @ 1.5 | |
|-------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0167 | 1 | 0.0079 | 1 | 0.0054 | 1 | 0.0041 |
| 3 | 0.0408 | 3 | 0.0200 | 3 | 0.0110 | 3 | 0.0069 |
| 5 | 0.0559 | 5 | 0.0297 | 5 | 0.0187 | 5 | 0.0082 |
| 7 | 0.0672 | 7 | 0.0354 | 7 | 0.0231 | 7 | 0.0126 |
| 11 | 0.0859 | 10 | 0.0459 | 10 | 0.0310 | 10 | 0.0164 |
| 14 | 0.0990 | 12 | 0.0523 | 12 | 0.0344 | 12 | 0.0177 |
| 21 | 0.1287 | 14 | 0.0564 | 14 | 0.0364 | 14 | 0.0200 |
| 28 | 0.1492 | 21 | 0.0733 | 21 | 0.0472 | 21 | 0.0241 |
| 35 | 0.1682 | 28 | 0.0903 | 28 | 0.0577 | 28 | 0.0282 |
| 42 | 0.1841 | 35 | 0.1054 | 35 | 0.0628 | 35 | 0.0333 |
| 49 | 0.1969 | 42 | 0.1210 | 42 | 0.0692 | 42 | 0.0367 |
| 56 | 0.2108 | 49 | 0.1336 | 49 | 0.0762 | 49 | 0.0403 |
| | | 56 | 0.1464 | 56 | 0.0828 | 56 | 0.0428 |

| 70% Spratt @ 1.5 | | 50% Spratt Repeat @ 1.5 | | 30% Spratt Repeat @ 1.5 | | Non-Reactive Coarse @ 1.5 | |
|------------------|------------------|-------------------------|------------------|-------------------------|------------------|---------------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0108 | 1 | 0.0049 | 1 | 0.0049 | 1 | 0.0036 |
| 3 | 0.0277 | 3 | 0.0195 | 3 | 0.0128 | 3 | 0.0049 |
| 5 | 0.0390 | 5 | 0.0279 | 5 | 0.0200 | 5 | 0.0059 |
| 7 | 0.0474 | 7 | 0.0349 | 7 | 0.0254 | 7 | 0.0085 |
| 11 | 0.0610 | 10 | 0.0459 | 10 | 0.0336 | 10 | 0.0103 |
| 14 | 0.0708 | 12 | 0.0528 | 12 | 0.0346 | 12 | 0.0103 |
| 21 | 0.0915 | 14 | 0.0559 | 14 | 0.0374 | 14 | 0.0108 |
| 28 | 0.1108 | 21 | 0.0721 | 21 | 0.0497 | 21 | 0.0115 |
| 35 | 0.1287 | 28 | 0.0885 | 28 | 0.0600 | 28 | 0.0123 |
| 42 | 0.1444 | 35 | 0.1023 | 35 | 0.0695 | 35 | 0.0128 |
| 49 | 0.1590 | 42 | 0.1164 | 42 | 0.0774 | 42 | 0.0151 |
| 56 | 0.1736 | 49 | 0.1279 | 49 | 0.0854 | 49 | 0.0159 |
| | | 56 | 0.1362 | 56 | 0.0915 | 56 | 0.0172 |

Table C.3 – Virgin Spratt aggregate with raised alkali average expansion results

| 30% HCFA | | 30% EQ. HCFA | | 25% LCFA | | 25% EQ. LCFA | |
|----------|------------------|--------------|------------------|----------|------------------|--------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0097 | 1 | 0.0092 | 1 | 0.0013 | 1 | 0.0090 |
| 3 | 0.0274 | 3 | 0.0346 | 3 | 0.0036 | 3 | 0.0210 |
| 5 | 0.0433 | 5 | 0.0528 | 5 | 0.0095 | 5 | 0.0338 |
| 7 | 0.0559 | 7 | 0.0662 | 7 | 0.0133 | 7 | 0.0441 |
| 10 | 0.0718 | 10 | 0.0803 | 10 | 0.0167 | 10 | 0.0587 |
| 12 | 0.0818 | 12 | 0.0879 | 12 | 0.0226 | 12 | 0.0654 |
| 14 | 0.0897 | 14 | 0.0969 | 14 | 0.0262 | 14 | 0.0731 |
| 21 | 0.1144 | 21 | 0.1244 | 21 | 0.0390 | 21 | 0.0972 |
| 28 | 0.1372 | 28 | 0.1500 | 28 | 0.0531 | 28 | 0.1192 |
| 35 | 0.1585 | 35 | 0.1759 | 35 | 0.0667 | 35 | 0.1421 |
| 42 | 0.1777 | 42 | 0.2015 | 42 | 0.0823 | 42 | 0.1656 |
| 49 | 0.1979 | 49 | 0.2254 | 49 | 0.0949 | 49 | 0.1859 |
| 56 | 0.2128 | 56 | 0.2464 | 56 | 0.1097 | 56 | 0.2044 |

| 30% Slag | | 30% EQ. Slag | | 30% LCFA | | 30% EQ. LCFA | |
|----------|------------------|--------------|------------------|----------|------------------|--------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0054 | 1 | 0.0059 | 1 | 0.0010 | 1 | 0.0077 |
| 3 | 0.0174 | 3 | 0.0208 | 3 | 0.0046 | 3 | 0.0159 |
| 5 | 0.0267 | 5 | 0.0349 | 5 | 0.0082 | 5 | 0.0256 |
| 7 | 0.0372 | 7 | 0.0438 | 7 | 0.0108 | 7 | 0.0364 |
| 10 | 0.0479 | 10 | 0.0567 | 10 | 0.0141 | 10 | 0.0472 |
| 12 | 0.0554 | 12 | 0.0638 | 12 | 0.0179 | 12 | 0.0572 |
| 14 | 0.0626 | 14 | 0.0700 | 14 | 0.0203 | 14 | 0.0638 |
| 21 | 0.0833 | 21 | 0.0946 | 21 | 0.0310 | 21 | 0.0892 |
| 28 | 0.1049 | 28 | 0.1182 | 28 | 0.0390 | 28 | 0.1115 |
| 35 | 0.1290 | 35 | 0.1428 | 35 | 0.0495 | 35 | 0.1336 |
| 42 | 0.1531 | 42 | 0.1631 | 42 | 0.0579 | 42 | 0.1528 |
| 49 | 0.1764 | 49 | 0.1859 | 49 | 0.0751 | 49 | 0.1715 |
| 56 | 0.1954 | 56 | 0.2054 | 56 | 0.0849 | 56 | 0.1844 |

Table C.4 – Virgin Spratt aggregate with modified SCM average expansion results

| 20% LCFA & 30% Slag | | 5% SF & 30% LCFA | | 5% SF & 20% LCFA | |
|---------------------|------------------|------------------|------------------|------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0023 | 1 | 0.0038 | 1 | 0.0036 |
| 3 | 0.0097 | 3 | 0.0054 | 3 | 0.0079 |
| 5 | 0.0128 | 5 | 0.0082 | 5 | 0.0154 |
| 7 | 0.0162 | 7 | 0.0131 | 7 | 0.0203 |
| 10 | 0.0190 | 10 | 0.0177 | 10 | 0.0246 |
| 12 | 0.0218 | 12 | 0.0203 | 12 | 0.0300 |
| 14 | 0.0241 | 14 | 0.0256 | 14 | 0.0328 |
| 21 | 0.0326 | 21 | 0.0364 | 21 | 0.0487 |
| 28 | 0.0405 | 28 | 0.0446 | 28 | 0.0603 |
| 35 | 0.0477 | 35 | 0.0528 | 35 | 0.0713 |
| 42 | 0.0541 | 42 | 0.0633 | 42 | 0.0879 |
| 49 | 0.0615 | 49 | 0.0718 | 49 | 0.0977 |
| 56 | 0.0695 | 56 | 0.0818 | 56 | 0.1149 |

| 5% SF & 45% Slag | | 5% SF & 25% Slag | | 5% SF & 20% LCFA @ 1.5 | |
|------------------|------------------|------------------|------------------|------------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000* |
| 1 | 0.0044 | 1 | 0.0115 | 1 | 0.0074* |
| 3 | 0.0082 | 3 | 0.0162 | 3 | 0.0182* |
| 5 | 0.0105 | 5 | 0.0254 | 5 | 0.0246* |
| 7 | 0.0159 | 7 | 0.0300 | 7 | 0.0334* |
| 10 | 0.0182 | 10 | 0.0382 | 10 | 0.0459* |
| 12 | 0.0233 | 12 | 0.0428 | 12 | 0.0518* |
| 14 | 0.0256 | 14 | 0.0490 | 14 | 0.0582* |
| 21 | 0.0356 | 21 | 0.0664 | 21 | 0.0885* |
| 28 | 0.0444 | 28 | 0.0823 | 28 | 0.1205* |
| 35 | 0.0536 | 35 | 0.0990 | 35 | 0.1495* |
| 42 | 0.0626 | 42 | 0.1200 | 42 | 0.1749* |
| 49 | 0.0733 | 49 | 0.1359 | 49 | 0.1977* |
| 56 | 0.0833 | 56 | 0.1541 | 56 | 0.2197* |

Table C.5 – 100% Spratt RCA with SCM average expansion results

0000* Results represent expansion attributed to ASR induced by agglomerated SF and confirmed by visual analysis that revealed significant reaction rings surrounding agglomerated SF particles.

| 70% Spratt RCA | | 70% Spratt with 25% LCFA | |
|----------------|------------------|--------------------------|------------------|
| Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0062 | 1 | 0.0036 |
| 3 | 0.0146 | 3 | 0.0078 |
| 5 | 0.0205 | 5 | 0.0136 |
| 7 | 0.0262 | 7 | 0.0169 |
| 10 | 0.0344 | 10 | 0.0244 |
| 12 | 0.0400 | 12 | 0.0274 |
| 14 | 0.0485 | 14 | 0.0333 |
| 21 | 0.0687 | 21 | 0.0446 |
| 28 | 0.0859 | 28 | 0.0523 |
| 35 | 0.1051 | 35 | 0.0638 |
| 42 | 0.1208 | 42 | 0.0721 |
| 49 | 0.1362 | 49 | 0.0821 |
| 56 | 0.1503 | 56 | 0.0931 |

| 70% Spratt RCA @ 1.5 | | 70% Spratt with 50% Slag | |
|----------------------|------------------|--------------------------|------------------|
| Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0056 | 1 | 0.0051 |
| 3 | 0.0138 | 3 | 0.0115 |
| 5 | 0.0254 | 5 | 0.0154 |
| 7 | 0.0331 | 7 | 0.0203 |
| 10 | 0.0451 | 10 | 0.0256 |
| 12 | 0.0510 | 12 | 0.0300 |
| 14 | 0.0572 | 14 | 0.0323 |
| 21 | 0.0774 | 21 | 0.0438 |
| 28 | 0.0987 | 28 | 0.0546 |
| 35 | 0.1169 | 35 | 0.0662 |
| 42 | 0.1351 | 42 | 0.0756 |
| 49 | 0.1513 | 49 | 0.0892 |
| 56 | 0.1656 | 56 | 0.1003 |

Table C.6 – 70% Spratt RCA with SCM average expansion results

| Alberta RCA 5-10 | | Alberta RCA 10-14 | | Potsdam RCA 5-10 | | Potsdam RCA 10-14 | |
|------------------|------------------|-------------------|------------------|------------------|------------------|-------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0121 | 1 | 0.0064 | 1 | 0.0087 | 1 | 0.0062 |
| 3 | 0.0192 | 3 | 0.0138 | 3 | 0.0177 | 3 | 0.0146 |
| 5 | 0.0277 | 5 | 0.0233 | 5 | 0.0262 | 5 | 0.0205 |
| 7 | 0.0364 | 7 | 0.0315 | 7 | 0.0344 | 7 | 0.0295 |
| 10 | 0.0500 | 10 | 0.0456 | 10 | 0.0462 | 10 | 0.0421 |
| 12 | 0.0605 | 12 | 0.0505 | 12 | 0.0551 | 12 | 0.0479 |
| 14 | 0.0685 | 14 | 0.0610 | 14 | 0.0638 | 14 | 0.0556 |
| 21 | 0.1000 | 21 | 0.0846 | 21 | 0.0938 | 21 | 0.0808 |
| 28 | 0.1292 | 28 | 0.1079 | 28 | 0.1205 | 28 | 0.1072 |
| 35 | 0.1538 | 35 | 0.1297 | 35 | 0.1454 | 35 | 0.1303 |
| 42 | 0.1777 | 42 | 0.1528 | 42 | 0.1695 | 42 | 0.1503 |
| 49 | 0.2005 | 49 | 0.1715 | 49 | 0.1936 | 49 | 0.1708 |
| 56 | 0.2200 | 56 | 0.1890 | 56 | 0.2151 | 56 | 0.1915 |

| Bernier RCA 5-10 | | Bernier RCA 10-14 | | Springhill RCA 5-10 | | Springhill RCA 10-14 | |
|------------------|------------------|-------------------|------------------|---------------------|------------------|----------------------|------------------|
| Age | % Change Average | Age | % Change Average | Age | % Change Average | Age | % Change Average |
| 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 | 0 | 0.0000 |
| 1 | 0.0072 | 1 | 0.0025 | 1 | 0.0077 | 1 | 0.0049 |
| 3 | 0.0141 | 3 | 0.0100 | 3 | 0.0197 | 3 | 0.0138 |
| 5 | 0.0215 | 5 | 0.0156 | 5 | 0.0315 | 5 | 0.0200 |
| 7 | 0.0292 | 7 | 0.0206 | 7 | 0.0438 | 7 | 0.0326 |
| 10 | 0.0369 | 10 | 0.0279 | 10 | 0.0592 | 10 | 0.0454 |
| 12 | 0.0431 | 12 | 0.0323 | 12 | 0.0697 | 12 | 0.0526 |
| 14 | 0.0485 | 14 | 0.0390 | 14 | 0.0792 | 14 | 0.0610 |
| 21 | 0.0656 | 21 | 0.0538 | 21 | 0.1138 | 21 | 0.0851 |
| 28 | 0.0856 | 28 | 0.0697 | 28 | 0.1415 | 28 | 0.1069 |
| 35 | 0.1038 | 35 | 0.0867 | 35 | 0.1692 | 35 | 0.1292 |
| 42 | 0.1218 | 42 | 0.1031 | 42 | 0.1926 | 42 | 0.1446 |
| 49 | 0.1374 | 49 | 0.1195 | 49 | 0.2164 | 49 | 0.1646 |
| 56 | 0.1549 | 56 | 0.1338 | 56 | 0.2372 | 56 | 0.1823 |

Table C.7 – Interlab RCA average expansion results

| 70% Spratt RCA AMBT | |
|---------------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0172 |
| 3 | 0.0751 |
| 5 | 0.1505 |
| 7 | 0.1992 |
| 10 | 0.2454 |
| 12 | 0.2651 |
| 14 | 0.2777 |
| 21 | 0.3008 |
| 28 | 0.3151 |

| 70% Spratt RCA with 25% LCFA AMBT | |
|--------------------------------------|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0036 |
| 3 | 0.0090 |
| 5 | 0.0141 |
| 7 | 0.0259 |
| 10 | 0.0354 |
| 12 | 0.0399 |
| 14 | 0.0477 |
| 21 | 0.0741 |
| 28 | 0.1028 |

| 100% RCA with 5% SF & 30% LCFA AMBT | |
|--|------------------|
| Age | % Change Average |
| 0 | 0.0000 |
| 1 | 0.0018 |
| 3 | 0.0087 |
| 5 | 0.0136 |
| 7 | 0.0192 |
| 10 | 0.0272 |
| 12 | 0.0331 |
| 14 | 0.0374 |
| 21 | 0.0646 |
| 28 | 0.1010 |

Table C.8 – Spratt RCA AMBT Comparison average expansion results

Appendix D – Porosity and RCPT Results

| Specimen ID | Dry Mass (g) | SSD Mass (g) | Mass in Water (g) | Density (Water) (kg/m ³) | Density (kg/m ³) | Volume (L) | Porosity % | RCPT | AVG. Por. % | AVG. RCPT |
|-------------|--------------|--------------|-------------------|--------------------------------------|------------------------------|------------|------------|------|-------------|-----------|
| CPT A | 954.9 | 1017.1 | 594.2 | 997.9 | 2400.0 | 0.4238 | 14.677 | 2527 | | |
| CPT B | 958.3 | 1017.8 | 596.0 | 997.9 | 2407.9 | 0.4227 | 14.077 | 1919 | 14.12 | 2241 |
| CPT C | 921.1 | 976.3 | 571.8 | 997.9 | 2408.5 | 0.4054 | 13.618 | 2276 | | |
| CPT 25% A | 927.3 | 993.4 | 576.5 | 997.9 | 2377.8 | 0.4178 | 15.822 | 317 | | |
| CPT 25% B | 937.2 | 995.8 | 582.1 | 997.9 | 2402.0 | 0.4146 | 14.135 | 231 | 14.23 | 272 |
| CPT 25% C | 957.4 | 1010.3 | 595.5 | 997.9 | 2430.5 | 0.4157 | 12.726 | 267 | | |
| CPT 23°C A | 948.9 | 1011.2 | 595.4 | 998.1 | 2427.3 | 0.4166 | 14.955 | 2698 | | |
| CPT 23°C B | 934.0 | 993.0 | 588.1 | 998.1 | 2447.8 | 0.4057 | 14.544 | 1981 | 14.39 | 2270 |
| CPT 23°C C | 938.3 | 993.6 | 589.5 | 998.1 | 2454.1 | 0.4049 | 13.659 | 2131 | | |

Table D.1 – Porosity and Permeability test results for CPT test specimens

| Specimen ID | Dry Mass (kg) | SSD Mass (kg) | Mass in Water (kg) | Density (Water) (kg/m ³) | Density (kg/m ³) | Volume (L) | Porosity % | RCPT | AVG. Por. % | AVG. RCPT |
|---------------|---------------|---------------|--------------------|--------------------------------------|------------------------------|------------|------------|-------|-------------|-----------|
| Ottawa A | 791.7 | 874.6 | 467.6 | 997.9 | 2144.4 | 0.4079 | 20.326 | 13000 | | |
| Ottawa B | 793.1 | 877.8 | 470.2 | 997.9 | 2149.1 | 0.4085 | 20.737 | 13000 | 20.66 | 13000 |
| Ottawa C | 799.6 | 885.8 | 474.5 | 997.9 | 2149.1 | 0.4122 | 20.914 | 13000 | | |
| Ottawa 25% A | 829.3 | 886.0 | 476.5 | 997.9 | 2159.1 | 0.4104 | 13.817 | 453 | | |
| Ottawa 25% B | 831.8 | 891.1 | 479.5 | 997.9 | 2160.4 | 0.4125 | 14.377 | 470 | 14.46 | 486 |
| Ottawa 25% C | 818.9 | 880.7 | 474.8 | 997.9 | 2165.2 | 0.4068 | 15.193 | 535 | | |
| Ottawa 23°C A | 803.2 | 879.0 | 467.4 | 998.1 | 2131.5 | 0.4124 | 18.381 | 8646 | | |
| Ottawa 23°C B | 809.5 | 880.8 | 469.5 | 998.1 | 2137.4 | 0.4121 | 17.302 | 9028 | 17.37 | 8933 |
| Ottawa 23°C C | 808.7 | 875.9 | 467.8 | 998.1 | 2142.2 | 0.4089 | 16.435 | 9126 | | |
| Spratt A | 831.2 | 913.6 | 507.4 | 997.6 | 2243.7 | 0.4072 | 20.237 | 10028 | | |
| Spratt B | 855.9 | 939.7 | 522.4 | 997.6 | 2246.5 | 0.4183 | 20.033 | 9175 | 20.01 | 9361 |
| Spratt C | 882.0 | 966.5 | 539.7 | 997.6 | 2259.1 | 0.4278 | 19.751 | 8881 | | |
| Spratt 25% A | 875.9 | 939.8 | 517.4 | 997.6 | 2219.6 | 0.4234 | 15.092 | 440 | | |
| Spratt 25% B | 876.2 | 942.7 | 520.1 | 997.6 | 2225.4 | 0.4236 | 15.698 | 443 | 15.61 | 454 |
| Spratt 25% C | 852.7 | 918.6 | 508.8 | 997.6 | 2236.2 | 0.4108 | 16.042 | 478 | | |

Table D.2 – Porosity and Permeability test results for AMBT test specimens

| Specimen ID | Dry Mass (kg) | SSD Mass (kg) | Mass in Water (kg) | Density (Water) | Density (kg/m ³) | Volume (L) | Porosity % | RCPT | AVG. Por. % | AVG. RCPT |
|----------------|---------------|---------------|--------------------|-----------------|------------------------------|------------|------------|------|-------------|-----------|
| CMBT A | 926.3 | 995.7 | 571.4 | 998.1 | 2342.2 | 0.4251 | 16.325 | 7114 | | |
| CMBT B | 899.6 | 970.1 | 553.8 | 998.1 | 2325.9 | 0.4171 | 16.903 | 7393 | 16.85 | 7547 |
| CMBT C | 904.7 | 978.0 | 555.6 | 998.1 | 2310.9 | 0.4232 | 17.320 | 8135 | | |
| CMBT 25% A | 911.0 | 964.0 | 555.8 | 998.0 | 2356.9 | 0.4090 | 12.958 | 432 | | |
| CMBT 25% B | 886.2 | 947.5 | 535.7 | 998.0 | 2296.3 | 0.4126 | 14.856 | 471 | 14.57 | 473 |
| CMBT 25% C | 863.7 | 929.1 | 518.2 | 998.0 | 2256.6 | 0.4117 | 15.884 | 516 | | |
| CMBT 25% EQ. A | 871.9 | 939.8 | 531.2 | 998.0 | 2295.4 | 0.4094 | 16.584 | 2046 | | |
| CMBT 25% EQ. B | 918.3 | 985.3 | 560.3 | 998.0 | 2313.7 | 0.4259 | 15.733 | 1975 | 15.73 | 1968 |
| CMBT 25% EQ. C | 904.5 | 966.0 | 553.0 | 998.0 | 2334.3 | 0.4138 | 14.861 | 1883 | | |
| CMBT 23°C A | 878.8 | 959.6 | 543.9 | 998.1 | 2304.0 | 0.4165 | 19.400 | 4675 | | |
| CMBT 23°C B | 916.2 | 991.2 | 568.6 | 998.1 | 2341.0 | 0.4234 | 17.714 | 6673 | 18.20 | 5482 |
| CMBT 23°C C | 908.5 | 981.7 | 564.1 | 998.1 | 2346.3 | 0.4184 | 17.495 | 5099 | | |

Table D.3 – Porosity and Permeability test results for CMBT test specimens

Appendix E – Alkali Leaching Test Results

| SCM | Mass of Paste (g) | Mass of RCA (g) | Mass of Solution (g) |
|-------------------|-------------------|-----------------|----------------------|
| 20/30 LCFA/Slag | 5.50 | | 55.0 |
| 20/30 LCFA/Sl (B) | 5.50 | | 55.0 |
| 25% MCFA | 5.50 | | 55.0 |
| 30% HCFA | 5.50 | | 55.0 |
| 5/30 SF/LCFA | 5.50 | | 55.0 |
| 5/25 SF/Slag | 5.50 | | 55.0 |
| 10% MK | 5.50 | | 55.0 |

Table E.1 – Specimen batch sizes for SCM paste specimens

| SCM | Mass of Paste (g) | Mass of RCA (g) | Mass of Solution (g) |
|------------------|-------------------|-----------------|----------------------|
| 20/30 LCFA/Slag | 4.99 | 11.98 | 49.9 |
| 25% MCFA | 5.02 | 12.05 | 50.2 |
| 30% HCFA | 4.99 | 11.98 | 49.9 |
| 5/30 SF/LCFA | 4.95 | 11.88 | 49.5 |
| 5/30 SF/LCFA (B) | 4.99 | 11.98 | 49.9 |
| 5/25 SF/Slag | 4.97 | 11.93 | 49.7 |
| 10% MK | 4.63 | 11.11 | 46.3 |

Table E.2 – Specimen batch sizes for SCM paste with RCA specimens

| SCM | Mass of Paste (g) | Mass of RCA (g) | Mass of Solution (g) |
|-----------------|-------------------|-----------------|----------------------|
| 20/30 LCFA/Slag | 4.93 | 8.28 | 49.3 |
| 5/30 SF/LCFA | 4.95 | 8.32 | 49.5 |
| 5/25 SF/Slag | 5.01 | 8.42 | 50.1 |
| 10% MK | 4.97 | 8.35 | 49.7 |

Table E.3 – Specimen batch sizes for SCM paste with 70% RCA specimens

| Control Type | Mass of Paste (g) | Mass of RCA (g) | Mass of Solution (g) |
|--------------|-------------------|-----------------|----------------------|
| PC | 5.50 | | 55.0 |
| PC (B) | 5.50 | | 55.0 |
| PC RCA | 4.93 | 11.83 | 49.3 |
| RCA | 4.93 | 11.83 | 49.3 |
| RCA (B) | 4.94 | 11.86 | 49.4 |
| 70% RCA | 4.99 | 8.38 | 49.9 |

Table E.4 – Specimen batch sizes for PC paste and RCA control specimens

| SCM | Cont. Mass (g) | Cont. + CM (g) | Cont. + Dry (g) | Evap. Water (%) |
|-----------------|----------------|----------------|-----------------|-----------------|
| 20/30 LCFA/Slag | 10.0195 | 11.9267 | 11.6176 | 16.207 |
| 25% MCFA | 10.1472 | 21.4251 | 19.1850 | 19.863 |
| 30% HCFA | 9.8980 | 21.8996 | 19.3772 | 21.017 |
| 5/30 SF/LCFA | 9.9445 | 11.2898 | 11.0498 | 17.840 |
| 5/25 SF/Slag | 9.7773 | 17.0538 | 15.5848 | 20.188 |
| 10% MK | 10.0080 | 17.7600 | 16.1800 | 20.382 |
| Control | 27.9547 | 29.2006 | 28.9702 | 18.493 |

Table E.5 – Evaporable water content of paste specimens

| SCM | Dry Mass (g) | Ignited Mass (g) | % Bound Water |
|-----------------|--------------|------------------|---------------|
| 20/30 LCFA/Slag | 2.3482 | 1.9824 | 18.452 |
| 25% MCFA | 6.0054 | 5.0797 | 18.224 |
| 30% HCFA | 2.9726 | 2.4740 | 20.154 |
| 5/30 SF/LCFA | 2.7153 | 2.3026 | 17.923 |
| 5/25 SF/Slag | 6.1827 | 5.2434 | 17.914 |
| 10% MK | 4.9164 | 4.1403 | 18.745 |
| Control | 1.9728 | 1.6638 | 18.572 |

Table E.6 – Non-evaporable water content of paste specimens

| SCM | %PC | %SCM ₁ | %SCM ₂ | LOI PC | LOI SCM ₁ | LOI SCM ₂ | LOI CM |
|-----------------|-----|-------------------|-------------------|--------|----------------------|----------------------|--------|
| 20/30 LCFA/Slag | 50 | 20 | 30 | 0.016 | 0.02 | 0.02 | 0.0180 |
| 25% MCFA | 75 | 25 | 0 | 0.016 | 0.02 | | 0.0170 |
| 30% HCFA | 70 | 30 | 0 | 0.016 | 0.025 | | 0.0187 |
| 5/30 SF/LCFA | 65 | 5 | 30 | 0.016 | 0.03 | 0.02 | 0.0179 |
| 5/25 SF/Slag | 70 | 5 | 25 | 0.016 | 0.03 | 0.02 | 0.0177 |
| 10% MK | 90 | 10 | 0 | 0.016 | 0.02 | | 0.0164 |
| Control | 100 | 0 | 0 | 0.016 | | | 0.0160 |

Table E.7 – Estimated loss on ignition for solids in paste specimens

| Alkali Concentration Bottle # | Test A | Na (PPM) | | | | | | K (PPM) | | | | | | Average *200 |
|----------------------------------|--------|----------|--------|--------|--------|--------|--------|---------|--------|--------|--------|--------|----------|--------------|
| | | Test B | Test C | Test D | Test E | Test F | Test A | Test B | Test C | Test D | Test E | Test F | Na (PPM) | |
| 20/30 LCFA/Slag | 32.4 | 31.4 | 30.4 | 32.0 | 32.4 | 30.6 | 2.4 | 2.4 | 2.4 | 2.4 | 2.2 | 2.4 | 6306.7 | 473.3 |
| 20/30 LCFA/Slag (B) | 31.4 | 31.0 | 30.0 | 31.2 | 30.4 | 29.6 | 2.4 | 2.2 | 2.2 | 2.4 | 2.4 | 2.2 | 6120.0 | 453.3 |
| 25% MCFA | 33.6 | 32.2 | 32.2 | 32.4 | 31.2 | 31.6 | 3.0 | 2.8 | 3.0 | 2.8 | 2.8 | 2.8 | 6440.0 | 573.3 |
| 30% HCFA | 33.2 | 32.6 | 31.8 | 33.2 | 31.8 | 32.4 | 3.0 | 3.0 | 3.0 | 2.8 | 2.8 | 3.0 | 6500.0 | 587.7 |
| 5/30 SF/LCFA | 33.2 | 33.4 | 32.4 | 32.0 | 30.4 | 30.6 | 2.8 | 2.6 | 2.8 | 2.8 | 2.8 | 2.8 | 6400.0 | 546.7 |
| 5/25 SF/Slag | 32.0 | 34.0 | 32.6 | 33.4 | 32.8 | 32.2 | 3.2 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 6566.7 | 606.7 |
| 10% MK | 33.4 | 34.0 | 32.6 | 33.0 | 32.4 | 32.4 | 3.8 | 3.6 | 3.8 | 3.6 | 3.6 | 3.6 | 6593.3 | 733.3 |

Table E.8 – Alkali concentration of solution in SCM paste specimens

| Alkali Concentration Bottle # | Test A | Na (PPM) | | | | | | K (PPM) | | | | | | Average * 200 |
|----------------------------------|--------|----------|--------|--------|--------|--------|--------|---------|--------|--------|--------|--------|----------|---------------|
| | | Test B | Test C | Test D | Test E | Test F | Test A | Test B | Test C | Test D | Test E | Test F | Na (PPM) | |
| 20/30 LCFA/Slag | 31.8 | 31.6 | 32.2 | 32.2 | 31.8 | 31.4 | 2.8 | 3.0 | 2.8 | 3.0 | 3.0 | 2.8 | 6366.7 | 580.0 |
| 25% MCFA | 35.8 | 34.8 | 32.8 | 33.8 | 34.2 | 33.2 | 3.8 | 4.0 | 4.0 | 3.8 | 3.8 | 3.8 | 6820.0 | 773.3 |
| 30% HCFA | 32.2 | 34.6 | 32.4 | 32.4 | 33.2 | 31.8 | 3.8 | 3.6 | 3.4 | 3.4 | 3.6 | 3.6 | 6553.3 | 713.3 |
| 5/30 SF/LCFA | 32.4 | 33.0 | 31.4 | 32.4 | 31.8 | 32.4 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 6446.7 | 720.0 |
| 5/30 SF/LCFA (B) | 31.2 | 34.2 | 32.8 | 32.8 | 32.6 | 32.4 | 3.6 | 3.8 | 3.6 | 3.8 | 3.8 | 3.8 | 6533.3 | 746.7 |
| 5/25 SF/Slag | 31.8 | 31.4 | 32.4 | 32.2 | 33.6 | 33.4 | 4.0 | 4.0 | 4.2 | 4.0 | 4.2 | 4.2 | 6493.3 | 813.3 |
| 10% MK | 32.0 | 32.0 | 31.4 | 30.0 | 30.4 | 31.0 | 3.8 | 4.2 | 4.0 | 4.0 | 4.2 | 4.2 | 6226.7 | 813.3 |

Table E.9 – Alkali concentration of solution in SCM paste with RCA

| Alkali Concentration | | Na (PPM) | | | | | | K (PPM) | | | | | | Average * 200 | |
|----------------------|----------|----------|--------|--------|--------|--------|--------|---------|--------|--------|--------|--------|--------|---------------|---------|
| Control Type | Bottle # | Test A | Test B | Test C | Test D | Test E | Test F | Test A | Test B | Test C | Test D | Test E | Test F | Na (PPM) | K (PPM) |
| PC | 17 | 33.6 | 32.8 | 32.8 | 33.2 | 31.8 | 32.8 | 4.2 | 4.4 | 4.2 | 4.2 | 4.4 | 4.2 | 6566.7 | 853.3 |
| PC (B) | 17B | 33.2 | 34.0 | 33.8 | 32.4 | 32.6 | 31.8 | 4.4 | 4.4 | 4.4 | 4.2 | 4.2 | 4.4 | 6593.3 | 866.7 |
| PC RCA | 18 | 33.4 | 33.4 | 31.8 | 32.8 | 32.2 | 32.0 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 6520.0 | 720.0 |
| RCA | 19 | 32.8 | 32.6 | 31.8 | 32.0 | 32.0 | 31.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 6433.3 | 200.0 |
| RCA (B) | 19B | 33.2 | 33.6 | 31.8 | 32.6 | 33.2 | 32.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 6566.7 | 200.0 |
| 70% RCA | 20 | 34.4 | 34.4 | 33.2 | 33.4 | 34.2 | 32.8 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 6746.7 | 120.0 |
| Solution A | A | 33.6 | 33.6 | 34.2 | 33.4 | 33.4 | 33.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6713.3 | 0.0 |
| Solution B | B | 33.2 | 33.6 | 34.0 | 32.8 | 34.6 | 33.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6713.3 | 0.0 |

Table E.10 – Alkali concentration of solution in SCM paste with RCA

| Alkali Concentration | | Na (PPM) | | | | | | K (PPM) | | | | | | Average * 200 | |
|----------------------|----------|----------|--------|--------|--------|--------|--------|---------|--------|--------|--------|--------|--------|---------------|---------|
| SCM | Bottle # | Test A | Test B | Test C | Test D | Test E | Test F | Test A | Test B | Test C | Test D | Test E | Test F | Na (PPM) | K (PPM) |
| 20/30 LCFA/Slag | 13 | 30.8 | 31.0 | 29.6 | 30.4 | 30.6 | 31.0 | 3.2 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 6113.3 | 606.7 |
| 5/30 SF/LCFA | 14 | 31.6 | 31.6 | 32.0 | 30.6 | 31.2 | 31.8 | 3.2 | 3.2 | 3.2 | 3.2 | 3.4 | 3.2 | 6293.3 | 646.7 |
| 5/25 SF/Slag | 15 | 32.6 | 30.8 | 31.0 | 31.2 | 31.4 | 31.2 | 3.6 | 3.8 | 3.8 | 4.0 | 3.8 | 3.6 | 6273.3 | 753.3 |
| 10% MK | 16 | 32.8 | 32.8 | 34.8 | 31.8 | 32.8 | 31.0 | 4.2 | 4.4 | 4.4 | 4.2 | 4.2 | 4.0 | 6533.3 | 846.7 |

Table E.11 – Alkali concentration of solution in PC paste and RCA control

| Row Identifier | Units | SCM Paste Specimens | | | | | | | | | | | | | |
|----------------|---|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | |
| 1 | Bottle Number | # | 1B | 25% MCFA | 30% HCFA | 5/30 SF/LCFA | 5/25 SF/Slag | 10% MK | | | | | | | |
| 2 | Sample ID | ID | 20/30 LCFA/Slag |
| 3 | Mass of CM | g | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 | 5.50 |
| 4 | Mass of Solution | g | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 | 55.00 |
| 5 | Initial Na Concentration | ppm | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 |
| 6 | Final Na Concentration | ppm | 6306.7 | 6120 | 6440.0 | 6500.0 | 6400.0 | 6566.7 | 6593.3 | 6593.3 | 6593.3 | 6593.3 | 6593.3 | 6593.3 | 6593.3 |
| 7 | Initial K Concentration | ppm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | Final K Concentration | ppm | 473.3 | 453.3 | 573.3 | 587.7 | 546.7 | 606.7 | 733.3 | 733.3 | 733.3 | 733.3 | 733.3 | 733.3 | 733.3 |
| 9 | CM Moisture Content | %/100 | 0.16207 | 0.16207 | 0.19863 | 0.21017 | 0.1784 | 0.20188 | 0.20382 | 0.20382 | 0.20382 | 0.20382 | 0.20382 | 0.20382 | 0.20382 |
| 10 | Mass of Dry CM | g | 4.6086 | 4.6086 | 4.4075 | 4.3441 | 4.5188 | 4.3897 | 4.3790 | 4.3790 | 4.3790 | 4.3790 | 4.3790 | 4.3790 | 4.3790 |
| 11 | LOI | %/100 | 0.18452 | 0.18452 | 0.18224 | 0.20154 | 0.17923 | 0.17914 | 0.18745 | 0.18745 | 0.18745 | 0.18745 | 0.18745 | 0.18745 | 0.18745 |
| 12 | Ignited Solids Mass | g | 3.7582 | 3.7582 | 3.6043 | 3.4686 | 3.7089 | 3.6033 | 3.5581 | 3.5581 | 3.5581 | 3.5581 | 3.5581 | 3.5581 | 3.5581 |
| 13 | CM LOI | %/100 | 0.0180 | 0.0180 | 0.0170 | 0.0187 | 0.0179 | 0.0177 | 0.0164 | 0.0164 | 0.0164 | 0.0164 | 0.0164 | 0.0164 | 0.0164 |
| 14 | Corrected Mass of CM | g | 3.8259 | 3.8259 | 3.6656 | 3.5334 | 3.7753 | 3.6671 | 3.6165 | 3.6165 | 3.6165 | 3.6165 | 3.6165 | 3.6165 | 3.6165 |
| 15 | Corrected Na Concentration | ppm | 6120.4 | 5939.2 | 6232.1 | 6275.6 | 6205.4 | 6354.9 | 6375.0 | 6375.0 | 6375.0 | 6375.0 | 6375.0 | 6375.0 | 6375.0 |
| 16 | Corrected K Concentration | ppm | 459.3 | 439.9 | 554.8 | 567.4 | 530.1 | 587.1 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 |
| 17 | Change in Na Concentration | ppm | -592.9 | -774.1 | -481.2 | -437.7 | -507.9 | -358.4 | -338.3 | -338.3 | -338.3 | -338.3 | -338.3 | -338.3 | -338.3 |
| 18 | Change in K Concentration | ppm | 459.3 | 439.9 | 554.8 | 567.4 | 530.1 | 587.1 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 | 709.0 |
| 19 | Change in Na Concentration | mol/L | -0.02579 | -0.03367 | -0.02093 | -0.01904 | -0.02209 | -0.01559 | -0.01472 | -0.01472 | -0.01472 | -0.01472 | -0.01472 | -0.01472 | -0.01472 |
| 20 | Change in K Concentration | mol/L | 0.01175 | 0.01125 | 0.01419 | 0.01451 | 0.01356 | 0.01502 | 0.01813 | 0.01813 | 0.01813 | 0.01813 | 0.01813 | 0.01813 | 0.01813 |
| 21 | Change in Concentration | mol/L | -0.01404 | -0.02242 | -0.00674 | -0.00453 | -0.00853 | -0.00057 | 0.00342 | 0.00342 | 0.00342 | 0.00342 | 0.00342 | 0.00342 | 0.00342 |
| 22 | Change in Moles | mol | -0.000772 | -0.001233 | -0.000371 | -0.000249 | -0.000469 | -0.000031 | 0.000188 | 0.000188 | 0.000188 | 0.000188 | 0.000188 | 0.000188 | 0.000188 |
| 23 | Change in Na ₂ O _e | mol | -0.00039 | -0.00062 | -0.00019 | -0.00012 | -0.00023 | -0.00002 | 0.00009 | 0.00009 | 0.00009 | 0.00009 | 0.00009 | 0.00009 | 0.00009 |
| 24 | Change in Na ₂ O _e | g | -0.02393 | -0.03821 | -0.01149 | -0.00771 | -0.01455 | -0.00097 | 0.00583 | 0.00583 | 0.00583 | 0.00583 | 0.00583 | 0.00583 | 0.00583 |
| 25 | Change in Na ₂ O _e as % of CM | % | -0.43514 | -0.69476 | -0.20885 | -0.14026 | -0.26448 | -0.01772 | 0.10594 | 0.10594 | 0.10594 | 0.10594 | 0.10594 | 0.10594 | 0.10594 |

Table E.12 – Alkali binding capacity of SCM paste specimens

| Row Identifier | Bottle Number | Units | SCM Paste Specimens with 70% RCA | | | |
|----------------|---|-------|----------------------------------|--------------|--------------|----------|
| | | | 13 | 14 | 15 | 16 |
| | Sample ID | ID | 20/30 LCFA/Slag | 5/30 SF/LCFA | 5/25 SF/Slag | 10% MK |
| 1 | Mass of CM | g | 4.93 | 4.95 | 5.01 | 4.97 |
| 2 | Mass of Solution | g | 49.30 | 49.50 | 50.10 | 49.70 |
| 3 | Initial Na Concentration | ppm | 6713.3 | 6713.3 | 6713.3 | 6713.3 |
| 4 | Final Na Concentration | ppm | 6113.3 | 6293.3 | 6273.3 | 6533.3 |
| 5 | Initial K Concentration | ppm | 0 | 0 | 0 | 0 |
| 6 | Final K Concentration | ppm | 606.7 | 646.7 | 753.3 | 846.7 |
| 7 | CM Moisture Content | %/100 | 0.16207 | 0.1784 | 0.20188 | 0.20382 |
| 8 | Mass of Dry CM | g | 4.1310 | 4.0669 | 3.9986 | 3.9570 |
| 9 | LOI | %/100 | 0.18452 | 0.17923 | 0.17914 | 0.18745 |
| 10 | Ignited Solids Mass | g | 3.3687 | 3.3380 | 3.2823 | 3.2153 |
| 11 | CM LOI | %/100 | 0.0180 | 0.0179 | 0.0177 | 0.0164 |
| 12 | Corrected Mass of CM | g | 3.4294 | 3.3978 | 3.3404 | 3.2680 |
| 13 | Corrected Na Concentration | ppm | 5932.7 | 6102.0 | 6071.0 | 6317.0 |
| 14 | Corrected K Concentration | ppm | 588.8 | 627.0 | 729.0 | 818.7 |
| 15 | Change in Na Concentration | ppm | -780.6 | -611.3 | -642.3 | -396.3 |
| 16 | Change in K Concentration | ppm | 588.8 | 627.0 | 729.0 | 818.7 |
| 17 | Change in Na Concentration | mol/L | -0.03395 | -0.02659 | -0.02794 | -0.01724 |
| 18 | Change in K Concentration | mol/L | 0.01506 | 0.01604 | 0.01865 | 0.02094 |
| 19 | Change in Concentration | mol/L | -0.01889 | -0.01055 | -0.00929 | 0.00370 |
| 20 | Change in Moles | mol | -0.000932 | -0.000522 | -0.000466 | 0.000184 |
| 21 | Change in Na ₂ O _e | mol | -0.00047 | -0.00026 | -0.00023 | 0.00009 |
| 22 | Change in Na ₂ O _e | g | -0.02887 | -0.01619 | -0.01443 | 0.00570 |
| 23 | Change in Na ₂ O _e as % of CM | % | -0.58553 | -0.32708 | -0.28801 | 0.56976 |

Table E.14 – Alkali binding capacity of SCM paste with 70% RCA specimens

| Row Identifier | Units | PC Paste and RCA Control Specimens | | | | | | | | | | | | | | | |
|----------------|---|------------------------------------|----------|----------|----------|-----------|-----------|-----------|-----------|-----------|----------|----------|-----------|-----------|-----------|-----------|-----------|
| | | 17B | 17C | 18 | 19 | 19B | 20 | 70% RCA | 17B | 17C | 18 | 19 | 19B | 20 | 70% RCA | | |
| 1 | Bottle Number | # | 17 | 17B | 17C | 18 | 19 | 19B | 20 | 70% RCA | 17B | 17C | 18 | 19 | 19B | 20 | 70% RCA |
| 2 | Sample ID | ID | PC | PC | PC RCA | PC RCA | PC RCA | RCA | RCA | RCA | PC | PC | PC RCA | PC RCA | RCA | RCA | RCA |
| 3 | Mass of CM | g | 5.50 | 5.50 | 4.93 | 4.93 | 0.00 | 0.00 | 0.00 | 0.00 | 5.50 | 5.50 | 4.93 | 4.93 | 0.00 | 0.00 | 0.00 |
| 4 | Mass of Solution | g | 55.00 | 55.00 | 49.30 | 49.30 | 49.30 | 49.30 | 49.30 | 49.30 | 55.00 | 55.00 | 49.30 | 49.30 | 49.30 | 49.30 | 49.30 |
| 5 | Initial Na Concentration | ppm | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 | 6713.3 |
| 6 | Final Na Concentration | ppm | 6566.7 | 6593.3 | 6520.0 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6593.3 | 6520.0 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6433.3 |
| 7 | Initial K Concentration | ppm | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | Final K Concentration | ppm | 853.3 | 866.7 | 720 | 200 | 200 | 200 | 200 | 200 | 866.7 | 720 | 200 | 200 | 200 | 200 | 200 |
| 9 | CM Moisture Content | %/100 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 | 0.18493 |
| 10 | Mass of Dry CM | g | 4.4829 | 4.4829 | 4.0183 | 4.0183 | 4.0183 | 4.0183 | 4.0183 | 4.0183 | 4.4829 | 4.0183 | 4.0183 | 4.0183 | 4.0183 | 4.0183 | 4.0183 |
| 11 | LOI | %/100 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 | 0.18572 |
| 12 | Ignited Solids Mass | g | 3.6503 | 3.6503 | 3.2720 | 3.2720 | 3.2720 | 3.2720 | 3.2720 | 3.2720 | 3.6503 | 3.2720 | 3.2720 | 3.2720 | 3.2720 | 3.2720 | 3.2720 |
| 13 | CM LOI | %/100 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 | 0.0160 |
| 14 | Corrected Mass of CM | g | 3.7087 | 3.7087 | 3.3244 | 3.3244 | 3.3244 | 3.3244 | 3.3244 | 3.3244 | 3.7087 | 3.3244 | 3.3244 | 3.3244 | 3.3244 | 3.3244 | 3.3244 |
| 15 | Corrected Na Concentration | ppm | 6359.6 | 6385.3 | 6314.4 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6385.3 | 6314.4 | 6433.3 | 6433.3 | 6433.3 | 6433.3 | 6433.3 |
| 16 | Corrected K Concentration | ppm | 826.4 | 839.4 | 697.3 | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 | 839.4 | 697.3 | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 |
| 17 | Change in Na Concentration | ppm | -353.7 | -328.0 | -398.9 | -280.0 | -280.0 | -280.0 | -280.0 | -280.0 | -328.0 | -398.9 | -280.0 | -280.0 | -280.0 | -280.0 | -280.0 |
| 18 | Change in K Concentration | ppm | 826.4 | 839.4 | 697.3 | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 | 839.4 | 697.3 | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 |
| 19 | Change in Na Concentration | mol/L | -0.01539 | -0.01427 | -0.01735 | -0.01218 | -0.01218 | -0.01218 | -0.01218 | -0.01218 | -0.01427 | -0.01735 | -0.01218 | -0.01218 | -0.01218 | -0.01218 | -0.01218 |
| 20 | Change in K Concentration | mol/L | 0.02114 | 0.02147 | 0.01783 | 0.00512 | 0.00512 | 0.00512 | 0.00512 | 0.00512 | 0.02147 | 0.01783 | 0.00512 | 0.00512 | 0.00512 | 0.00512 | 0.00512 |
| 21 | Change in Concentration | mol/L | 0.00575 | 0.00720 | 0.00048 | -0.00706 | -0.00706 | -0.00706 | -0.00706 | -0.00706 | 0.00720 | 0.00048 | -0.00706 | -0.00706 | -0.00706 | -0.00706 | -0.00706 |
| 22 | Change in Moles | mol | 0.000316 | 0.000396 | 0.000024 | -0.000348 | -0.000348 | -0.000348 | -0.000348 | -0.000348 | 0.000396 | 0.000024 | -0.000348 | -0.000348 | -0.000348 | -0.000348 | -0.000348 |
| 23 | Change in Na ₂ O _e | mol | 0.00016 | 0.00020 | 0.00001 | -0.00017 | -0.00017 | -0.00017 | -0.00017 | -0.00017 | 0.00020 | 0.00001 | -0.00017 | -0.00017 | -0.00017 | -0.00017 | -0.00017 |
| 24 | Change in Na ₂ O _e | g | 0.00980 | 0.01228 | 0.00073 | -0.01079 | -0.01079 | -0.01079 | -0.01079 | -0.01079 | 0.01228 | 0.00073 | -0.01079 | -0.01079 | -0.01079 | -0.01079 | -0.01079 |
| 25 | Change in Na ₂ O _e as % of CM | % | 0.17819 | 0.22320 | 0.01490 | -1.07922 | -1.07922 | -1.07922 | -1.07922 | -1.07922 | 0.22320 | 0.01490 | -1.07922 | -1.07922 | -1.07922 | -1.07922 | -1.07922 |

Table E.15 – Alkali binding capacity of PC paste and RCA control specimens

Appendix F – Alkali Leaching Test Calculation Procedure

Row Identifiers as shown in Tables E.12 through E.15

| Row # | Row Content | Units | Description of Content and Required Operations |
|-------|---|-------|---|
| 1 | Bottle Number | # | Bottle Identifier |
| 2 | Sample ID | ID | Specimen Description |
| 3 | Mass of CM | g | Initial mass of CM added to bottle |
| 4 | Mass of Solution | g | Solution mass added to the bottle |
| 5 | Initial Na Concentration | ppm | Average concentration of Na in control solution |
| 6 | Final Na Concentration | ppm | Average concentration of Na solution after 28 days |
| 7 | Initial K Concentration | ppm | Average concentration of K in control solution |
| 8 | Final K Concentration | ppm | Average concentration of K solution after 28 days |
| 9 | CM Moisture Content | %/100 | Evaporable water content of CM |
| 10 | Mass of Dry CM | g | Correction for evaporable water in CM $Row\ 3 * (1 - Row\ 9)$ |
| 11 | LOI | %/100 | Loss On Ignition of CM |
| 12 | Ignited Solids Mass | g | Correction for LOI of CM $Row\ 10 * (1 - Row\ 11)$ |
| 13 | Raw CM LOI | %/100 | LOI of raw CM |
| 14 | Corrected Mass of CM | g | Correction for non-evaporable water in CM $Row\ 12 * (1 + Row\ 13)$ |
| 15 | Corrected Na Concentration | ppm | Na concentration adjusted for water in CM $Row\ 6 * \left(\frac{Row\ 4}{Row\ 4 + (Row\ 3 - Row\ 14)} \right)$ |
| 16 | Corrected K Concentration | ppm | K concentration adjusted for water in CM $Row\ 8 * \left(\frac{Row\ 4}{Row\ 4 + (Row\ 3 - Row\ 14)} \right)$ |
| 17 | Change in Na Concentration | ppm | $Row\ 15 - Row\ 5$ |
| 18 | Change in K Concentration | ppm | $Row\ 16 - Row\ 7$ |
| 19 | Change in Na Concentration | mol/L | Corrected for molar mass of Na * 1000 unit correction $Row\ 17 * 22,989.8$ |
| 20 | Change in K Concentration | mol/L | Corrected for molar mass of K * 1000 unit correction $Row\ 18 * 39,093.8$ |
| 21 | Change in Concentration | mol/L | Total change in concentration $Row\ 19 + Row\ 20$ |
| 22 | Change in Moles | mol | Change in moles in the solution sample $Row\ 21 * \left(\frac{Row\ 4}{1000} \right)$ |
| 23 | Change in Na ₂ O _e | mol | Difference in alkalis in Na ₂ O _e $\left(\frac{Row\ 22}{2} \right)$ |
| 24 | Change in Na ₂ O _e | g | Mass change of Na ₂ O _e $Row\ 23 * 61.9788$ |
| 25 | Change in Na ₂ O _e as % of CM | % | Change in alkali in solution as a percentage of the CM mass $\left(\frac{Row\ 24}{2} \right) * 100$ |

Table F.1 – Outline of correction procedures for calculating results of the alkali leaching test

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