LEACHING FROM GRANULAR WASTE MATERIALS USED IN HIGHWAY INFRASTRUCTURES DURING INFILTRATION COUPLED WITH FREEZING AND THAWING

Final Report

Submitted to:
The Recycled Material Resource Center
University of New Hampshire
220 Environmental Technology Building
35 Colovos Road
Durham, NH 03824

Submitted by:
Florence Sanchez, Ph.D.
E-mail: Florence.sanchez@vanderbilt.edu

Vanderbilt University
Department of Civil and Environmental Engineering
VU Station B-35 1831 - Nashville, TN 37235.

May 2006

ACKNOWLEDGEMENTS

The research presented here is based on work supported by the Federal Highway Administration (FHWA) under Cooperative Agreement No. DTFH61-98-X-00095 through the Recycled Materials Resource Center at the University of New Hampshire, Durham, New Hampshire. The Recycled Material Resource Center at the University of New Hampshire sponsored this research project under the subcontract #04-819.

Laboratory testing described herein was carried out by Anh Hoang and Katherine Langley White as part of their Masters Thesis[1,2] in Environmental Engineering at Vanderbilt University. Rossane DeLapp, laboratory research engineer in the Civil and Environmental Engineering department at Vanderbilt University was responsible for the chemical analyses.

---

[1] Anh Thi Lan Hoang. M.S. August 2004. Thesis: “Effect of freezing and thawing on recycled concrete during a flow around scenario.”

[2] Mary Katherine Langley White. M.S. May 2005. Thesis: “Leaching from granular waste materials used in highway infrastructures during infiltration coupled with freezing and thawing.”

ABSTRACT

Many secondary materials are being considered for use as substitutes for natural aggregates in highway applications due to suitable engineering and economic properties. The durability of aggregate materials against the forces of weathering is an important consideration in the selection of the material. A primary exposure of concern is alternate freezing and thawing. Current test methods for evaluating the soundness of aggregates that undergo freezing and thawing are based only upon meeting physical test criteria and do not integrate environmental material performance. However, during the design life of the application, materials are exposed to freeze/thaw cycles coupled with intermittent infiltration/wetting by precipitation events. In such a scenario, leaching of material constituents is a primary pathway for environmental impact. Material freeze/thaw durability and its impact on flow mechanisms may then be of concern. The objective of the research reported here was to study the effect of freezing and thawing processes on flow mechanisms and constituent leaching from granular materials used in highway infrastructures. Scenarios considered included water percolating through the material and run-off (flow-around), both of which are important routes in the highway environment for leaching of constituent of potential concern present in recycled materials. The effect of material moisture content at the time of freezing, the number of freeze/thaw cycles, and material gradation were investigated.

GLOSSARY OF TERMS

ANOVA	Analysis of the variance
C&D	Construction-demolition debris
F/T	Freezing and thawing
ICP-MS	Inductively coupled plasma mass spectroscopy
LFC	Laboratory formulated concrete
LS	Liquid-to-solid ratio (LS ratio)
MCL	Maximum concentration limit (for drinking water)
MDL	Method detection limit
ML	Minimum level of quantification
PCC	Portland cement concrete
QA/QC	Quality assurance/Quality control
RCA	Recycled concrete aggregates
XRF	X-ray fluorescence

EXECUTIVE SUMMARY

This report evaluates the effect of freezing and thawing processes on flow mechanisms and constituent leaching from recycled concrete aggregates (RCA) used in highway construction applications. This research effort was sponsored by the Federal Highway Administration (FHWA) through the Recycled Material Resource Center (RMRC) at the University of New Hampshire.

The specific objectives of the research reported here were to:

1. Determine the effect of material moisture content at the time of freezing on material integrity (i.e., change in particle size distribution) and constituent release during percolation flow controlled scenarios;
2. Examine the effect of the number of freeze/thaw cycles on material integrity and constituent release during percolation flow and flow-around controlled scenarios;
3. Determine the effect of material gradation in conjunction with freezing and thawing on material integrity and constituent leaching during flow-around controlled scenarios; and,
4. Develop guidelines for simplified test methods and accelerated aging procedures that can be used by end-users to assess the potential impact of freezing and thawing processes on constituent leaching during percolation flow controlled scenarios.

The approach to satisfying these objectives was to use a laboratory formulated concrete (LFC) spiked with metal oxides as a model system to simulate RCA and to perform laboratory flow-through column studies and flow-around mass transfer studies coupled with freeze/thaw exposure. As an initial method validation, the performance of construction-demolition debris (C&D material) was evaluated using intermittent flow-through columns coupled with F/T exposure.

For the flow-through scenario, three moisture contents of the packed material and four levels of freeze/thaw (F/T) aging were examined to simulate different extents of freeze/thaw exposure. The moisture contents used (7%, 15%, and 29%) included the moisture content of the LFC material at its optimum packing density (29%), the moisture content of the material as is (7%), which represented ca. 24% of the value of the optimum moisture content, and a moisture content of 15%, which represented ca. 52% of the value of the optimum moisture content. The LFC material packed at each of the three moisture contents was subjected to 0, 10, 20, and 40 F/T cycles consisting of 8 hours of freezing at -12°C and 16 hours of thawing at room temperature (20 ± 3°C). At the conclusion of F/T exposure, a variety of response variables were measured. These included (i) material integrity (i.e., change in particle size distribution), (ii) infiltration patterns and flow mechanisms using column tracer experiments, and (iii) constituent leaching during percolation flow controlled scenarios using flow-through saturated column experiments.

For the flow-around scenario, two material gradations (less than 2 mm and less than 9.5 mm) and three levels of F/T exposure (0, 10, and 20 F/T cycles) of the LFC material packed at the optimum moisture content were examined. At the conclusion of F/T exposure, the following response variables were measured: (i) material integrity (i.e., change in particle size distribution), (ii) material height and weight, and (iii) constituent leaching during flow around controlled scenarios using flow-around mass transfer tests.

Additionally, a limited number of intermittent flow-around mass transfer tests coupled with F/T exposure and a limited number of intermittent flow-through columns coupled with F/T exposure were run on the less than 9.5 mm graded LFC material to simulate field-like conditions. This allowed for evaluation of leaching fluxes while distress due to freezing and thawing was occurring concurrently with constituent transport.

Analysis of the variance (ANOVA) was used for the flow-around mass transfer studies and flow-through column studies to determine the significance of the effects and interactions of (i) material moisture content at the time of freezing, (ii) material gradation, and (iii) level of F/T exposure on constituent release.

Summary of conclusions and significance

This research has shown that F/T exposure results in consolidation of granular cement-based materials (self-cementing properties) and therefore can have a significant impact in long-term release of constituents from RCA, depending upon flow scenario.

For applications where run-off is the primary route for leaching from RCA, F/T exposure can result in a significant decrease in the cumulative release of constituents as a function of time. A greater decrease was observed when the granular material was more finely grained (i.e., for lower material gradation). This research indicated that where F/T exposure is expected to be an important factor in the potential application, continuous tank leaching is a conservative estimate of the long-term release of constituents from RCA.

For applications where water percolating through the material is the primary route for leaching from RCA, the moisture content of the packed material at the time of freezing is an important parameter. Greater effects of F/T exposure (increase or decrease in the release) were observed when moisture content at the time of freezing was less than that of the optimum packing density (optimum moisture content). The effect of F/T exposure at the optimum moisture content was minimal and had no significance in the long-term release of constituents. Increases in the release compared to the no F/T exposure cases were observed after exposure to 10 and 20 F/T cycles for most constituents examined except for calcium and in some instances for chloride and sulfate, for which a decrease was observed. Exposure to 40 F/T cycles resulted for most cases in a decrease in the release compared to the no F/T exposure cases. Intermittent saturated flow conditions coupled with F/T exposure resulted in similar or lower release of constituents than under continuously saturated flow conditions. In general, batch testing provided a conservative estimate of column testing results. However, for arsenic and zinc, batch testing may under predict the release where F/T is an important factor and more complex testing may then be necessary. Further investigations are recommended.

This research suggests that, due to the self-cementing properties of RCA, leaching from RCA during run-off or percolation in applications where F/T exposure might be of importance will most likely be minimized with time and increased exposure to F/T cycles. However, an increase in the release might be initially observed during flow-through controlled scenarios due to preferential flow and/or cracks before subsequent decreases, as a result of self-cementing phenomena during further thawing and permeation, are observed.

Further research is needed to better understand the controlling factors of self-cementing processes during freezing and thawing and subsequent permeation.

TABLE OF CONTENTS

Acknowledgements i
Abstract ii
Glossary of terms iii
Executive summary iv
Table of contents vii
List of tables ix
List of figures xiii
1. Introduction 1
  1.1. Background 1
  1.2. Research objectives 1
  1.3. Research significance 2
2. Literature review 3
  2.1. Recycled concrete aggregates in construction applications 3
    2.1.1. Introduction 3
    2.1.2. RCA properties 3
    2.1.3. Performance of RCA as unbound road subbase 3
  2.2. Recycled materials in the highway environment and environmental consideration 4
  2.3. Overview of freezing and thawing in the environment 4
    2.3.1. Effect of F/T exposure on granular material structure and properties 5
    2.3.2. Factors affecting granular material response to F/T 6
  2.4. Conclusions 7
3. Materials and methods 8
  3.1. Experimental design 8
  3.2. Materials 9
    3.2.1. Laboratory formulated concrete 9
    3.2.2. Construction-demolition debris 9
  3.3. Methods 10
    3.3.1. Optimum moisture content 10
    3.3.2. F/T exposure 11
    3.3.3. Physical and chemical stability of the granular LFC material with respect to F/T exposure 12
    3.3.4. Flow-around mass transfer tests 13
    3.3.5. Flow-through column testing 14
    3.3.6. Intermittent wetting/flow-through coupled with F/T exposure 15
    3.3.7. Analytical methods 16
4. Results and Discussion 19
  4.1. Optimum moisture content 19
  4.2. F/T exposure and temperature profiles 19
  4.3. Physical and chemical stability of the granular LFC material with respect to F/T exposure 20
    4.3.1. Material physical stability 20
    4.3.2. Thermal stability of the mineral/chemical components of the LFC material 23
  4.4. Effect of F/T exposure on constituent leaching during flow-around controlled scenario 30
    4.4.1. Effect of F/T exposure on leachate pH and conductivity 30

4.4.2. Effect of F/T exposure on the release of major material constituents 31
4.4.3. Effect of F/T exposure on the release of primary contaminants................................. 42
4.4.4. ANOVA analysis 52
4.5. Effect of F/T exposure on flow pattern during percolation flow controlled scenario 62
4.5.1. Water flow 62
4.5.2. Transport of bromide 64
4.6. Effect of F/T exposure on constituent leaching during percolation flow controlled (flow-through) scenario 66
4.6.1. Effect of F/T exposure on leachate pH and conductivity 66
4.6.2. Effect of F/T exposure on the release of major material constituents 68
4.6.3. Effect of F/T exposure on the release of primary contaminants................................. 89
4.6.4. ANOVA analysis 110
4.7. Constituent leaching during intermittent wetting/flow-through coupled with F/T exposure.. 120
4.7.1. Intermittent wetting (flow-around) coupled with F/T exposure 120
4.7.2. Intermittent flow-through coupled with F/T exposure... 126
4.8. Initial method validation on construction demolition-debris.. 130
5. Conclusions and significance.. 134
6. References.. 138
7. Appendix (tables of supporting data).. 141
Appendix A - Chemical stability of the LFC material with respect to F/T exposure........... 141
Appendix B - Flow-around mass transfer tests.. 144
Appendix C - Flow-through column experiments 150
Appendix D - Intermittent wetting/flow-through coupled with F/T exposure 165

LIST OF TABLES

Table 1. Experimental design. 9
Table 2. Total elemental composition of the C&D material as determined by XRF (Lopez, 2006). 10
Table 3. Leaching and F/T exposure intervals for the intermittent flow-around mass transfer case. 16
Table 4. Leaching and F/T exposure intervals for the intermittent flow-through case. 16
Table 5. Detection limits for ICP-MS analysis for arsenic, calcium, cadmium, copper, potassium, sodium, lead, and zinc. 17
Table 6. Detection limits for IC analysis. 18
Table 7. ANOVA analysis of main and interaction effects on measured leachate pH and conductivity after 504 hours of leaching. 53
Table 8. ANOVA analysis of main and interaction effects on measured cumulative mass release of sodium, potassium, calcium, chloride, and sulfate after 504 hours (21 days) of leaching. 54
Table 9. ANOVA analysis of main and interaction effects on measured cumulative mass release of arsenic, cadmium, copper, lead, and zinc after 504 hours (21 days) of leaching. 58
Table 10. ANOVA analysis of main and interaction effects on measured leachate pH and conductivity at LS of 2 L/kg. 110
Table 11. ANOVA analysis of main and interaction effects on measured cumulative mass release of sodium, potassium, and calcium at LS of 2 L/kg. 111
Table 12. ANOVA analysis of main and interaction effects on measured cumulative mass release of arsenic, cadmium, copper, lead, and zinc at LS of 2 L/kg. 115

Appendix A

Table A 1. SR002 data for LFC material after exposure to 0 F/T cycles - Major material constituents. 141
Table A 2. SR002 data for LFC material after exposure to 0 F/T cycles - Primary contaminants. 141
Table A 3. SR002 data for LFC material after exposure to 10 F/T cycles - Major material constituents. 142
Table A 4. SR002 data for LFC material after exposure to 10 F/T cycles - Primary contaminants. 142
Table A 5. SR003 data for LFC material after exposure to 0 F/T cycles - Major material constituents. 142
Table A 6. SR003 data for LFC material after exposure to 0 F/T cycles - Primary contaminants. 142
Table A 7. SR003 data for LFC material after exposure to 10F/T cycles - Major material constituents. 143
Table A 8. SR003 data for LFC material after exposure to 10F/T cycles - Primary contaminants. 143

Appendix B

Table B 1. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – pH and conductivity. 144
Table B 2. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – Major material constituents. 144
Table B 3. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – Primary contaminants. 144
Table B 4. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – pH and conductivity. 145
Table B 5. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – Major material constituents. 145

Table B 6. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – Primary contaminants. 145
Table B 7. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – pH and conductivity. 146
Table B 8. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – Major material constituents. 146
Table B 9. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – Primary contaminants. 146
Table B 10. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – pH and conductivity. 147
Table B 11. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – Major material constituents. 147
Table B 12. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – Primary contaminants. 147
Table B 13. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – pH and conductivity. 148
Table B 14. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – Major material constituents. 148
Table B 15. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – Primary contaminants. 148
Table B 16. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – pH and conductivity. 149
Table B 17. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – Major material constituents. 149
Table B 18. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – Primary contaminants. 149

Appendix C

Table C 1. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles - pH and conductivity. 150
Table C 2. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles – Major material constituents. 150
Table C 3. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles – Primary contaminants. 150
Table C 4. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles - pH and conductivity. 151
Table C 5. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles – Major material constituents. 151
Table C 6. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles – Primary contaminants. 151
Table C 7. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles - pH and conductivity. 152
Table C 8. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles – Major material constituents. 152

Table C 9. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles – Primary contaminants. 152
Table C 10. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles - pH and conductivity....... 153
Table C 11. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles – Major material constituents....... 153
Table C 12. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles – Primary contaminants. 154
Table C 13. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles - pH and conductivity. 155
Table C 14. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles – Major material constituents. 155
Table C 15. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles – Primary contaminants....... 155
Table C 16. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles - pH and conductivity. 156
Table C 17. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles – Major material constituents. 156
Table C 18. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles – Primary contaminants....... 156
Table C 19. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles - pH and conductivity. 157
Table C 20. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles – Major material constituents. 157
Table C 21. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles – Primary contaminants....... 157
Table C 22. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles - pH and conductivity. 158
Table C 23. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles – Major material constituents. 158
Table C 24. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles – Primary contaminants....... 159
Table C 25. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles - pH and conductivity....... 160
Table C 26. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles – Major material constituents....... 160
Table C 27. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles – Primary contaminants....... 160
Table C 28. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles - pH and conductivity....... 161
Table C 29. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles – Major material constituents....... 161
Table C 30. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles – Primary contaminants....... 161

Table C 31. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles - pH and conductivity. 162

Table C 32. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles – Major material constituents. 162

Table C 33. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles – Primary contaminants. 162

Table C 34. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles - pH and conductivity. 163

Table C 35. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles – Major material constituents. 163

Table C 36. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles – Primary contaminants. 164

Appendix D

Table D 1. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – pH and conductivity. 165

Table D 2. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – Major material constituents. 165

Table D 3. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – Primary contaminants. 165

Table D 4. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – pH and conductivity. ... 166

Table D 5. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – Major material constituents. 167

Table D 6. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – Primary contaminants. 168

LIST OF FIGURES

Figure 1. Column filled with LFC material during freezing. 11

Figure 2. Tracer experiments. 15

Figure 3. Dry density curve of the less than 9.5 mm graded LFC material. 19

Figure 4. Temperature profiles at the top, middle, and bottom of the column during A) freezing at -12°C and B) thawing at room temperature (20 ± 3°C). 20

Figure 5. Changes in A) sample height and B) bulk dry density vs. the number of F/T cycles for two gradations of the LFC material (< 2 mm and < 9.5 mm) compacted at the optimum moisture content and freezing at -12°C. 21

Figure 6. Particle size distribution of the A) less than 2 mm graded LFC material and B) less than 9.5 mm graded LFC material before F/T exposure. 22

Figure 7. Less than 9.5 mm graded LFC material immediately after exposure to 10 F/T cycles (note consolidation of the material). 22

Figure 8. Less than 2 mm graded LFC material after exposure to 10 F/T cycles and flow around leaching for 21 days (note consolidation of the material). 22

Figure 9. Less than 9.5 mm graded LFC material after exposure to 10F/T cycles and column leaching for 25 days (note aggregation of the concrete particles). 23

Figure 10. pH titration curves for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 23

Figure 11. Leachate pH as a function of LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 24

Figure 12. Calcium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 25

Figure 13. Sodium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 26

Figure 14. Potassium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 26

Figure 15. Arsenic release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 27

Figure 16. Cadmium solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 27

Figure 17. Copper solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 28

Figure 18. Lead solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 28

Figure 19. Zinc solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles. 29

Figure 20. Leachate pH after exposure to 0, 10, and 20 F/T cycles of the less than A) 2 mm graded LFC material and B) 9.5 mm graded LFC material. 30

Figure 21. Leachate conductivity after exposure to 0, 10, and 20 F/T cycles of the less than A) 2 mm graded LFC material and B) 9.5 mm graded LFC material. 31

Figure 22. Sodium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 33

Figure 23. Sodium concentration as a function of pH from mass transfer testing compared to batch testing after exposure to 0, 10, and 20 F/T cycles for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded material. 34

Figure 24. Potassium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 35

Figure 25. Potassium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. 36

Figure 26. Calcium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 37

Figure 27. Calcium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. 38

Figure 28. Chloride release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 39

Figure 29. Sulfate release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 41

Figure 30. Arsenic release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 43

Figure 31. Arsenic concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. 44

Figure 32. Cadmium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 45

Figure 33. Cadmium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. 46

Figure 34. Copper release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 47

Figure 35. Copper concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. 48

Figure 36. Lead release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 49

Figure 37. Lead concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. ... 50

Figure 38. Zinc release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. 51

Figure 39. Zinc concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material. ... 52
Figure 40. Main effects plots (data means) for leachate conductivity after 504 hours (21 days) of leaching. ... 53
Figure 41. Main effects plots (data means) for sodium cumulative release after 504 hours (21 days) of leaching. ... 55
Figure 42. Main effects plots (data means) for potassium cumulative release after 504 hours (21 days) of leaching. ... 55
Figure 43. Main effects plots (data means) for calcium cumulative release after 504 hours (21 days) of leaching. ... 56
Figure 44. Main effects plots (data means) for chloride cumulative release after 504 hours (21 days) of leaching. ... 56
Figure 45. Main effects plots (data means) for sulfate cumulative release after 504 hours (21 days) of leaching. ... 57
Figure 46. Interaction plots (data means) for calcium cumulative release after 504 hours (21 days) of leaching. ... 57
Figure 47. Interaction plots (data means) for sulfate cumulative release after 504 hours (21 days) of leaching. ... 58
Figure 48. Main effects plots (data means) for arsenic cumulative release after 504 hours (21 days) of leaching. ... 59
Figure 49. Main effects plots (data means) for cadmium cumulative release after 504 hours (21 days) of leaching. ... 59
Figure 50. Main effects plots (data means) for copper cumulative release after 504 hours (21 days) of leaching. ... 60
Figure 51. Main effects plots (data means) for lead cumulative release after 504 hours (21 days) of leaching. ... 60
Figure 52. Main effects plots (data means) for zinc cumulative release after 504 hours (21 days) of leaching. ... 61
Figure 53. Output flow rate as a function of time after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content. ... 63
Figure 54. Average output flow rate after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content. ... 64
Figure 55. Percentage of bromide recovery after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content. ... 65
Figure 56. Leachate pH after exposure to 0, 10, 20, and 40 F/T cycles for the LFC material packed at A) 7% moisture content, B) 15% moisture content, and C) 29% moisture content (optimum moisture content). ... 67
Figure 57. Leachate conductivity after exposure to 0, 10, 20, and 40 F/T cycles for the LFC material packed at A) 7% moisture content, B) 15% moisture content, and C) 29% moisture content (optimum moisture content). ... 68
Figure 58. Sodium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). ... 70

Figure 59. Sodium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 71

Figure 60. Sodium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 72

Figure 61. Potassium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 74

Figure 62. Potassium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 75

Figure 63. Potassium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 76

Figure 64. Calcium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 78

Figure 65. Calcium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 79

Figure 66. Calcium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 80

Figure 67. Chloride release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 82

Figure 68. Chloride release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch

testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 83

Figure 69. Chloride release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 84

Figure 70. Sulfate release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 86

Figure 71. Sulfate release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 87

Figure 72. Sulfate release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 88

Figure 73. Arsenic release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 91

Figure 74. Arsenic release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 92

Figure 75. Arsenic release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 93

Figure 76. Cadmium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 95

Figure 77. Cadmium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 96

Figure 78. Cadmium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 97

Figure 79. Copper release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 99

Figure 80. Copper release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 100

Figure 81. Copper release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 101

Figure 82. Lead release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 103

Figure 83. Lead release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 104

Figure 84. Lead release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 105

Figure 85. Zinc release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 107

Figure 86. Zinc release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 108

Figure 87. Zinc release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch

testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles). 109
Figure 88. Main effects plots (data means) for sodium release at LS 2 L/kg. 112
Figure 89. Main effects plots (data means) for potassium release at LS 2 L/kg. 112
Figure 90. Main effects plots (data means) for calcium release at LS 2 L/kg. 113
Figure 91. Interaction plots (data means) for potassium release at LS 2 L/kg. 113
Figure 92. Interaction plots (data means) for calcium release at LS 2 L/kg. 114
Figure 93. Boxplot of the cumulative release of sodium, potassium, and calcium at LS of 2 L/kg. 114
Figure 94. Main effects plots (data means) for arsenic release at LS 2 L/kg. 116
Figure 95. Main effects plots (data means) for copper release at LS 2 L/kg. 116
Figure 96. Main effects plots (data means) for zinc release at LS 2 L/kg. 117
Figure 97. Interaction plots (data means) for arsenic release at LS 2 L/kg. 117
Figure 98. Interaction plots (data means) for copper release at LS 2 L/kg. 118
Figure 99. Interaction plots (data means) for lead release at LS 2 L/kg. 118
Figure 100. Interaction plots (data means) for zinc release at LS 2 L/kg. 119
Figure 101. Boxplot of the cumulative release of arsenic, cadmium, copper, lead, and zinc at LS of 2 L/kg. 119
Figure 102. Effect of intermittent wetting (flow-around) coupled with F/T exposure on A) leachate pH and B) leachate conductivity of the less than 9.5 mm graded LFC material. 120
Figure 103. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of sodium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 122
Figure 104. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of potassium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 122
Figure 105. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of calcium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 123
Figure 106. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of arsenic for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 123
Figure 107. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of cadmium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 124
Figure 108. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of copper for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 124
Figure 109. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of lead for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 125
Figure 110. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of zinc for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time. 125

Figure 111. Effect of intermittent flow-through coupled with F/T exposure on A) leachate pH and B) leachate conductivity of the LFC material packed at 29% moisture content (optimum moisture content). 126

Figure 112. Effect of flow-through coupled with F/T exposure on the cumulative release of major material constituents for the LFC material packed at 29% moisture content (optimum moisture content). A) Cumulative release of sodium. B) Cumulative release of potassium. C) Cumulative release of calcium. 127

Figure 113. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of primary contaminants for the LFC material packed at 29% moisture content (optimum moisture content). A) Cumulative release of arsenic. B) Cumulative release of cadmium. C) Cumulative release of copper. D) Cumulative release of lead. E) Cumulative release of zinc. 129

Figure 114. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of major material constituents for the C&D material packed at the optimum moisture content compared to the LFC material. A) Cumulative release of sodium. B) Cumulative release of potassium. C) Cumulative release of calcium. 131

Figure 115. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of primary contaminants for the C&D material packed at the optimum moisture content compared to the LFC material. A) Cumulative release of arsenic. B) Cumulative release of cadmium. C) Cumulative release of copper. D) Cumulative release of lead. E) Cumulative release of zinc. 133

1. INTRODUCTION

1.1. BACKGROUND

Many secondary materials such as bottom ash, slag, foundry sands, concrete debris, and other waste materials are being considered for use as substitutes for natural aggregates or materials in civil engineering applications due to suitable engineering and economic properties. These applications include road bases, shoulders, embankments, and other fill applications. However, the increased interest in new applications for waste utilization has resulted in concern over the long-term physical and environmental performance of the waste-derived products. Prediction of the future behavior of the proposed products, both physical and environmental, is critical for approval by both highway practitioners and environmental regulators. This concern has resulted in the need for accelerated aging techniques that reflect the physical and environmental long-term behavior of the waste-derived products.

The durability of aggregate materials against the forces of weathering is an important consideration in the selection of the material. A primary exposure of concern is alternate freezing and thawing. Current test methods for evaluating the soundness of aggregates due to freezing and thawing (AASHTO T 103 (AASHTO, 1992) and brine freeze-thaw ITM 209 (ITM, 2001)) are based only upon meeting physical test criteria and do not integrate environmental material performance. However, during the design life of the construction application, materials are exposed to freezing and thawing coupled with intermittent infiltration/wetting as a consequence of precipitation events. In such a scenario, leaching of material constituents is a primary pathway for environmental impact. The thermal stability of the material’s components and the overall freeze/thaw durability of the material itself and its impact on flow mechanisms may be of concern for constituent leachability.

1.2. RESEARCH OBJECTIVES

The overall objective of the research reported here was to study the effect of freezing and thawing processes on flow mechanisms and constituent leaching from recycled granular materials used in highway construction applications. Scenarios considered included water percolating through the material and run-off (flow-around), both of which are important routes in the highway environment for leaching of constituents of potential concern present in recycled materials.

The specific objectives were to:

1. Determine the effect of material moisture content at the time of freezing on material integrity (i.e., change in particle size distribution) and constituent release during percolation flow controlled scenarios;
2. Examine the effect of the number of freeze/thaw cycles on material integrity and constituent release during percolation flow and flow-around controlled scenarios;
3. Determine the effect of material gradation in conjunction with freezing and thawing on material integrity and constituent leaching during flow-around controlled scenarios; and,
4. Develop guidelines for simplified test methods and accelerated aging procedures that can be used by end-users to assess the potential impact of freezing and thawing processes on constituent leaching during percolation flow controlled scenarios.

The approach to satisfying these objectives was to use a laboratory formulated concrete (i.e., cement-based material spiked with metal oxide) as a model system to simulate recycled concrete aggregates (RCA) and to perform laboratory flow-through column studies and flow-around mass transfer studies coupled with freeze/thaw exposure. As an initial method validation, the performance of construction-demolition debris (C&D material) was evaluated using intermittent flow-through columns coupled with F/T exposure.

1.3. RESEARCH SIGNIFICANCE

The research presented herein evaluates the environmental performance of RCA for use in highway construction and provides test methods and aging procedures that can be used by end-users to assess the potential impact of freezing and thawing processes on constituent leaching from recycled waste materials during percolation flow controlled and flow-around controlled scenarios.

This investigation provides insights concerning the moisture content and material gradation that result in the most significant impact of freezing and thawing processes and the number of cycles for freezing and thawing to use in simplified test methods.

In addition, the study expands current efforts underway by the USEPA for the development of a more consistent and flexible framework for evaluating leaching for multiple applications.

2. LITERATURE REVIEW

This section provides a brief overview of the use and performance of recycled materials in construction applications and discusses the effect of freezing and thawing in the environment.

2.1. RECYCLED CONCRETE AGGREGATES IN CONSTRUCTION APPLICATIONS

2.1.1. Introduction

Demand for RCA for use in construction applications has grown worldwide over the last decades. Driving the demand is the need for more sustainable waste management practices that provide an alternative to limited natural resources and satisfy the growing need for construction aggregates. RCA generally includes old Portland cement concrete (PCC) pavements, bridge structures and decks, sidewalks, and construction-demolition debris. In the US, RCA are primarily used as fill or sub-base materials, and less often, as aggregates in new concrete pavements (FHWA, 2004; US Army Corps of Engineers, 2004). The Federal Highway Administration (FHWA) report (FHWA, 2004) provides detailed information on the use of RCA in transportation applications for reducing barriers to recycling and facilitating the transfer of successful practices across state boundaries.

2.1.2. RCA properties

RCA is composed mainly of calcite and portlandite (Limbachiya *et al.*, in press). RCA from concrete recycled from buildings may be contaminated with sulfates from plaster and gypsum wallboard. Chloride ions may be found in RCA obtained from concrete recycled from pavements due to the deicing salts used to control ice formation or from structures previously exposed to marine environments (US Army Corps of Engineers, 2004). The presence of sulfate and chloride in RCA can adversely affect the performance of the construction application in which RCA is used due to the possibility of sulfate attack or chloride induced corrosion of reinforcing steel.

Compared to natural aggregates, waste aggregates derived mainly from recycled concrete have low specific gravity and high water absorption characteristics (Cho *et al.*, 2004; Park, 2003) due to the lightweight, porous cement mortar attached to them. The lower compacted unit weight of RCA compared to natural aggregates results in a higher yield volume (greater volume per weight) enhancing RCA economic attractiveness for contractors (US Army Corps of Engineers, 2004).

2.1.3. Performance of RCA as unbound road subbase

Studies on RCA used in road base or subbase courses have shown an increase over time in the stiffness of unbound base/subbase layers made with crushed demolished concrete, resulting in improved load carrying capacity. This is thought to be due to the self-cementing properties of the RCA (Arm, 2001). The principal cause of self-cementing phenomenon is attributed to unhydrated cement in the fine portion (<0.6 mm) of the RCA (Poon *et al.*, in press). Furthermore, Poon's studies (Poon *et al.*, in press) on the permeability of RCA subbase materials indicated that the more permeable nature of RCA subbases is offset by the self-cementing properties of the RCA fines. Additionally, the use of RCA has been observed to increase the optimum moisture content and decrease the maximum dry density of the subbase material compared to those obtained with virgin aggregates (Park, 2003; Poon *et al.*, 2006).

2.2. RECYCLED MATERIALS IN THE HIGHWAY ENVIRONMENT AND ENVIRONMENTAL CONSIDERATION

While the use of recycled materials is gaining broader acceptance in the US, there are no national standards or specifications for their use. Additionally, little data is available on the long-term durability and environmental performance of the utilization of recycled materials.

During the design life of the application, recycled materials in highway environments are exposed to freezing and thawing coupled with intermittent wetting as a consequence of infiltration through the pavement surfaces and shoulders, melting of ice during freezing/thawing cycles, capillary action, and seasonal changes in the water table (Apul *et al.*, 2002). In such scenarios, leaching of material constituents is a primary pathway for environmental impact. The thermal stability of the material's components and the overall freeze/thaw durability of the material itself and its impact on flow mechanisms may be of concern for constituent leachability.

Current test methods for evaluating the soundness of aggregates due to freezing and thawing include AASHTO T 103 (AASHTO, 1992) and brine freeze-thaw ITM 209 (ITM, 2001). These methods are based only upon meeting physical test criteria and do not integrate environmental material performance.

2.3. OVERVIEW OF FREEZING AND THAWING IN THE ENVIRONMENT

F/T cycling can pose significant problems for civil engineering structures such as roads, building foundations, retaining walls, driveways, and similar structures. Frost action leads to the solidification of water in soils or concrete structures with an attendant volume change. As soils freeze, ice formation blocks the soil pores, greatly diminishing the permeability of the soil (Couper, 2003). This effect is aggravated by the tendency of water saturated with solutes to migrate to the freezing front, elevating ice content and causing frost heave (Talamucci, 2003). When concrete saturated over 90% is exposed to freezing temperatures, the water in the pore spaces freezes and expands by approximately 9%, resulting in material damage (Corr *et al.*, 2003; Ghafoori *et al.*, 1998; Penttala, 1998; Penttala *et al.*, 2002).

2.3.1. Effect of F/T exposure on granular material structure and properties

2.3.1.1. Structure alteration

Freezing and thawing has been observed to cause changes in soil structure due to particle rearrangement (migration of fines, particle sorting, and coarse particle heave), initiation of cracks, and consolidation of the material (Chamberlain *et al.*, 1979; Eigenbrod, 2003; Viklander, 1998a; Viklander *et al.*, 2000).

2.3.1.2. Volume change

The change in volume of the granular material during F/T exposure is dependent on the porosity of the material and the amount of water in the pores. Frost heave occurs due to the decrease in density as water changes to ice and to the migration of water from the unfrozen zone to the freezing front, which is controlled by the freezing rate, dry density, particle size, and permeability of the material (Talamucci, 2003). Generally, after thawing dense soils expand while loose soils compact (Viklander, 1998b). Frost heave can move soils by as much as two feet (Corr *et al.*, 2003).

2.3.1.3. Alteration of particle size distribution

Freezing and thawing is known to affect granular material integrity (Oztas *et al.*, 2003). Freezing has been observed to change the particle size distribution in soils by breaking up soil particles resulting in an increase in the fine particle size fraction (Li *et al.*, 2002). The breakup of the soil particles is a result of the forces of the ice expanding in the soil pores (Li *et al.*, 2002). The stability of soil aggregates depends on the initial aggregate size, the initial moisture content at the time of freezing, the number of F/T cycles, and the freezing temperature (Benoit, 1973; Oztas *et al.*, 2003; Staricka *et al.*, 1995). Oztas et al. (Oztas *et al.*, 2003) found that the stability of aggregate in soils usually increased during the first few F/T cycles and decreased thereafter. Furthermore, Oztas et al. (Oztas *et al.*, 2003) found that the decrease in aggregate stability was more pronounced with increasing moisture contents at the time of freezing.

2.3.1.4. Strength

Soil increases in strength during freezing due to the bonding of the ice and soil particles. However, freezing followed by thawing can either increase or decrease the soil strength (Marion, 1995). The loss of strength upon thawing depends on the rate of water liberation from the thawing of ice and the rate at which this water drains away (which is a function of the rate of consolidation and permeability of the soil) (Williams, 1989).

2.3.1.5. Permeability

During freezing, the hydraulic conductivity of soils has been found to decrease exponentially from 0°C to -1°C and then remain constant at lower temperatures (Marion, 1995). While soil is frozen, ice formation blocks water flow through a porous medium (Hansson *et al.*, 2004). While the hydraulic conductivity decreases during freezing, F/T cycling can result in a final increase in hydraulic conductivity due to aggregation of soil particles and/or crack formation by ice lensing and shrinkage, providing a path of decreased flow resistance (Chamberlain *et al.*, 1979; Kim *et al.*, 1992; Othman *et al.*, 1993). Studies on fine-grained soils have shown increases in

permeability up to several orders of magnitude after F/T exposure (Chamberlain *et al.*, 1979; Othman *et al.*, 1993; Viklander, 1998b).
The moisture content of the soil at the time of freezing affects the degree of permeability increase as a result of F/T cycling. Kim et al. (Kim *et al.*, 1992) observed an increase in hydraulic conductivity of 2 to 6 times for soil compacted drier than the optimum moisture content, while 100 times for soils compacted wetter than the optimum moisture content. Furthermore, Viklander et al. (Viklander *et al.*, 2000) observed that after 6 F/T cycles the permeability of till soil increased by 81 times as a result of stone movement in samples packed at optimum moisture content, while by only 3 times in samples compacted at 6% above the optimum moisture content, suggesting that till soils should be placed wetter than the optimum moisture content in applications that are affected by cyclic freezing and thawing, to minimize permeability changes.

2.3.1.6. Constituent redistribution

Freezing and thawing cause movement of water content and influence constituent redistribution in soils (Marion, 1995; Pawluk, 1998; Shoop *et al.*, 1997). This is due to the migration of water saturated with solutes toward the freezing front. Additionally, when soil is frozen, an unfrozen film of liquid water exists around the soil particles (Williams, 1989). Approximately 8-20% of the soil water remains in the liquid state when the soil has been maintained at -5°C for several days (Teepe *et al.*, 2001). This water film allows for the movement of solutes in the frozen soil (Marion, 1995). More liquid water exists in frozen fine textured soils than coarse soils (Hansson *et al.*, 2004).

2.3.2. Factors affecting granular material response to F/T

2.3.2.1. Soil moisture content

The freezing of soils in the environment can occur with or without water migration (Ershov, 1998), resulting in different extent of F/T damage.

Moisture content at the time of freezing can affect the extent of F/T damage and may change between F/T cycles. Potential moisture content loss with increasing number of F/T cycles was indicated by (Couper, 2003), who observed that ice was formed in soil samples after 8 F/T cycles but became rare after 25 F/T cycles. Couper (Couper, 2003) further suggested that the moisture content was the primary property that influenced expansion and contraction of soil during F/T cycling, rather than porosity or degree of packing.

Moisture content affects aggregate integrity after thawing by weakening the bonds between micro aggregates. Soil aggregates in soils with low moisture content are less affected by freezing and thawing than those in soils with 90% saturated moisture content (Oztas *et al.*, 2003). Furthermore, soil aggregates are easily dispersed after thawing in soils with high moisture content (Oztas *et al.*, 2003).

Moisture content affects soil heave (volume change) and change in soil permeability during freezing and thawing. Viklander et al. (Viklander *et al.*, 2000) observed in till soils that the amount of soil heave decreased when the compaction water content was increased above the optimum moisture content. They reported, additionally, that stone heave was greater during freezing and thawing in a system with unrestricted water movement compared to a system for which access of water during freezing was limited.

2.3.2.2. Material gradation

Material gradation is an important factor that influences frost susceptibility. Different responses to F/T exposure have been observed for coarse-grained soils and fine-grained soils. Fine-grained soils are more susceptible to freezing and experience greater frost heave damage than coarse-grained soils (Talamucci, 2003). The difference in fine-grained and coarse-grained soil behavior is also seen in differences in volume reduction, settlement, and loss of strength during thawing. When coarse-grained soils thaw, little volume change and little loss of strength are generally observed. For fine-grained soils, consolidation generally takes place upon thawing as a result of loss of water and an attendant decrease in the size of the soil pores (Williams, 1989).

2.3.2.3. Pore water composition

During the freezing process, solutes migrate due to salting out effects and osmotic pressure differentials toward the unfrozen bulk pore-water with the highest concentration of solutes just ahead of the freezing front. Temperature, solute concentration, and soil adsorption capability control the freezing-point depression and the amount of unfrozen water content (Marion, 1995). In general, the presence of salts reduce frost heaving (Chamberlain, 1983).

2.3.2.4. Number of F/T cycles

Freezing and thawing of frost susceptible soils has been observed to cause changes in their structure after only a very few number of F/T cycles (Eigenbrod, 1996; Viklander *et al.*, 2000). Increase in soil permeability up to several orders of magnitude, increase or decrease in aggregate stability, and soil heave have been reported to develop during the initial 3 to 10 F/T cycles, depending upon the soil type, the soil moisture at freezing, the freezing temperature, and the F/T cycle duration (Othman *et al.*, 1993; Oztas *et al.*, 2003; Viklander, 1998a; Viklander *et al.*, 2000). Additional F/T cycles have been observed to decrease wet aggregate stability (Oztas *et al.*, 2003) and to decrease soil permeability (Viklander *et al.*, 2000).

2.4. CONCLUSIONS

The relationships between the factors described above and leaching behavior have not been well established. Due to the many processes that occur during freezing and thawing that change to a lesser or greater extent fundamental soil properties, the effect of freezing and thawing processes may be significant enough to impact the environmental acceptability of a proposed application. Similar processes and effects can be expected for other granular porous media, including RCA.

3. MATERIALS AND METHODS

3.1. EXPERIMENTAL DESIGN

To achieve the research objectives, laboratory flow-through column studies and flow-around mass transfer studies coupled with freeze/thaw exposure were used. A laboratory formulated concrete (i.e., cement-based material spiked with metal oxides) was used as a model system to simulate RCA. The laboratory formulated concrete (LFC) was formed as blocks and then crushed and graded to less than 9.5 mm and less than 2 mm.

For the flow-through scenario, three moisture contents of the packed material and four levels of freeze/thaw (F/T) aging were examined to simulate different extents of F/T exposure (Table 1). The moisture contents used (7%, 15%, and 29%) included the moisture content of the LFC material as is (i.e., 7%) and the moisture content of the LFC material at its optimum packing density (i.e., 29%). The four levels of F/T aging were obtained by using different numbers of F/T cycles. Preliminary trials were performed to determine the number of F/T cycles and reasonable cycle times necessary to produce moderate F/T deterioration. The time required to completely freeze and completely thaw the material was used to determine the minimum cycle time. The LFC material packed at each of the three moisture contents was subjected to 0, 10, 20, and 40 F/T cycles consisting of 8 hours of freezing at -12°C and 16 hours of thawing at room temperature (20 ± 3°C). At the conclusion of F/T exposure, a variety of response variables were measured. These include (i) material integrity (i.e., change in particle size distribution), (ii) infiltration patterns and flow mechanisms using column tracer experiments, and (iii) constituent leaching during percolation flow controlled scenarios using flow-through saturated column experiments. A full factorial design with two replicates was used for the column tracer experiments and the flow-through saturated column experiments on the less than 9.5 mm graded LFC material.

For the flow-around scenario, two material gradations and three levels of F/T exposure were examined (Table 1). The less than 2 mm graded LFC material and less than 9.5 mm graded LFC material packed at the optimum moisture content were subjected to 0, 10, and 20 F/T cycles consisting of 8 hours of freezing at -12°C and 16 hours of thawing at room temperature (20 ± 3°C). At the conclusion of F/T exposure, the following response variables were measured: (i) material integrity (i.e., change in particle size distribution), (ii) material height and weight, and (iii) constituent leaching during flow-around controlled scenarios using flow-around mass transfer tests. A full factorial design with two replicates was used for the mass transfer tests on the less than 2 mm and less than 9.5 mm graded LFC materials.

Additionally, a limited number of intermittent flow-around mass transfer tests coupled with F/T exposure and a limited number of intermittent flow-through columns coupled with F/T exposure were run on the less than 9.5 mm graded LFC material packed at the optimum moisture content to simulate field-like conditions. This allowed for evaluation of leaching fluxes while distress due to freezing and thawing was occurring concurrently with constituent transport.

As an initial method validation, the performance of a C&D material was evaluated using intermittent flow-through columns coupled with F/T exposure.

Analysis of the variance (ANOVA) was used for the flow-around mass transfer studies and flow-through column studies to determine the significance of the effects and interactions of (i) material moisture content at the time of freezing, (ii) material gradation, and (iii) level of F/T exposure on constituent release. MINITAB for Windows was used for the analysis.

Table 1. Experimental design.

	Flow-through scenarios (<9.5 mm)			Flow-around scenarios (<2 mm and <9.5 mm)
Factors	Levels			Levels
Moisture content of packed LFC material	7%	15%	29%	29%
Number of F/T cycles	0, 10, 20, 40	0, 10, 20, 40	0, 10, 20, 40	0, 10, 20

3.2. MATERIALS

3.2.1. Laboratory formulated concrete

A laboratory formulated concrete (LFC) was used as a model system for the study. The use of a synthetic material provides a relatively controlled and known system and allows for the examination of several contaminants that represent a range of characteristic behavior (e.g., lead, cadmium, and arsenic) at concentrations that can be detected in the leachate with typical analytical techniques, and that allow for constituent recovery studies.

The LFC material was prepared by mixing 36.0 wt% ordinary Portland cement, 49.1 wt% sand, 12.7% water, and a mixture of five metal oxide powders (arsenic, cadmium, copper, lead, and zinc) at approximately 0.30 wt% of each cation. Sodium chloride at 0.29 wt% was added to the cement recipe as a source of tracer ions (Na, Cl) with high and non-pH-dependent solubility.

The LFC material was prepared as blocks and cured in bulk form at room temperature in a humid environment for a minimum of 28 days. During the curing process, an aqueous solution of sodium hydroxide was used as a CO_2 scavenger to prevent material carbonation. At the end of the curing period, the LFC material was crushed either to less than 9.5 mm or less than 2 mm using a combination of a jaw crusher, compression machine, and rock hammer. The particle size reduction chosen was determined based on the following two criteria: (i) the size should be representative of the actual size used in highway construction applications and (ii) the ratio of the inner column diameter to particle size should be no greater than 10.

3.2.2. Construction-demolition debris

The C&D material was collected from one of the buildings at Vanderbilt University during renovation, which was completed in 2002. The material was composed mainly of concrete blocks and bricks and had been exposed to weathering forces for more than 40 years.

The C&D material was particle size reduced with a hammer and a jaw-crusher to less than 2 mm. Table 2 presents the total elemental content of major constituents as determined by x-ray fluorescence (XRF) analysis (Lopez, 2006). The C&D material had a moisture content of ca. 6.4% as determined using ASTM Method D 2261-80 (ASTM, 1980).

Table 2. Total elemental composition of the C&D material as determined by XRF (Lopez, 2006).

Element	Concentration (mg/kg)
K	5702
Ca	155560
Ti	1846
Fe	12050
Co	284
Ni	108
Cu	60
Zn	77
As	47
Sr	251
Mo	5
Rb	54
Ba	151
Mo	5
Ag	29

3.3. METHODS

3.3.1. Optimum moisture content

The optimum moisture content refers to the amount of moisture [fractional mass of water (g water/g dry material)] in the granular sample that is present at the optimum packing density (g dry material/cm^3) and that provides packing densities that approximate field conditions.

Modifications of the ASTM Method D 1557 (ASTM, 1978) was used to determine the optimum moisture content of the LFC material. The dry density of the compacted LFC material as a function of varying water contents was determined using ca. 450g of the LFC material “as is” compacted in a 10.2 cm diameter mold. Three consecutive layers of materials were compacted 25 times using a ca. 1 kg hammer and ca. 45 cm drop. The height and weight of the resulting compacted LFC material was measured. A known amount of water was then added and mixed with the same LFC material sample and the same procedure as for the “as is” material was followed. This step was repeated several times and the curve of the dry density vs. the water content was plotted. The maximum dry density corresponded to the optimum moisture content.

3.3.2. F/T exposure

Preliminary tests were conducted to determine the number of F/T cycles and cycle times to be used in the study. The time required to completely freeze and completely thaw the material was used to determine the minimum cycle time.

3.3.2.1. Determination of the F/T cycle duration

The time required to completely freeze and thaw a column filled with water-saturated granular LFC material was determined by measuring the temperature profiles as a function of time. Thermocouples were inserted through holes drilled in a PVC column of 10.2 cm diameter and 25.4 cm height to measure the temperature at the top, middle, and bottom portion of the column (Figure 1). The column was frozen at -12°C in a temperature controlled deep freezer and then thawed at room temperature (20 ± 3°C). During the freezing period, the temperature of the material was recorded approximately every hour for a total of 8 hours. This was followed by recording the temperature as the column thawed.

Figure 1. Column filled with LFC material during freezing.

3.3.2.2. Determination of the numbers of F/T cycles

The numbers of F/T cycles used were determined based on results of a literature survey on freezing and thawing of soil systems (see section 2.3). 0, 10, 20, and 40 F/T cycles were chosen for the project as they were expected to produce four different levels of freeze-thaw deterioration.

3.3.2.3. F/T exposure

The material packed in columns or molds at the appropriate moisture content (i.e., 7%, 15%, or 29%) was frozen at -12°C in a temperature controlled deep freezer for 8 hours and then thawed at room temperature (20 ± 3°C) for 16 hours. This was repeated 10, 20, and 40 times, as appropriate, to reach the pre-determined levels of F/T exposure. At the end of each F/T exposure, the height of the packed material was measured to examine any change due to expansion during freezing. The mass of the material was also recorded to examine any changes that may have occurred during freezing and thawing.

3.3.3. Physical and chemical stability of the granular LFC material with respect to F/T exposure

3.3.3.1. Material physical stability

The stability of the granular LFC material with respect to freezing and thawing was determined by measuring the material bulk density and material physical integrity (particle size distribution) after exposure to 0, 10 and 20 F/T cycles. The material bulk density was used as an indicator of the amount of compaction and pore space present before and after F/T aging. The material stability was examined on two LFC material gradations (i.e., material that has been reduced to less than 2 mm and material that has been size reduced to less than 9.5 mm).

The less than 2 mm and less than 9.5 mm graded LFC materials were compacted at the optimum moisture content into molds of 10.2 cm in diameter and 7 cm high. After compaction, the mass of the sample mold with the compacted material was recorded. The volume changes were measured by recording the sample depth in the sample mold at the end of the 10 and 20 F/T cycles. The original dry weight of the sample divided by the new volume gave new bulk dry densities.

The LFC material size distribution was measured by the standard sieving method. The following size fractions were separated for the less than 9.5 mm size reduced LFC material: 9.5-4.75 mm; 4.75-2.38 mm; 2.38-1.168mm; 1.168-0.495 mm; 0.495-0.3 mm and less than 0.3mm. The following size fractions were separated for the less than 2 mm size reduced LFC material: 2-1.19 mm; 1.19-0.85 mm; 0.85-0.495 mm and less than 0.495 mm.

3.3.3.2. Thermal stability of the mineral/chemical components of the LFC material

The thermal stability of the material's mineral/chemical components was examined using the SR002.1 (Alkalinity, Solubility and Release as a Function of pH) protocol (Kosson *et al.*, 2002) and SR003.1 (Solubility and Release as a Function of LS ratio) protocol (Kosson *et al.*, 2002) on the less than 2 mm size reduced LFC material before and after 10 F/T cycles.

The SR002.1 protocol was used to determine the acid neutralization capacity of the LFC material before and after F/T exposure and to examine the effect of F/T aging on constituent leaching at equilibrium over a broad range of pH conditions. Eleven points of pH ranging from 3-12 were examined by contacting the material with varying equivalents of acid at a liquid to solid (LS) ratio of 10 L/kg. The eleven extractions were tumbled in an end-over-end fashion at 28±2 rpm for 48 hr followed by filtration separation of the solid phase from the extract. Each extract then was analyzed for constituents of interest. The acid and base neutralization behavior of the materials was evaluated by plotting the pH of each extract as a function of equivalents of acid or base added per gram of dry solid. Concentration of constituents of interest for each extract was plotted as a function of extract final pH to provide liquid-solid partitioning equilibrium as a function of pH.

The SR003.1 protocol was used to determine the effect of F/T cycles on initial pore-water conditions and initial leachate compositions expected to be observed during a percolation scenario. Five parallel batch extractions over a range of LS ratios (i.e., 10, 5, 2, 1, and 0.5 mL/g dry material) were performed using deionized (DI) water as the extractant with aliquots of non-aged and 10 F/T cycle aged LFC material that has been size reduced to less than 2 mm. All extractions were conducted at room temperature (20 ± 2 °C) in leak-proof vessels that were tumbled in an end-over-end fashion at 28 ± 2 rpm for 48 hours. Following gross separation of the solid and liquid phases by centrifugation, leachate pH and conductivity measurements were taken and the phases were separated by vacuum filtration using 0.45-µm polypropylene filter membrane. The five leachates were collected, and preserved as appropriate for chemical analysis. Each extraction condition was carried out in duplicate.

3.3.4. Flow-around mass transfer tests

The MT002.1 (Mass Transfer rate in granular materials) protocol (Kosson *et al.*, 2002) was used to evaluate the effect of F/T aging on constituent release from the LFC material during a flow-around controlled scenario (i.e., scenario where the infiltrating water is diverted around the material – run-off). The test was performed on the LFC material packed at the optimum moisture content (i.e., 29%) and subjected to three levels of F/T aging (i.e., 0, 10, and 20 F/T cycles). Two LFC material gradations (i.e., material that has been size reduced to less than 2 mm and less than 9.5 mm, respectively) were examined.

The MT002.1 protocol consists of tank leaching of continuously water-saturated compacted granular material with periodic renewal of the leaching solution. The LFC material was compacted at its optimum moisture content into 10.2 cm molds. Three consecutive layers of material were compacted 25 times using a 2lbs hammer and 45-cm drop according to ASTM D 1557 (ASTM, 1978). The mass of sample mold and compacted sample were measured and recorded. The sample was packed to the depth of 10 cm. After completion of compaction, the height of the compacted matrix was recorded by measuring the outer height of the mold to the rim and subtracting the inside depth from the rim to the matrix. The mold and the sample were then immersed in a clean leaching vessel containing 1000 mL of DI water. Only the surface area of the top face of the sample contacted the leaching medium. The vessel was covered with an air-tight lid. The leachant was refreshed with equal volume of DI water using a liquid to surface area of 12 mL/cm^2 at cumulative times of 2, 5, 8 h, 1, 2, 4, 8, 14 and 21 days. At the end of each leaching interval, the sample and the mold were removed from the vessel; the leachate from the surface of the specimen was drained into the leachate for approximately 20s. The mass of the sample and the mold were measured and recorded. The sample and the holder were placed into the clean leaching vessel of a new leachant. A minimum 200 mL of unpreserved supernatant from each extraction was decanted and filtered by vacuum filtration through a 0.45-µm pore size polypropylene filtration membrane. A portion of filtered liquid was used to measure the pH. The sample was then collected and separated in two sub-samples; one was preserved with nitric acid 2% for metal analysis and the other remained unpreserved for anion analysis.

3.3.5. Flow-through column testing

3.3.5.1. Column design

Transparent PVC columns 4 inches in diameter and 10 inches long were used for the study. Transparent PVC pipes were used for a better visual observation during the experiments. PVC female adapter fittings were glued to one end of the pipe section and caps were glued to the opposite end of the pipe with PVC cement and sealed with silicone on the outside of the column. Four-inch PVC plugs were used to cap the top end of the pipe and the threads were sealed with Teflon tape. Holes were drilled into the plugs and caps and 3/8” x ¼” splicers were used to connect ¼” tubing to each end of the column. Plastic beads occupied empty space between plastic mesh separating the concrete from the tubing and the tubing connection.

3.3.5.2. Column preparation

Appropriate amounts of water were added to the granular material to achieve the desired levels of material moisture content (i.e., 7%, 15%, and 29%). Upon completion of moisture content adjustment, the material was packed in the cylindrical PVC columns for subsequent testing. A separate set of columns were prepared for the tracer and leaching studies.

3.3.5.3. Tracer experiments

Tracer experiments were conducted to evaluate the effect of F/T exposure on infiltration patterns and flow mechanisms. Three moisture contents of the packed LFC material (i.e., 7%, 15%, and 29%) and four levels of F/T exposure (i.e., 0, 10, 20, and 40 cycles; a cycle being 8 hours of freezing and 16 hours of thawing) were examined.

At the conclusion of each respective F/T exposure of the column packed material, tracer experiments (Figure 2) were performed by adding a minimum of 400 mg/L[3] of potassium bromide (KBr) to the column at a flow rate of ca. 300 mL/d for ca. 6 hours. The influent solution was then switched to tracer-free deionized (DI) water until the bromide levels in the effluent became negligible and the conductivity of the leachate stabilized to a baseline value of ca. 6 mS/cm. Duplicates were run for each case. The potassium bromide solution was pumped vertically up-flow through the column. The columns were sampled at the top of the column everyday over a 4-hour period. At the end of each sample collection, leachate pH and conductivity were measured prior to leachate filtration through a 0.45 μm pore size polypropylene membrane. The output flow rate was monitored based on the volume of leachate exiting the column and bromide concentration in each collected sample was analyzed using ion chromatography (IC).

---

[3] Minimum concentration required for bromide breakthrough concentration greater than the method detection limit of 0.4 mg/L of the IC.

Figure 2. Tracer experiments.

3.3.5.4. Saturated column experiments

Saturated column experiments (Lopez *et al.*, 2001) were conducted to examine the effect of F/T cycles on constituent leaching. Three moisture contents of the column packed material (i.e., 7%, 15%, and 29%) and four levels of F/T exposure (i.e., 0, 10, 20, and 40 cycles; a cycle being 8 hours of freezing and 16 hours of thawing) were examined.

At the conclusion of each respective F/T exposure of the column packed material, saturated column experiments were performed using DI water. Duplicates were run for each column. The columns were run up-flow to ensure saturation. An average flow rate of approximately 300 mL/d was used. The leaching extracts were collected over a sample period of 8 hours at the top of the column every time an LS ratio (based on total volume passed through the column) of 0.1, 0.2, 0.5, 1, 2, 5, 8 and 10 L/kg of dry material was achieved. The columns were run for a minimum cumulative leaching time of approximately 1 1/2 months, which corresponded to an LS ratio of ca. 5 L/kg. In some cases, leaching times were extended up to an equivalent LS ratio of 10 L/kg (3 months).

3.3.6. Intermittent wetting/flow-through coupled with F/T exposure

Intermittent wetting (flow-around) and intermittent flow-through coupled with F/T exposure were performed to simulate field-like conditions for which distress due to freezing and thawing occurs concurrently with constituent transport.

3.3.6.1. Intermittent flow-around mass transfer test coupled with F/T exposure

The intermittent flow-around mass transfer test consisted of mass transfer experiments (tank leaching experiments) interspersed with periods of storage during which the material was exposed to one F/T cycle consisting of 8 hours of freezing at -12°C and 16 hours of thawing at room temperature. Table 3 shows the schedule used in this study as intervals of leaching and F/T exposure.

Table 3. Leaching and F/T exposure intervals for the intermittent flow-around mass transfer case.

	Leaching intervals (hr)				F/T exposure (cycles)
1	2	3	3	16	1
2	24	--	--	--	2
3	48	--	--	--	4
4	96	--	--	--	--
Extracts	7 per replicate 8 days (7 intervals)				7 cycles of 1 day each (3 intervals)
Cumulative time	15 days				

3.3.6.2. Intermittent flow-though columns coupled with F/T exposure

The intermittent flow-through columns consisted of saturated column experiments interspersed with periods of storage during which the columns were exposed to one F/T cycle consisting of 8 hours of freezing at -12°C and 16 hours of thawing at room temperature. The columns filled with LFC material or C&D material packed at the optimum moisture content were intermittently subjected to leaching and F/T exposure according to the schedule shown in Table 4.

Table 4. Leaching and F/T exposure intervals for the intermittent flow-through case.

	Leaching intervals – LS ratio reached			F/T exposure (cycles)
	LFC - A	LFC - B	C&D - A	
1	0.2	0.3	0.3	1
2	0.3	0.5	0.5	1
3	0.4	0.9	1	1
4	1	1.5		1
Extracts	4	4	3	
Cumulative LS ratio (L/kg)	1	1.5	1	

3.3.7. Analytical methods

3.3.7.1. pH and conductivity

pH was measured for all aqueous extracts using a Corning pH/ion 450 meter (VWR International, West Chester, PA). The pH of the leachates was measured using a combined pH electrode accurate to 0.1 pH units. A 3-point calibration was performed using pH buffer solutions at pH 4.0, 7.0, and 10.0.

Conductivity was measured for all aqueous extracts using an Accumet AR20 pH/conductivity meter (Fisher Scientific, Springfield, NJ). The conductivity of the leachates was measured using a standard conductivity probe, which was calibrated using appropriate standard conductivity solutions for the conductivity range of concern.

3.3.7.2. Moisture contents

Initial moisture content of the granular LFC material was determined using American Society for Testing and Materials ASTM D2261 (ASTM, 1980).

3.3.7.3. Metal analysis (ICP-MS, Method 3052 and Method 6020)

Leachate cation concentrations of major material constituents (i.e., calcium, sodium, and potassium) and primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) were determined using a Perkin-Elmer inductively coupled plasma mass spectroscopy (ICP-MS) ELAN DRC II (PerkinAlmer Instruments, Shelton, CT) in both standard and dynamic reaction chamber (DRC) modes. Standard analysis mode was used for calcium, cadmium, copper, potassium, sodium, lead, and zinc and DRC mode with 0.6 mL/min of methane as the reaction gas was used for arsenic. Liquid samples for ICP-MS analysis were preserved through addition of 2% by vol. of concentrated nitric acid (trace metal grade).

Multipoint calibration curves using at least 7 standards and an initial calibration verification (ICV) using a standard obtained from a different source than the calibration standards were completed daily or after every 50 samples, whichever was more frequent. In addition, instrument blanks and continuing calibration verification (CCV) standards were analyzed after every 10 analytical samples and required to be within 10 percent of the expected value. CCV standards and instrument blanks also were run at the end of each batch of samples. Analytical spikes for the constituents of interest (i.e., aliquot of the sample plus a known spike concentration of the element of interest) were carried out for one replicate of each test case to assess analytical recoveries. A “spike recovery” of within 80 – 120% of the expected value was considered acceptable. Samples for analysis were diluted gravimetrically to within the targeted analytical range using 2 % by volume Optima grade nitric acid. 20 μL of a 10 mg/L of internal standard (indium - In or holmium - Ho) was added to each sample prior to analysis. Table 5 provides for each element analyzed the method detection limit (MDL) and minimum level of quantification (ML).

Table 5. Detection limits for ICP-MS analysis for arsenic, calcium, cadmium, copper, potassium, sodium, lead, and zinc.

Element	MDL (µg/L)	ML (µg/L)
As	0.64	3
Ca	1.02	4
Cd	0.15	1
Cu	0.70	3
K	1.29	5
Na	0.69	3
Pb	0.23	1
Zn	0.92	4

3.3.7.4. Anions by ion chromatography

Leachate anion concentrations (i.e., bromide, chloride, and sulfate) were determined using a DX-600 ion chromatograph (Dionex, Sunnyvale, CA). The instrument was calibrated using both Dionex Five Anion Standard and an independent standard (SPEX Certiprep). The detection limits for IC analysis are shown in Table 6. A 5-point calibration curve, analytical blanks and spikes were performed. Ten samples were run, followed by a duplicate and a spike of the 10th sample. In addition, CCV standards obtained from a different source than the calibration standards were run after every group of 10 samples.

Table 6. Detection limits for IC analysis.

Element	MDL (mg/L)
Cl	0.2
Br	0.4
SO_4^{2-}	0.2

4. RESULTS AND DISCUSSION

4.1. OPTIMUM MOISTURE CONTENT

Figure 3 shows the curve of the dry density versus the amount of water added for the less than 9.5 mm size reduced LFC material. An optimum moisture content of 29.0 wt% (total mass of water (g)/mass of material dry (g)) was obtained.

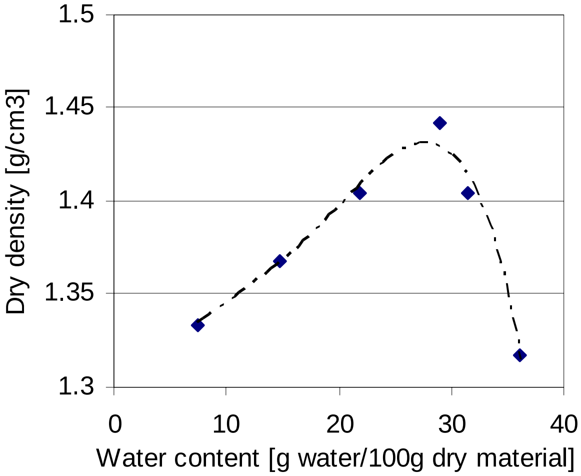


Figure 3. Dry density curve of the less than 9.5 mm graded LFC material.

4.2. F/T EXPOSURE AND TEMPERATURE PROFILES

Temperature profiles as a function of time at the top, middle, and bottom portion of the column obtained during freezing at -12°C and thawing at room temperature (20 ± 3°C) are shown in Figure 4A and 4B, respectively. All portions of the column reached a temperature below 0°C within ca. 4 hours of freezing. Longer exposure time to freezing resulted in the development of a temperature gradient within the column, with the lowest temperature (i.e., -9°C) obtained at the top of the column after 8 hours of freezing. During thawing, the top and middle portions of the column reached a temperature above 0°C within ca. 3.5 hours.

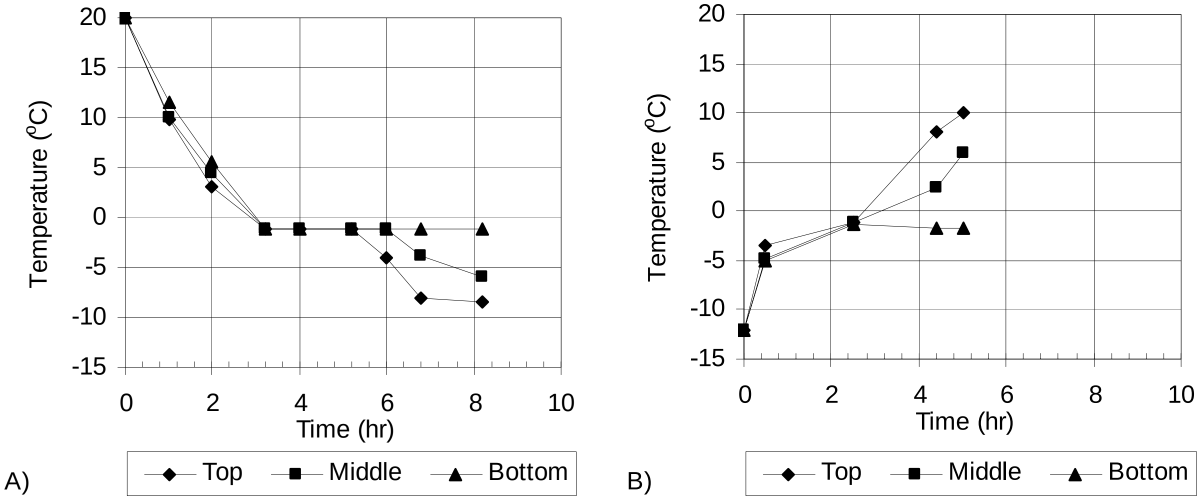


Figure 4. Temperature profiles at the top, middle, and bottom of the column during A) freezing at -12°C and B) thawing at room temperature (20 ± 3°C).

4.3. PHYSICAL AND CHEMICAL STABILITY OF THE GRANULAR LFC MATERIAL WITH RESPECT TO F/T EXPOSURE

4.3.1. Material physical stability

4.3.1.1. Material bulk dry density

Exposure to F/T cycles of compacted granular LFC material resulted in an increase in sample height and a decrease in the material bulk dry density (Figure 5).

An increase in sample height by 1 mm and a decrease in bulk dry density by ca. 1.4% were observed after 10 F/T cycles, independent of the material gradation (i.e., less than 2 mm or less than 9.5 mm). Subsequent F/T cycles did not result in additional changes in sample height or bulk dry density for the less than 9.5 mm size reduced LFC material while it resulted in a total increase in sample height of 2 mm and decrease in bulk dry density of ca. 2.9% for the less than 2 mm size reduced LFC material. This behavior is consistent with that typically observed for fine-grained soils, which experience greater frost heave damage than coarse-grained soils (Talamucci, 2003). The decrease in bulk dry density was caused by expansion of the volume of pore water when it was frozen and the force of the ice heaving up in the granular LFC material.

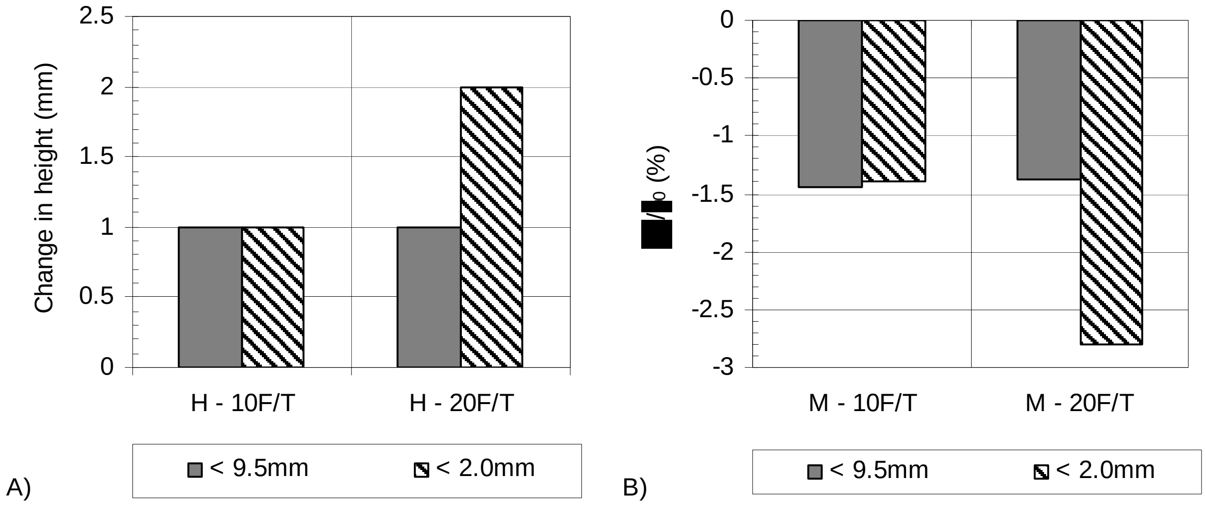


Figure 5. Changes in A) sample height and B) bulk dry density vs. the number of F/T cycles for two gradations of the LFC material (< 2 mm and < 9.5 mm) compacted at the optimum moisture content and freezing at -12°C.

4.3.1.2. Material physical integrity

Before exposure to F/T cycles, ca. 43% of the less than 2 mm size reduced LFC material had a particle size less than 0.5 mm and ca. 28 wt% had a particle size greater than 1 mm. For the less than 9.5 mm size reduced LFC material, the fraction of material with a particle size greater than 2 mm was dominant with more than 65% and more than 45% of the material had a particle size greater than 4 mm. Particle size distributions for the two material gradations are shown in Figure 6.

Exposure to F/T cycles resulted in aggregation of concrete particles and overall consolidation of the packed granular material, as shown in Figure 7. Aggregation of particles during F/T exposure has been reported for soils as a result of particle rearrangement and void filling/clogging by fine and loose particles during F/T expansion and contraction (Eigenbrod, 1996; Viklander, 1998a; Viklander *et al.*, 2000). Similar processes are likely to have occurred for the LFC material since a relatively large fraction of the two gradations examined was less than 500 µm (ca. 43% and ca.17% for the less than 2 mm and less than 9.5 mm graded LFC material, respectively). Consolidation of the granular material was further observed after leaching (see Figure 7 and Figure 8), suggesting a process similar to autogenous healing of the material. Autogenous healing in the presence of moisture of cracked concrete and granular cementitious based materials and self-cementing phenomena during thawing and subsequent permeation have been reported by several authors (Arm, 2001; Ding *et al.*, 1998; Eigenbrod, 2003; Jacobsen *et al.*, 1996a; Jacobsen *et al.*, 1996b; Poon *et al.*, in press; Ramm *et al.*, 1998; Reinhardt *et al.*, 2003). The consolidated granular LFC material did not show, however, a sufficient strength to be further tested for compressive strength (see Figure 9).

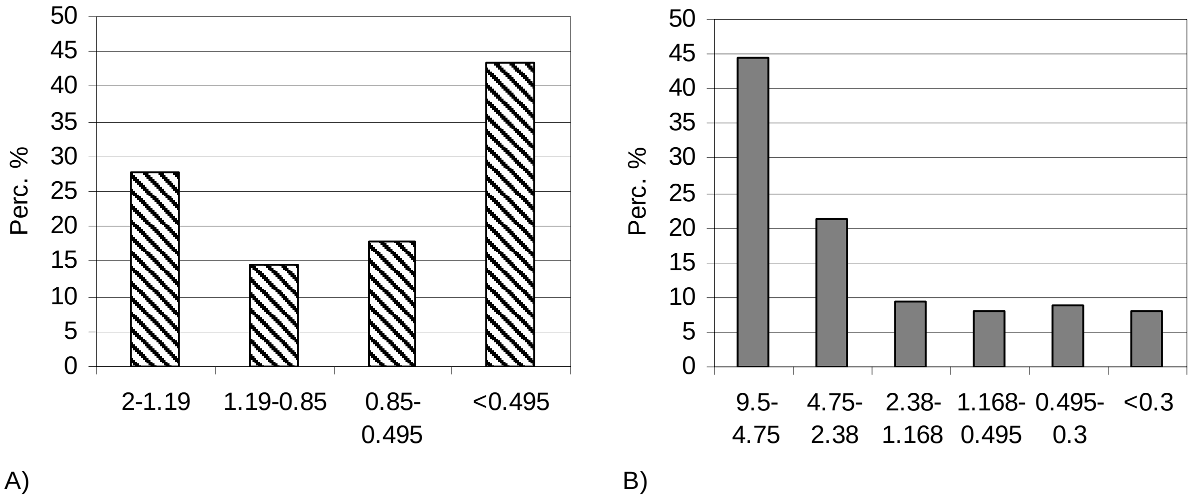


Figure 6. Particle size distribution of the A) less than 2 mm graded LFC material and B) less than 9.5 mm graded LFC material before F/T exposure.

Figure 7. Less than 9.5 mm graded LFC material immediately after exposure to 10 F/T cycles (note consolidation of the material).

Figure 8. Less than 2 mm graded LFC material after exposure to 10 F/T cycles and flow around leaching for 21 days (note consolidation of the material).

Figure 9. Less than 9.5 mm graded LFC material after exposure to 10F/T cycles and column leaching for 25 days (note aggregation of the concrete particles).

4.3.2. Thermal stability of the mineral/chemical components of the LFC material

4.3.2.1. Effect of F/T exposure on material buffering capacity

The acid neutralization capacity curves of the LFC material before and after 10 F/T cycles are show in Figure 10. The curves indicate the amount of acid required to neutralize a certain alkalinity and to reach a particular pH value. Exposure to 10 F/T cycles did not affect the buffering capacity of the LFC material. The acid neutralization capacity curve of both the 0 F/T and 10 F/T cycles aged materials decreased from the natural pH of the material (pH of ca. 12.5) to a pH of ca. 11.2 for the addition of 4 meq of acid/g of dry sample. At this point, the pH curve dropped steeply to a pH less than 4 for an acid addition of ca. 7.3 meq/g dry material. The acid neutralization response of the 10 F/T cycles aged LFC material suggested additionally that no material carbonation occurred during exposure to 10 F/T cycles.

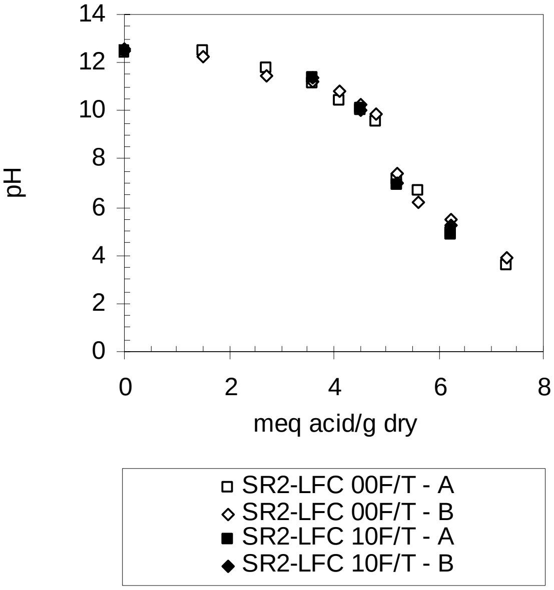


Figure 10. pH titration curves for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

Exposure to F/T cycles did not affect the leachate pH as a function of LS ratio (Figure 11). Leachate pH slightly increased (by ca. 0.8 pH units) as the LS ratio decreased.

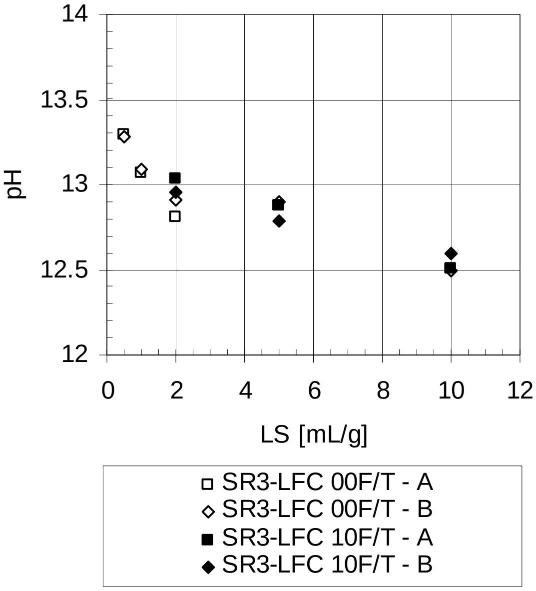


Figure 11. Leachate pH as a function of LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

4.3.2.2. Effect of F/T exposure on constituent leaching at equilibrium as a function of pH and LS ratio

No significant effect of F/T exposure was observed on leaching at equilibrium of major LFC constituents (i.e., Ca, Na, and K) and trace metals (i.e., As, Cd, Cu, Pb, and Zn) over the entire range of pH and LS ratios examined (Figure 12 to Figure 19). These results indicated that F/T exposure did not have an effect on the stability of the mineral/chemical components of the LFC material.

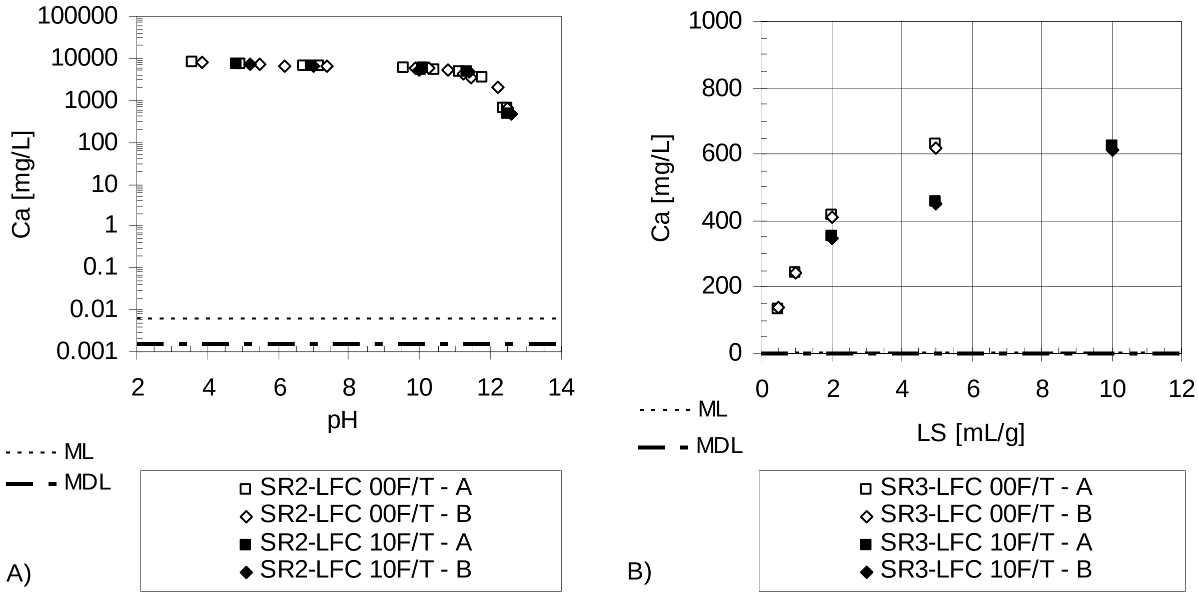


Figure 12. Calcium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

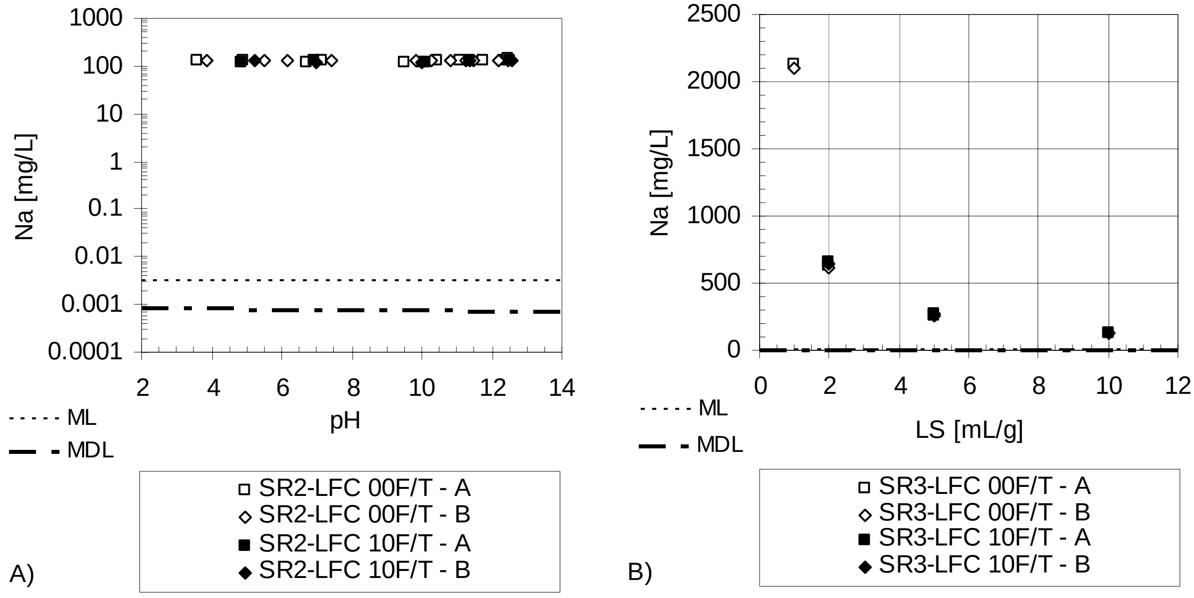


Figure 13. Sodium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

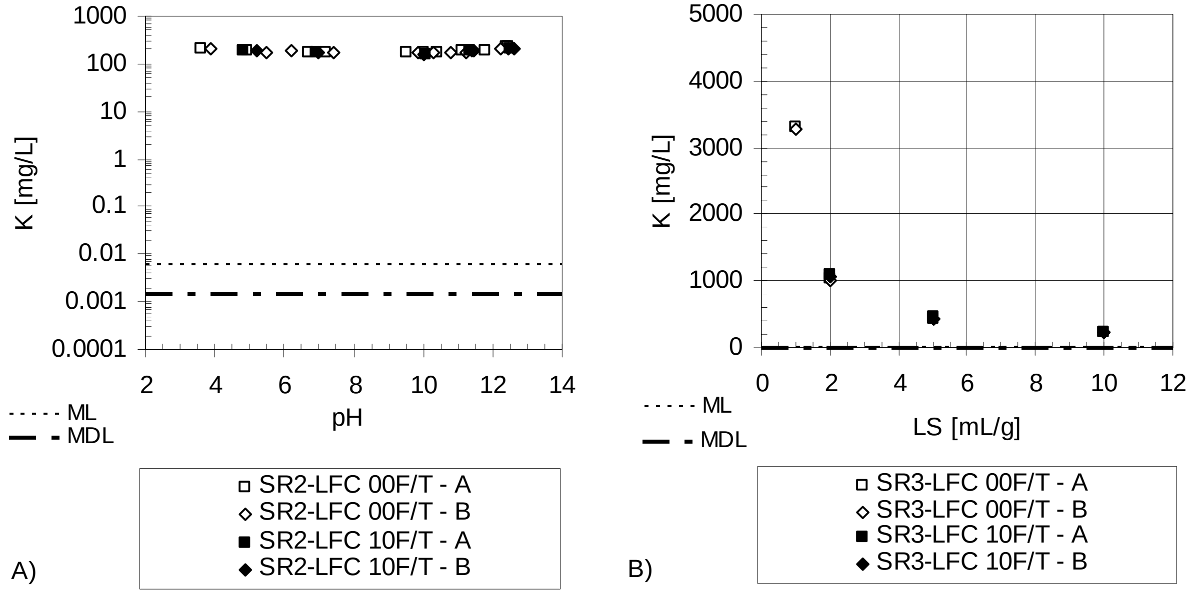
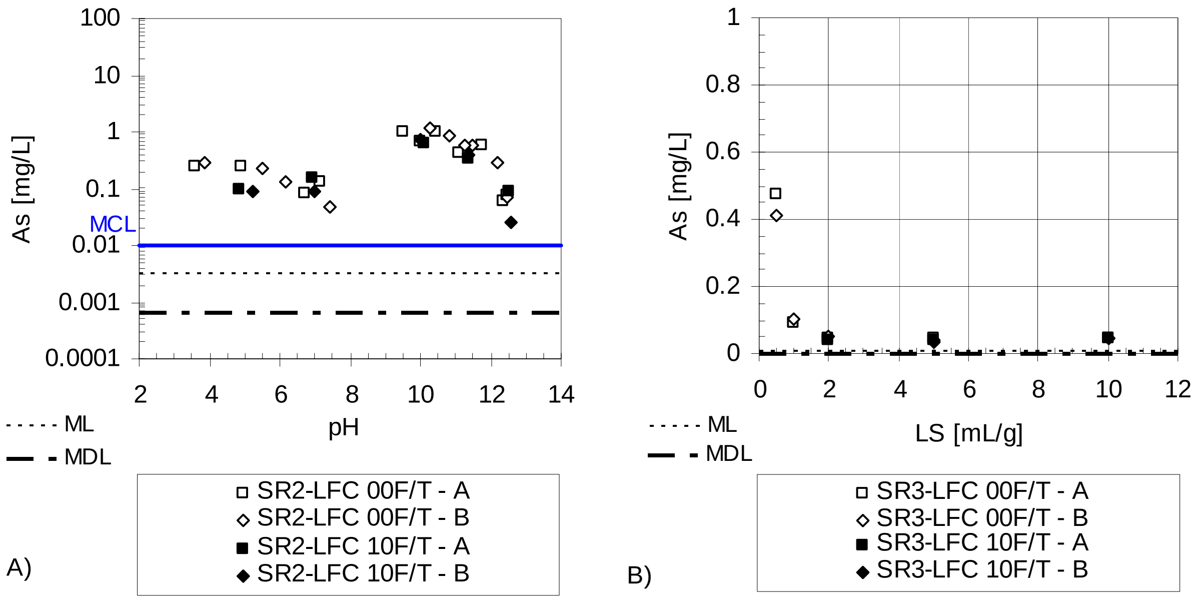


Figure 14. Potassium release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.



MCL: Maximum concentration limit (for drinking water).

Figure 15. Arsenic release as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

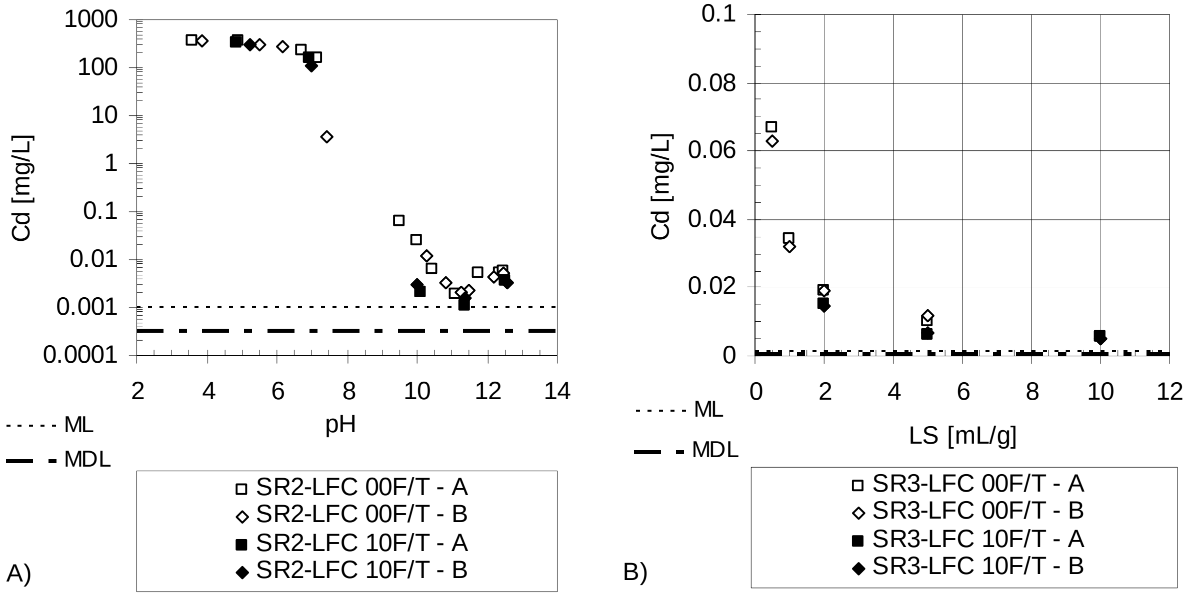


Figure 16. Cadmium solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

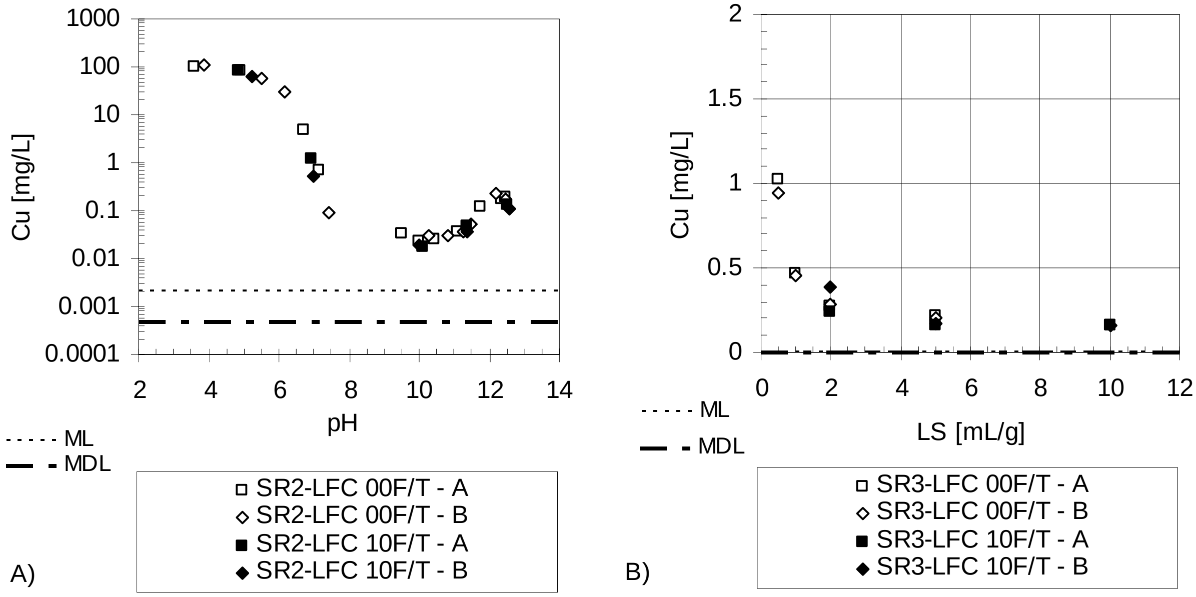
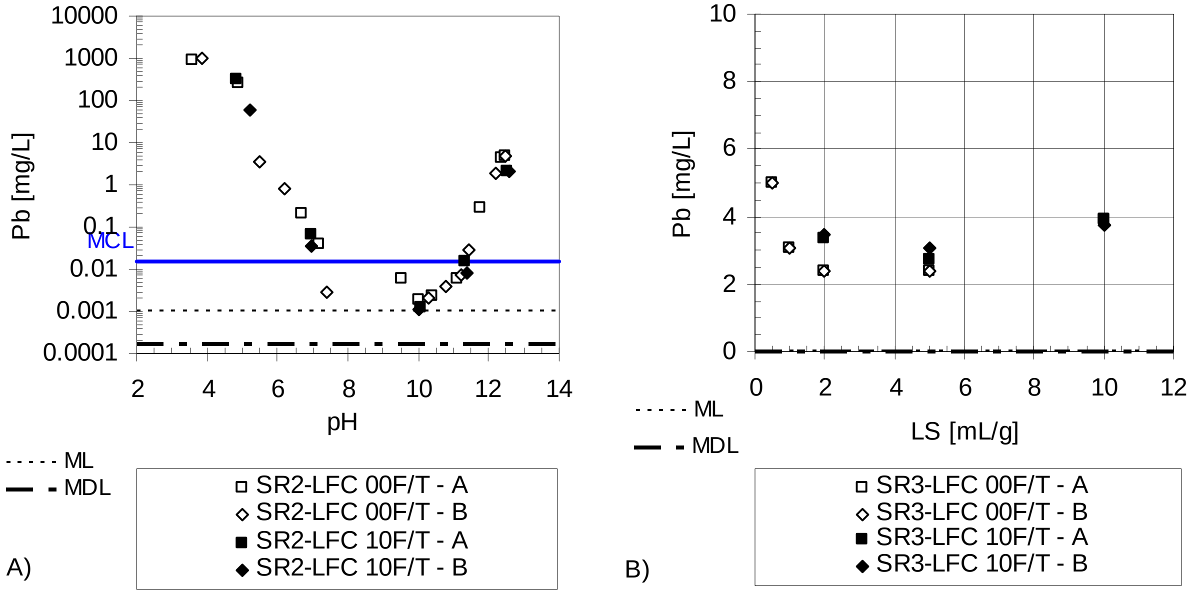


Figure 17. Copper solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.



MCL: Maximum concentration limit (for drinking water).

Figure 18. Lead solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

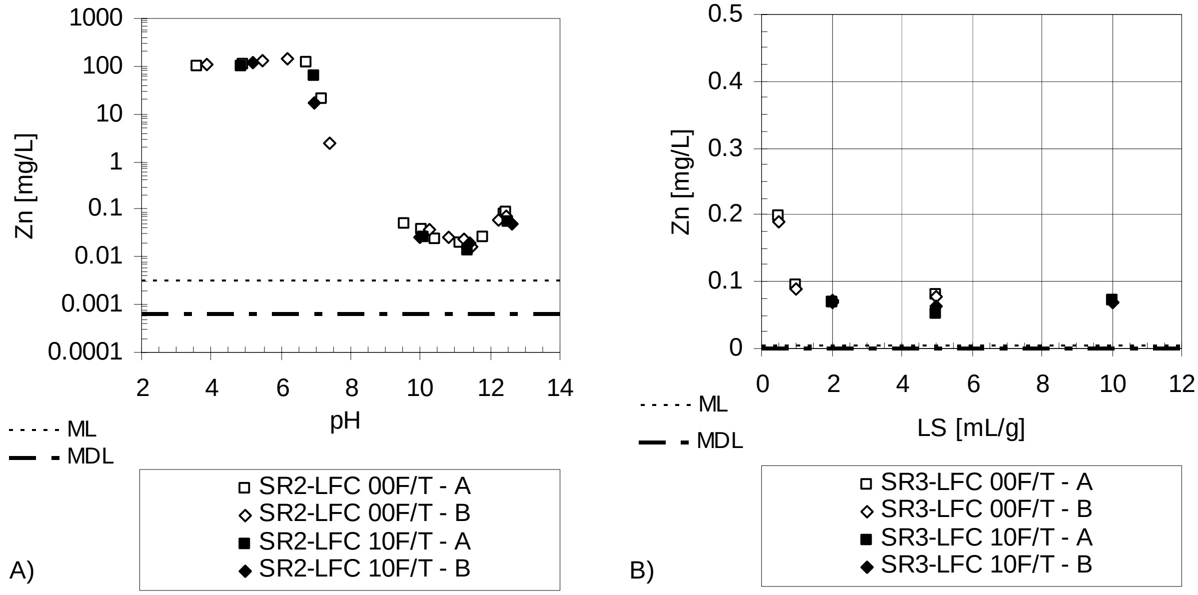


Figure 19. Zinc solubility as a function of A) pH and B) LS ratio for the less than 2 mm graded LFC material after exposure to 0 and 10 F/T cycles.

4.4. EFFECT OF F/T EXPOSURE ON CONSTITUENT LEACHING DURING FLOW-AROUND CONTROLLED SCENARIO

4.4.1. Effect of F/T exposure on leachate pH and conductivity

No significant effect of F/T exposure was observed on the leachate pH of both material gradations (Figure 20). Slightly lower leachate pH (i.e., by as much as ca. 0.5 pH unit) were observed on the first initial 3 extracts for the less than 2 mm graded material compared to the less than 9.5 mm graded material. This was consistent with an initial lower porosity for the smallest material gradation (i.e., less than 2 mm).

Exposure to 10 and 20 F/T cycles resulted in lower leachate conductivity (i.e., by as much as 4 times) of the initial 3 extracts of both material gradations (Figure 21). No significant effect of F/T exposure was observed for subsequent extracts. Additionally, as with the leachate pH, for the initial 3 extracts, the leachate conductivity of the less than 2 mm graded material was slightly lower than that of the less than 9.5 mm graded material (by as much as 2 times).

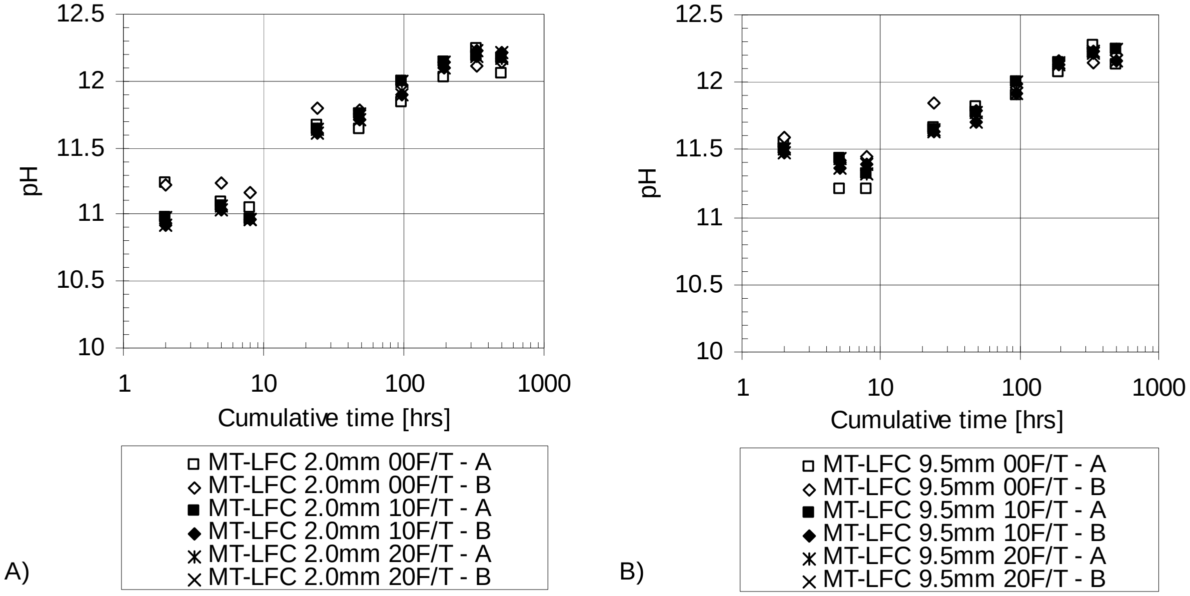


Figure 20. Leachate pH after exposure to 0, 10, and 20 F/T cycles of the less than A) 2 mm graded LFC material and B) 9.5 mm graded LFC material.

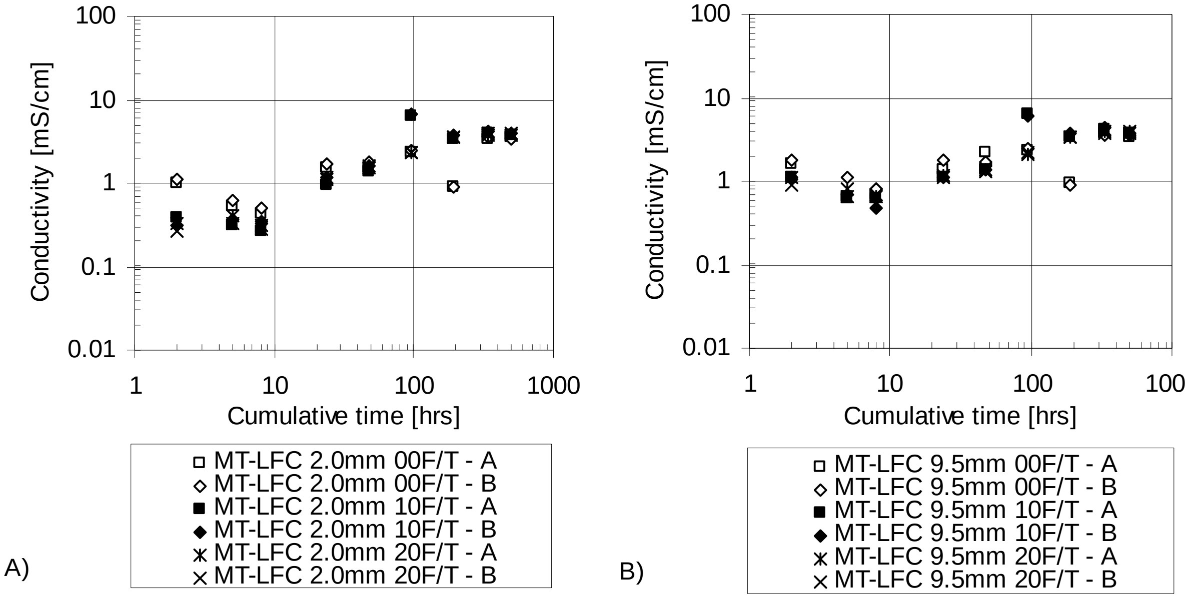


Figure 21. Leachate conductivity after exposure to 0, 10, and 20 F/T cycles of the less than A) 2 mm graded LFC material and B) 9.5 mm graded LFC material.

4.4.2. Effect of F/T exposure on the release of major material constituents

For each constituent of concern, a common format is used for presenting the results. Two sets of figures are used for each material gradation showing the different levels of F/T exposure. In the first set of figures, figures A and C show the cumulative release and flux as a function of time for the less than 2 mm graded LFC material and figures B and D show the cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. In the second set of figures, concentrations as a function of pH from mass transfer testing compared to batch testing are presented for the less than 2 mm graded LFC material (Figure A) and the less than 9.5 mm graded LFC material (Figure B).

4.4.2.1. Sodium release

The effect of F/T exposure on the release of sodium from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 22A and Figure 22B, respectively. Sodium concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 23.

The following general observations for sodium were made:

- A lower release flux of sodium was observed during the initial five leaching intervals (initial 50 hours of leaching) for the F/T cycle aged samples compared to the baseline samples (i.e., no F/T exposure), suggesting material consolidation during F/T exposure. However, for each F/T cycle aged sample, the observed incremental difference in the release flux decreased as the number of leaching intervals increased. After ca. 100 hours of leaching, no significant difference in the release fluxes of sodium between the F/T cycle aged samples and the baseline samples was then observed.

- Exposure to F/T cycles resulted in an overall lower cumulative release of sodium for both material gradations. For the less than 9.5 mm, ca. 60%, 50%, and 47% were released from the 0, 10, and 20 F/T cycle aged samples, respectively after ca. 500 hours of continuous leaching with periodic renewals. For the less than 2 mm, ca. 43%, 38%, and 35% were released from the 0, 10, and 20 F/T cycle aged samples, respectively.
- A greater decrease in the release of sodium was observed as the number of F/T cycles increased. This was consistent with observation made on material consolidation during exposure to F/T cycles.
- Overall, for all cases, a lower release of sodium was observed from the less than 2 mm graded material compared to the less than 9.5 mm graded material. This was consistent with an initial lower porosity for the less than 2 mm graded material.
- In all cases, sodium concentrations in leachates from mass transfer testing were lower than those from batch testing at similar pH.

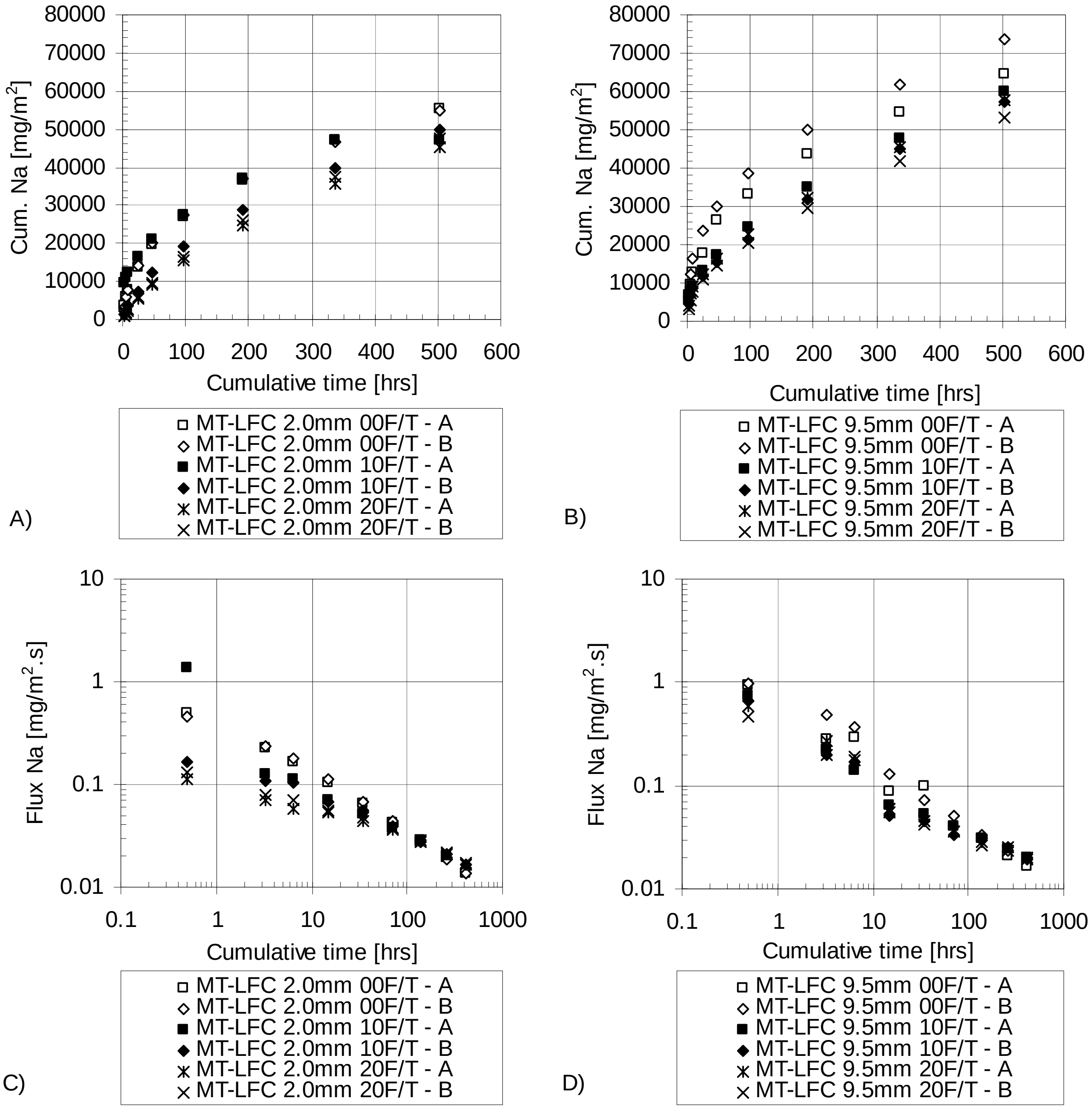


Figure 22. Sodium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

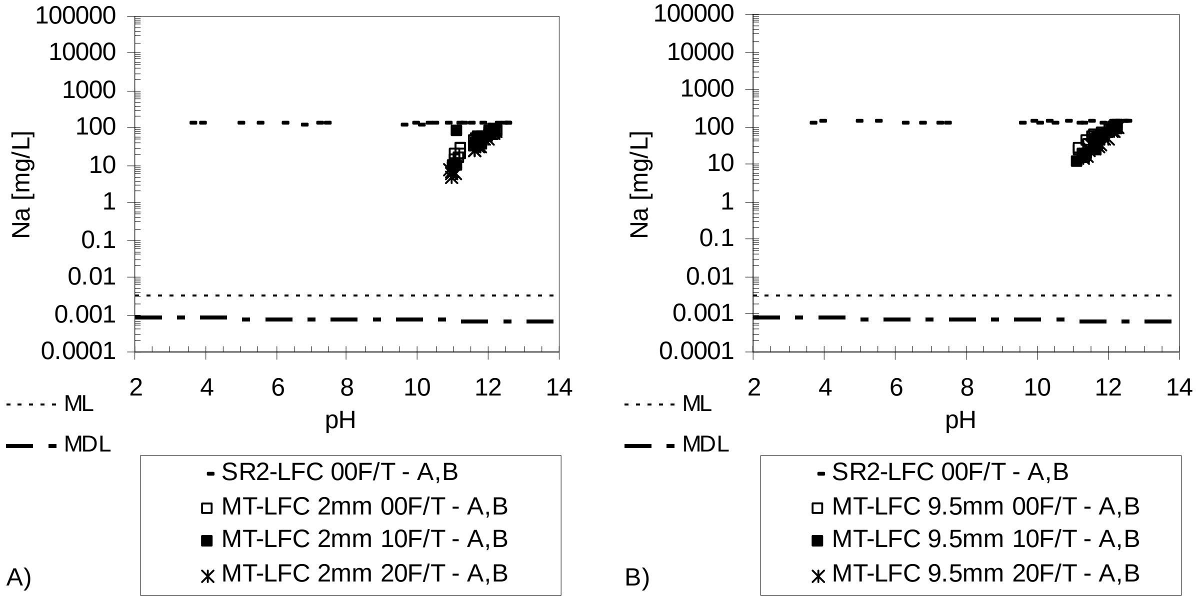


Figure 23. Sodium concentration as a function of pH from mass transfer testing compared to batch testing after exposure to 0, 10, and 20 F/T cycles for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm LFC graded material.

4.4.2.2. Potassium release

The effect of F/T exposure on the release of potassium from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 24A and Figure 24B, respectively. Potassium concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 25.

The following general observations for potassium were made:

- As with sodium, a lower release flux of potassium was observed during the initial five leaching intervals (initial 50 hours of leaching) for the F/T cycle aged samples compared to the baseline samples (i.e., no F/T exposure). This was more pronounced for the less than 2 mm graded LFC material than the less than 9.5 mm graded LFC material. The observed incremental difference in the release flux decreased as the number of leaching intervals increased. After ca. 100 hours of leaching, no significant difference in the release fluxes of potassium between the F/T cycle aged samples and the baseline samples was then observed.
- Overall, a lower cumulative release of potassium was observed for the F/T cycle aged samples compared to the baseline samples. For the less than 2 mm, ca. 111,600 mg/kg, ca. 102,000 mg/kg, and ca. 97,000 mg/kg were released from the 0, 10, and 20 F/T cycle aged samples, respectively (Figure 24A) after ca. 500 hours of continuous leaching with periodic renewals. For the less than 9.5 mm, ca. 142,000 mg/kg, ca. 124,000 mg/kg, and ca. 114,000 mg/kg were released from the 0, 10, and 20 F/T cycle aged samples, respectively (Figure 24B).

- A greater decrease in the release of potassium was observed as the number of F/T cycles increased. This was consistent with observation made on material consolidation during exposure to F/T cycles.
- In all cases, potassium concentrations in leachates from mass transfer testing were close to or lower than those from batch testing at similar pH.

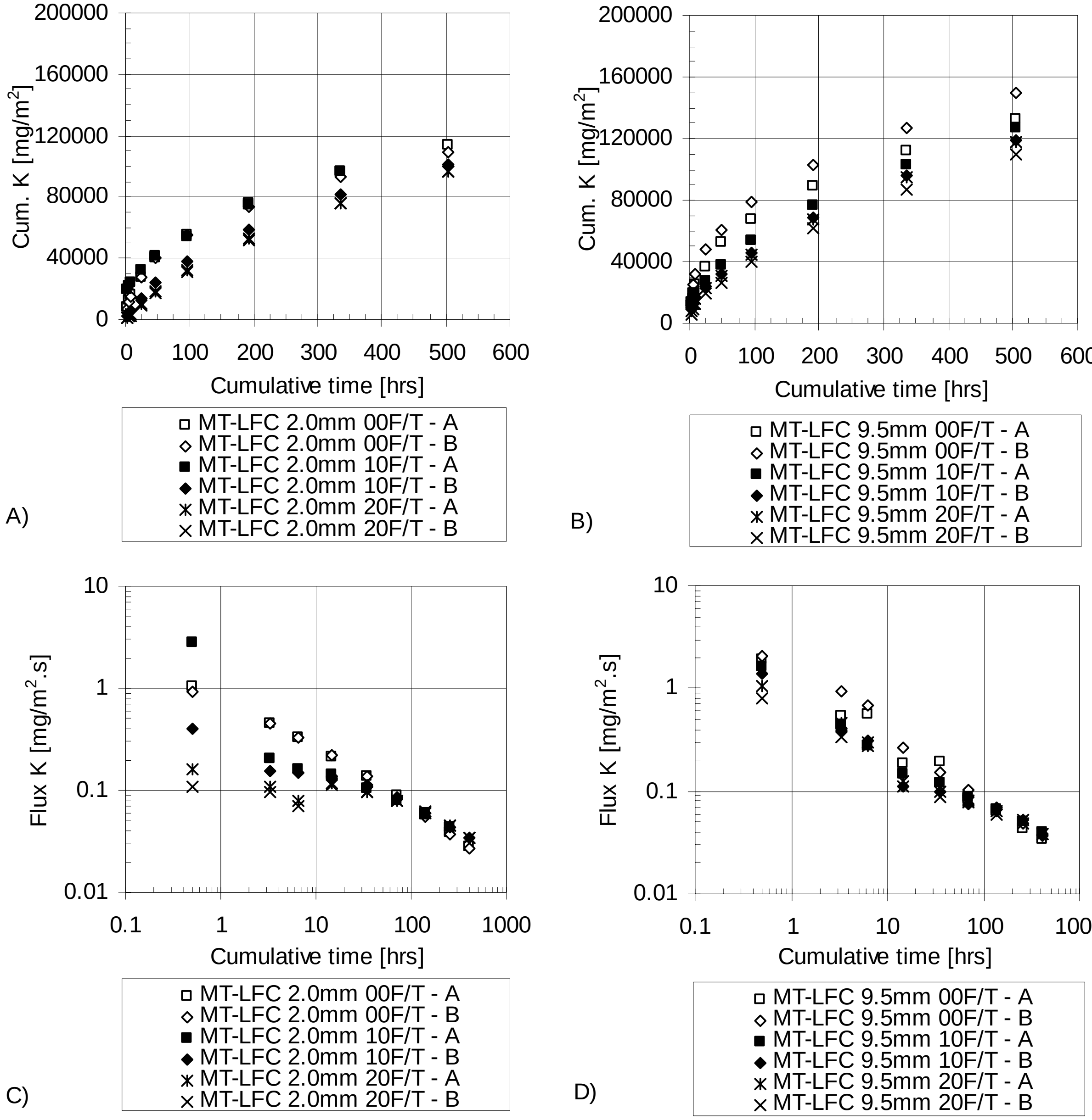


Figure 24. Potassium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

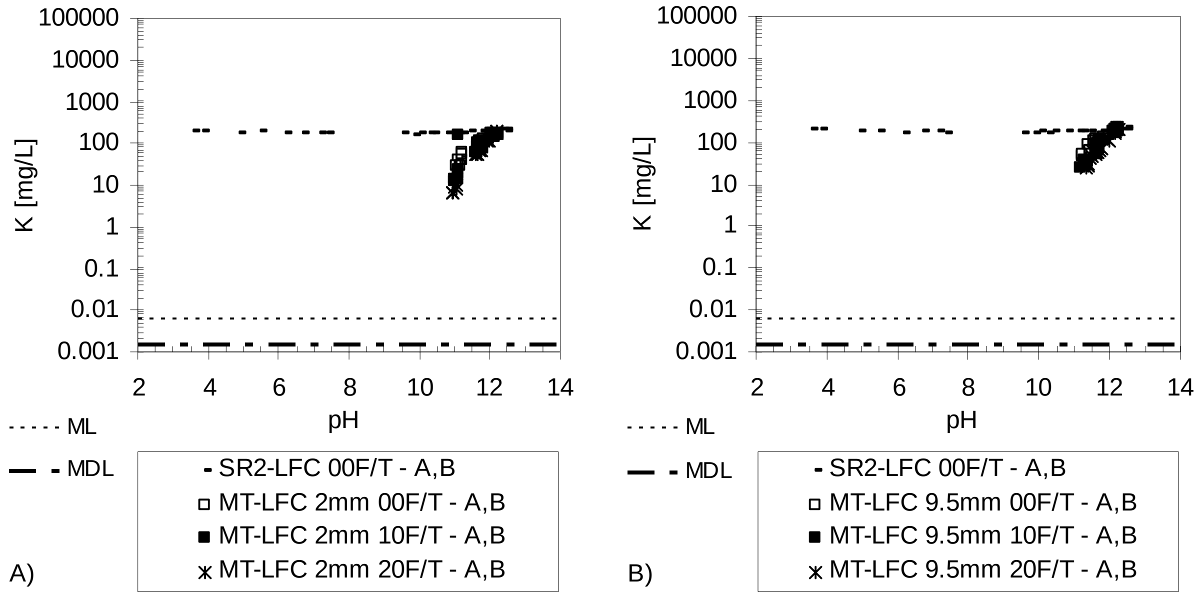


Figure 25. Potassium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.2.3. Calcium release

The effect of F/T exposure on the release of calcium from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 26A and Figure 26B, respectively. Calcium concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 27.

The following general observations for calcium were made:

- For the less than 2 mm graded LFC material, F/T exposure resulted in a significant decrease in calcium release (by as much as 2.5 times) compared to that obtained for the baseline samples (i.e., no F/T exposure prior to leaching), indicating material consolidation during F/T exposure.
- For the less than 9.5 mm graded material, F/T exposure initially increased the release of calcium (initial 5 extracts – more pronounced for 20 F/T cycles) and then decreased the release of calcium, resulting in an overall calcium release after 500 hours of leaching that was lower.
- For the baseline samples (i.e., no F/T exposure), a much greater release of calcium was observed from the less than 2 mm graded LFC material than the less than 9.5 mm graded LFC material (ca. 120,000 mg/m^2 and ca. 50,000 mg/m^2 after 500 hours of leaching, respectively). This was the result of diffusion limitation within large particles for the less than 9.5 mm graded LFC material (ca. 65% had a particle size greater than 2 mm) and a greater surface area exposed to leaching for the less than 2 mm graded LFC material (ca. 45% had a particle size less than 500 μm).

- For the baseline samples, after ca. 10 hours of leaching (initial 3-4 extracts), a change in flux behavior was observed that could be indicative of either initial surface wash-off or self-cementing processes occurring in conjunction with leaching.
- In all cases, calcium concentrations in leachates from mass transfer testing were lower than those from batch testing at similar pH.

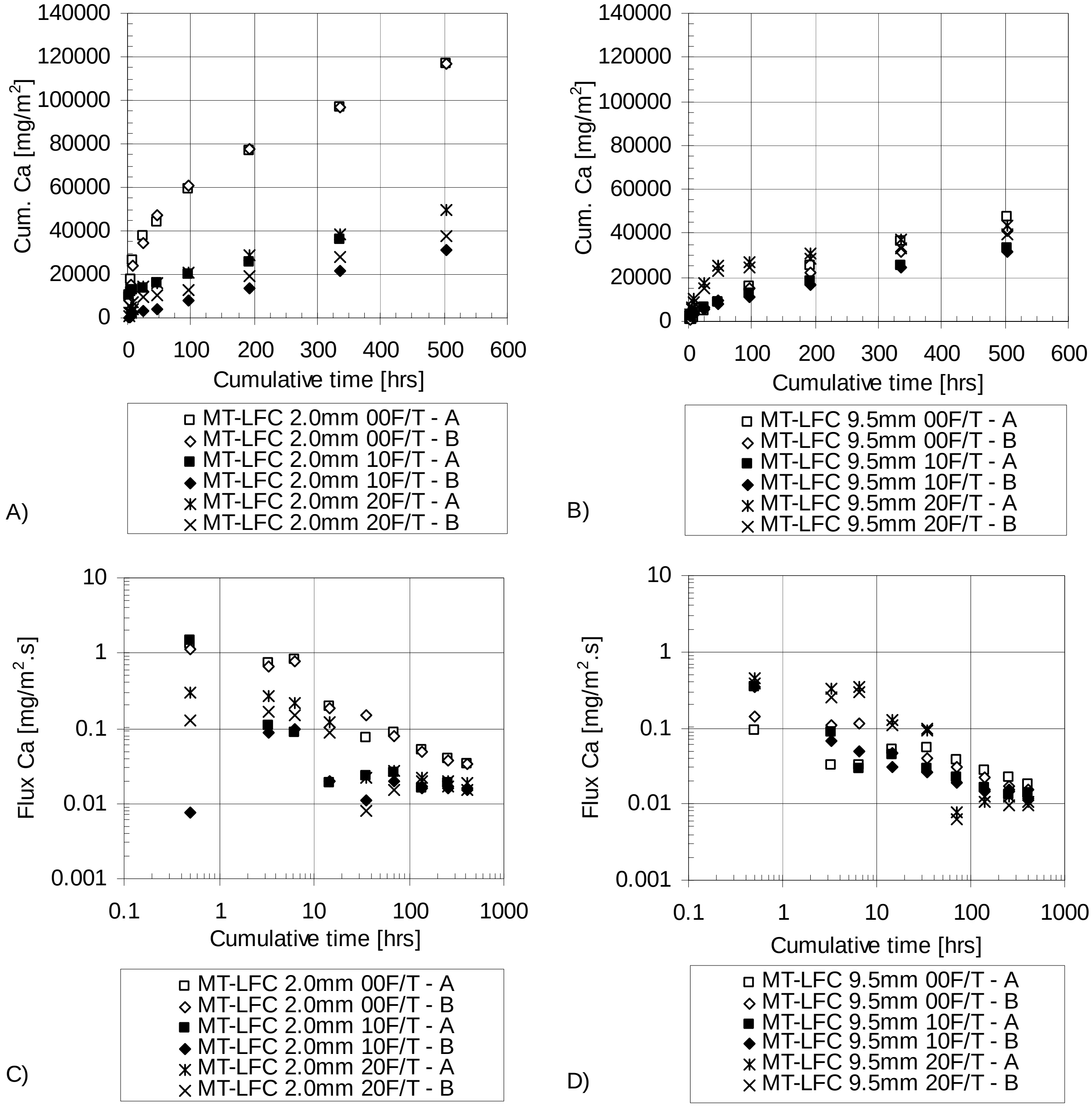


Figure 26. Calcium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

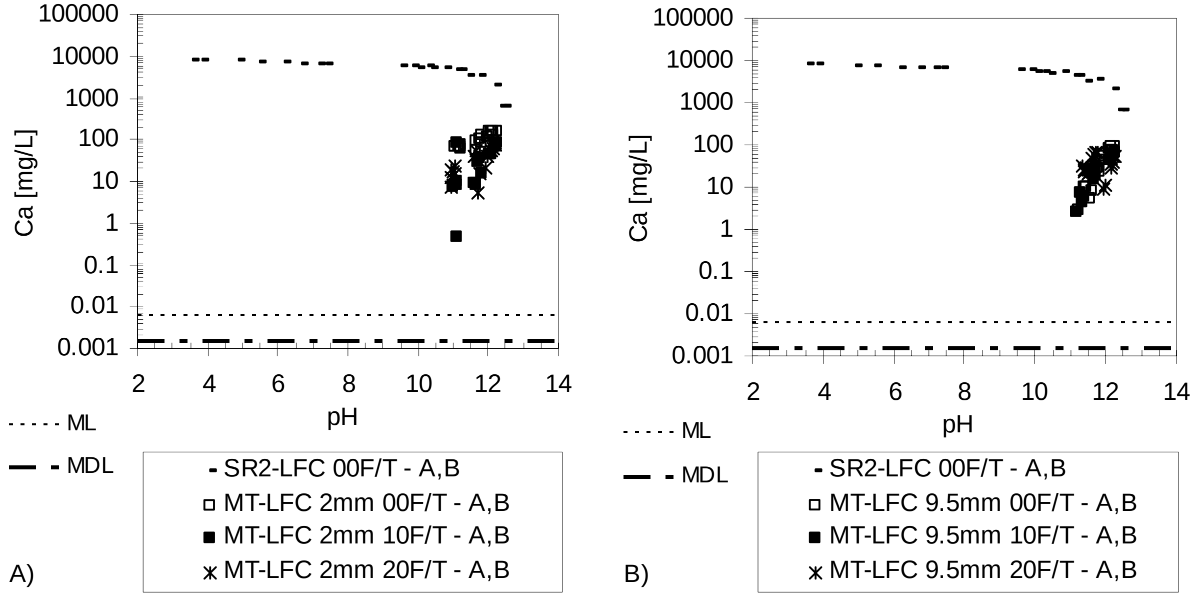


Figure 27. Calcium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.2.4. Chloride release

The effect of F/T exposure on the release of chloride from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 28A and Figure 28B, respectively.

The following general observations for chloride were made:

- A similar behavior as that observed for sodium and potassium was obtained for chloride. A lower cumulative release of chloride as a function of time was observed from the 10 and 20 F/T cycle aged samples compared to the baseline samples on both material gradations.
- For the less than 9.5 mm, ca. 9%, ca. 7%, and ca. 7% were released from the 0, 10, and 20 F/T cycle aged samples, respectively after ca. 500 hours of continuous leaching with periodic renewals. For the less than 2 mm, ca. 7%, ca. 6%, and ca. 5% were released from the 0, 10, and 20 F/T cycle aged samples, respectively.
- A lower release flux of chloride was observed during the initial five leaching intervals (initial 50 hours of leaching) from the F/T cycle aged samples compared to the baseline samples (i.e., no F/T exposure). This was more pronounced for the less than 2 mm graded LFC material for which the release flux was as much as 4 times lower. The observed incremental difference in the release flux decreased as the number of leaching intervals increased. After ca. 100 hours of leaching, no significant difference in the release fluxes of chloride between the F/T cycle aged samples and the baseline samples was then observed.
- For the less than 2 mm graded LFC material, the greatest decrease in the cumulative release of chloride was observed for the greatest number of F/T cycles used (i.e., 20 F/T cycles). For the less than 9.5 mm graded LFC material, no significant difference in the

release of chloride could be observed when the number of F/T cycles was further increased (no significant difference in the release between 10 and 20 F/T cycles).

- Overall, a lower release of chloride was observed from the less than 2 mm graded material compared to the less than 9.5 mm graded material. This was consistent with an initial lower porosity for the less than 2 mm graded material.

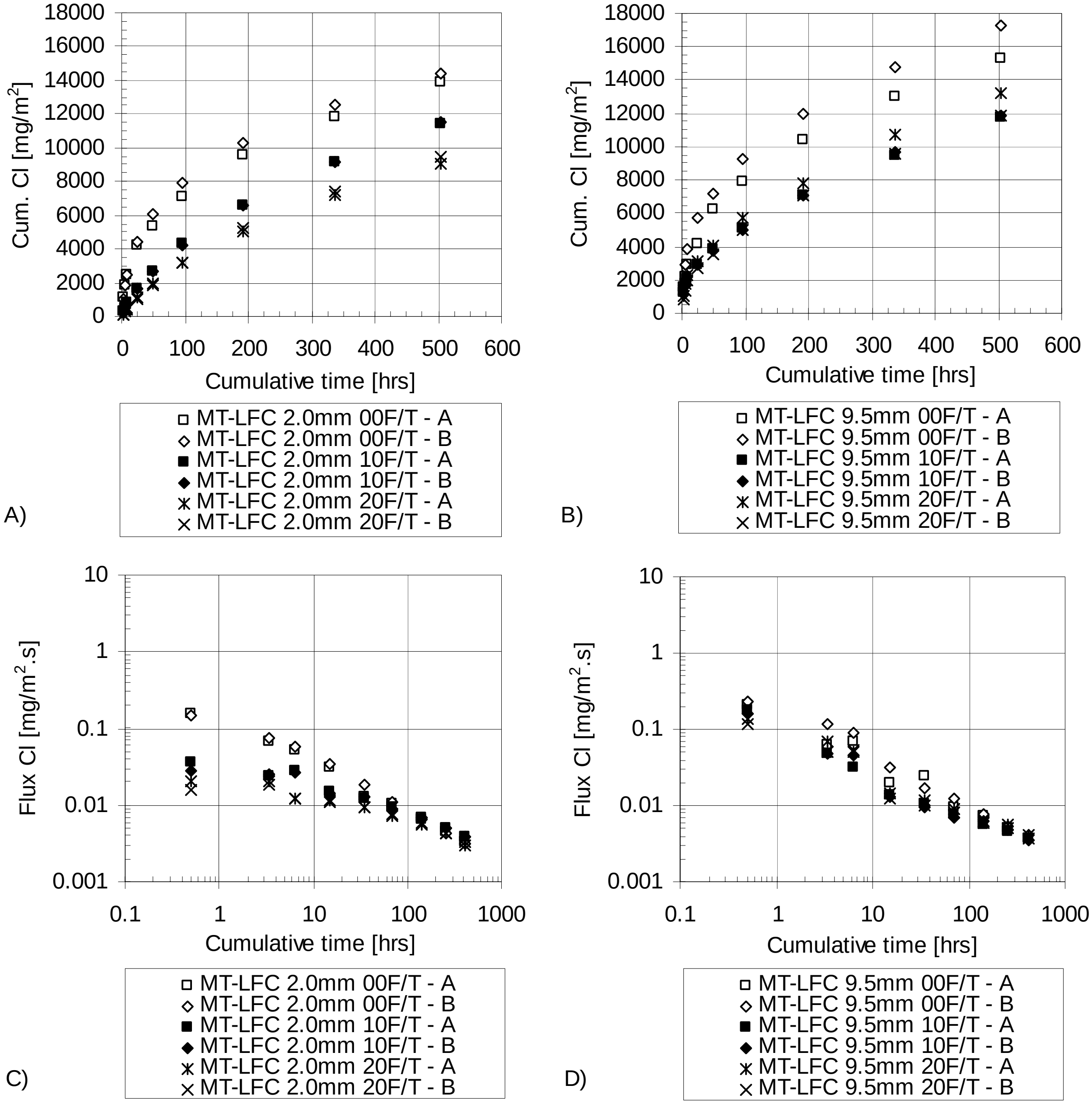


Figure 28. Chloride release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

4.4.2.5. Sulfate release

The effect of F/T exposure on the release of sulfate from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 29A and Figure 29B, respectively.

The following general observations for sulfate were made:

- Exposure to F/T cycles resulted in a decrease in the cumulative release of sulfate for both material gradations.
- The effect of F/T exposure was much greater on the less than 2 mm graded LFC material than the less than 9.5 mm graded LFC material (decrease by ca. 80% and ca. 50%, respectively after 500 hours of leaching).
- The greatest decrease in the cumulative release of sulfate was observed for the greatest number of F/T cycles used (i.e., 20 F/T cycles) in the case of the less than 2 mm graded material, while for the lowest number of F/T cycles used (i.e., 10 F/T cycles) in the case of the less than 9.5 mm graded material.
- A lower release flux of sulfate was observed during the initial 7 leaching intervals (initial 200 hours of leaching) from the F/T cycle aged samples compared to the baseline samples (i.e., no F/T exposure). This was more pronounced for the less than 2 mm graded LFC material for which the release flux was as much as 25 times lower. The observed incremental difference in the release flux decreased as the number of leaching intervals increased. After ca. 200 hours of leaching, no significant difference in the release fluxes of sulfate between the F/T cycle aged samples and the baseline samples was then observed.
- As with calcium, for the baseline samples (i.e., no F/T exposure), a much greater release of sulfate was observed for the less than 2 mm graded LFC material compared to the less than 9.5 mm graded LFC material, as a result of diffusion limitation within large particles for the less than 9.5 mm graded LFC material and greater surface area exposed to leaching for the less than 2 mm graded LFC material.

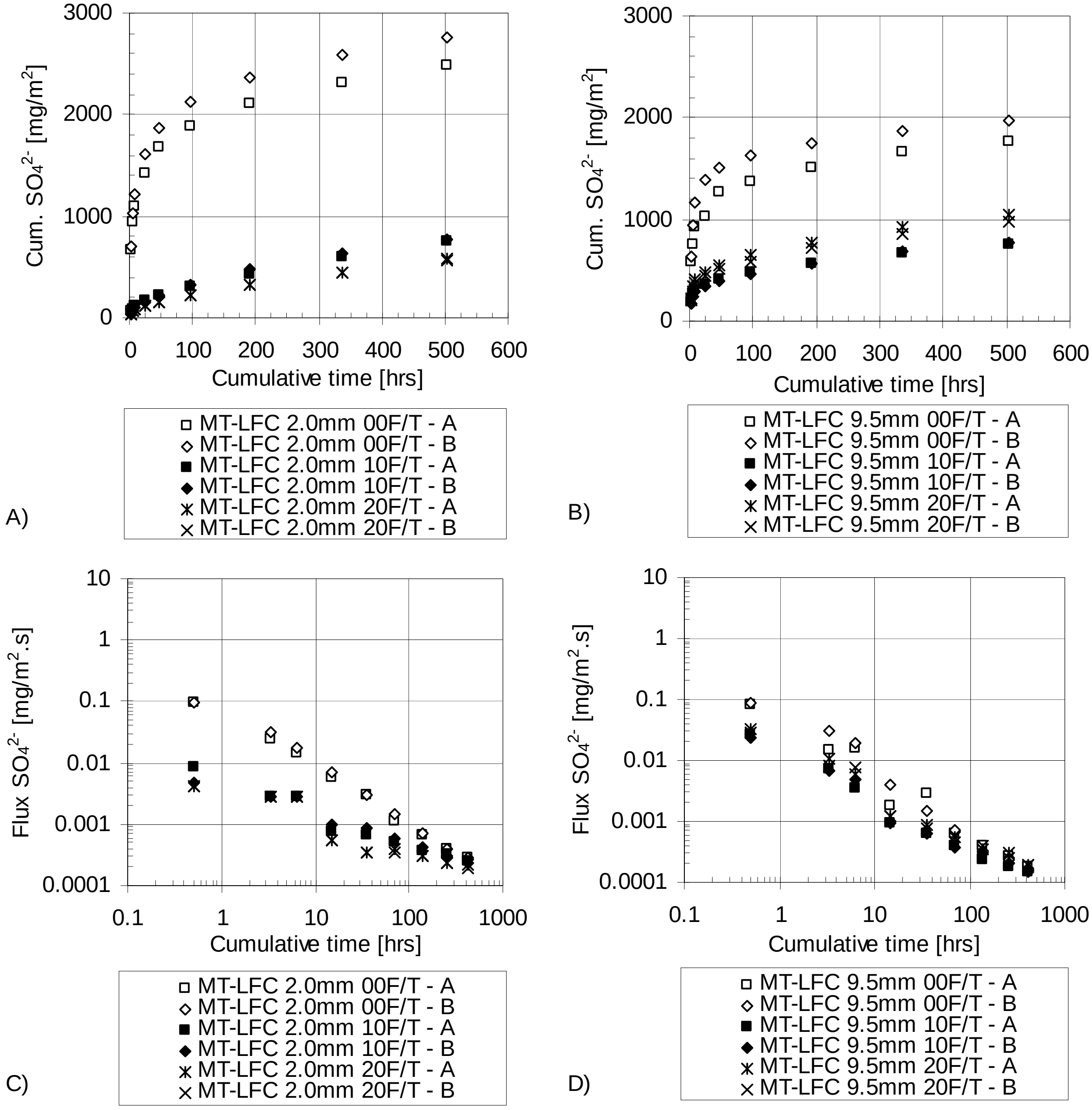


Figure 29. Sulfate release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

4.4.2.6. Conclusions

Exposure to F/T cycles suppressed the release flux during the initial leaching intervals for all of the major material constituents examined (i.e., sodium, potassium, calcium, chloride, and sulfate), suggesting material consolidation during F/T exposure. This resulted in a significant decrease in the cumulative release for all of the major material constituents. For calcium, chloride, and sulfate, the decrease was more significant for the less than 2 mm graded LFC material than the less than 9.5 mm graded LFC material (decrease in sodium, potassium, calcium, chloride, and sulfate of ca. 18%, 15%, 74%, 37%, and 80%, respectively for the less than 2 mm graded LFC material while decrease of ca. 23%, 27%, 33%, 31%, and 61%, respectively for the less than 9.5 mm graded LFC material). These results are in agreement with the visual observation of particle aggregation and overall consolidation of the packed granular material.

Additionally, for most cases, lower release flux and cumulative release were observed as the number of F/T cycles increased. However, for longer leaching exposure, similar release fluxes of sodium, potassium, chloride, and sulfate were observed from the F/T cycle aged and the baseline samples. This was not the case for calcium for which the release flux from the F/T cycle aged samples remained lower than that from the baseline samples.

4.4.3. Effect of F/T exposure on the release of primary contaminants

For each contaminant of concern, a common format is used for presenting the results. Two sets of figures are used for each material gradation showing the different levels of F/T exposure. In the first set of figures, figures A and C show the cumulative release and flux as a function of time for the less than 2 mm graded LFC material and figures B and D show the cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material. In the second set of figures, concentrations as a function of pH from mass transfer testing compared to batch testing are presented for the less than 2 mm graded LFC material (Figure A) and the less than 9.5 mm graded LFC material (Figure B).

4.4.3.1. Arsenic release

The effect of F/T exposure on the release of arsenic from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 30A and Figure 30B, respectively. Arsenic concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 31.

The following general observations for arsenic were made:

- Poor reproducibility in the release of arsenic was observed for the baseline samples for both material gradations.
- F/T exposure suppressed the release flux of arsenic for both material gradations. This resulted in a decrease in the cumulative release of arsenic by as much as 80% in both cases after 500 hours of leaching.
- A slightly greater release of arsenic was observed from the 20 F/T cycle aged samples compared to the 10 F/T cycle aged samples for both material gradations.
- In all cases, arsenic concentrations in leachates from mass transfer testing were lower than those from batch testing at similar pH, indicating that arsenic release was not limited by saturation of the leachates.

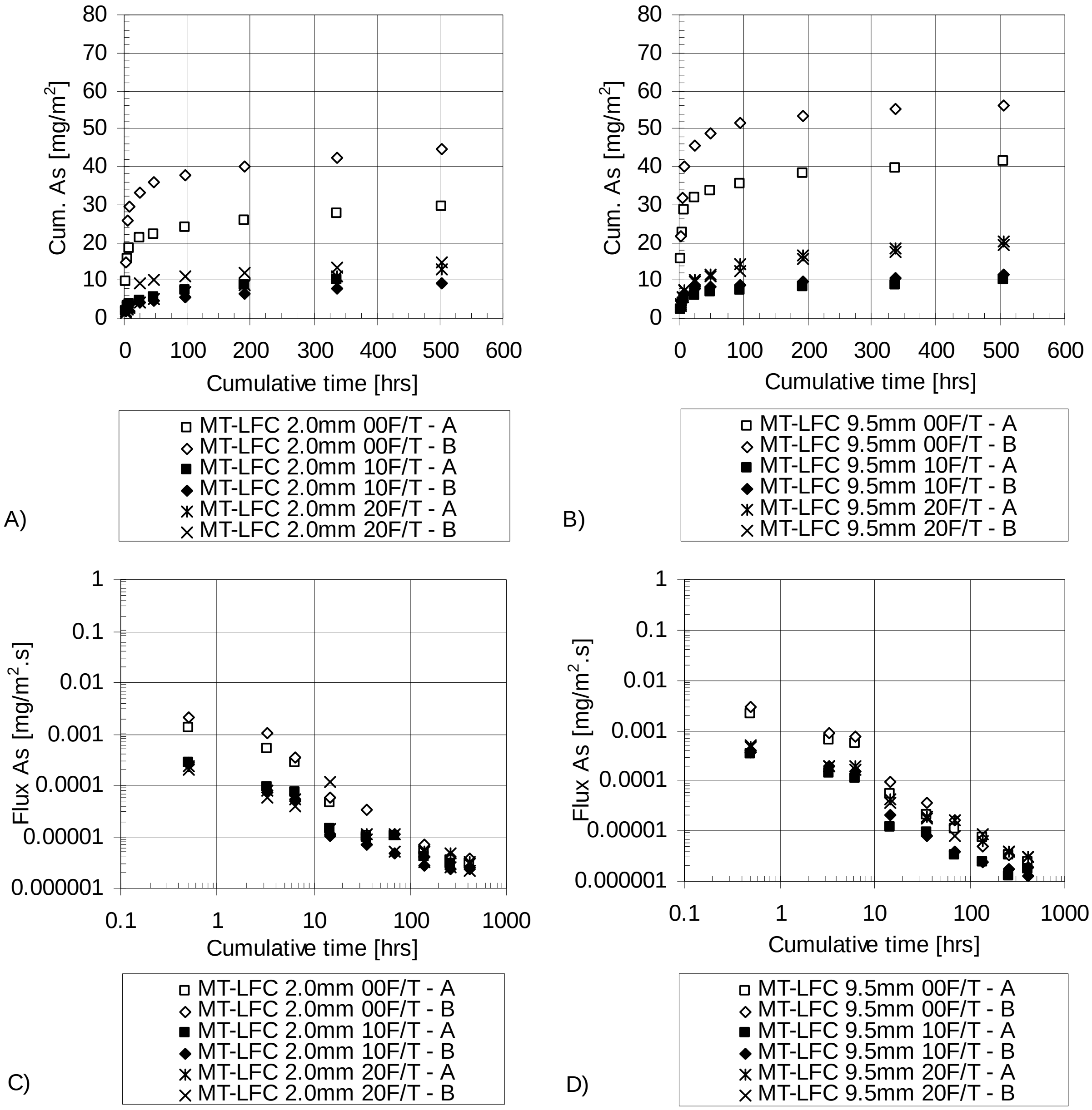


Figure 30. Arsenic release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

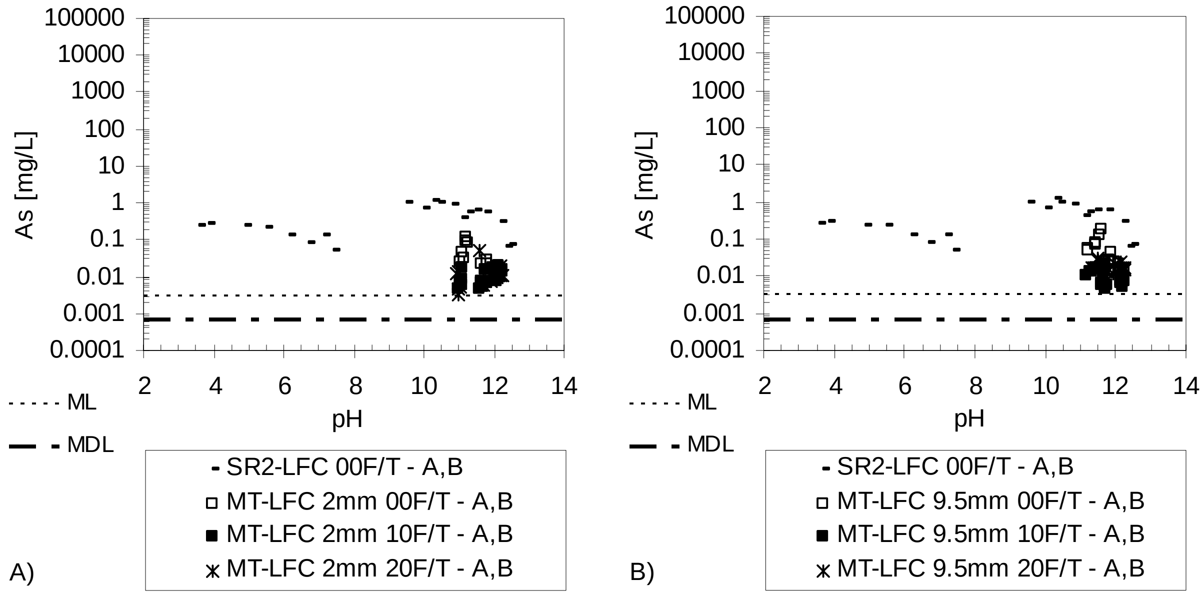


Figure 31. Arsenic concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.3.2. Cadmium release

The effect of F/T exposure on the release of cadmium from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 32A and Figure 32B, respectively. Cadmium concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 33.

The following general observations for cadmium were made:

- Poor reproducibility in the release of cadmium was observed for the baseline samples for both material gradations. Poor reproducibility was also observed for the 10 F/T cycle aged samples of the less than 9.5 mm graded LFC material.
- F/T exposure decreased the release flux of cadmium for both material gradations. This resulted in a decrease in the cumulative release of cadmium by as much as 72% for the less than 2 mm graded LFC material and 60% for the less than 9.5 mm graded LFC material after 500 hours of leaching.
- For both material gradations, exposure to 20 F/T cycles resulted in a lower release flux and cumulative release of cadmium than exposure to 10 F/T cycles.
- In all cases, cadmium concentrations in leachates from mass transfer testing were close to or lower than those from batch testing at similar pH. In some instance, cadmium release might have been limited by saturation of the leachates.

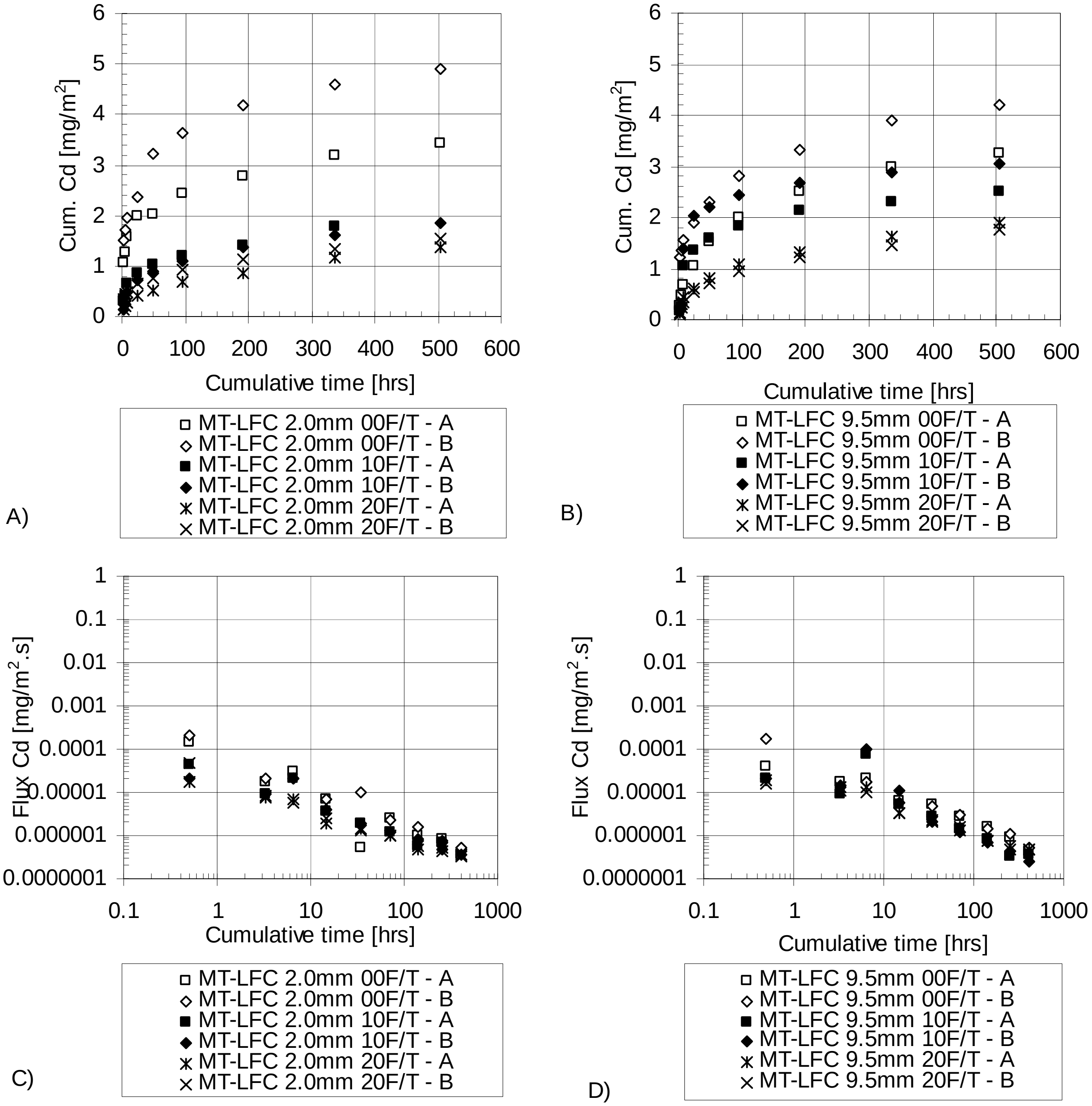


Figure 32. Cadmium release after exposure to 0, 10, and 20 F/T cycles. A) and C) Cumulative release and flux as a function of time for the less than 2 mm graded LFC material. B) and D) Cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

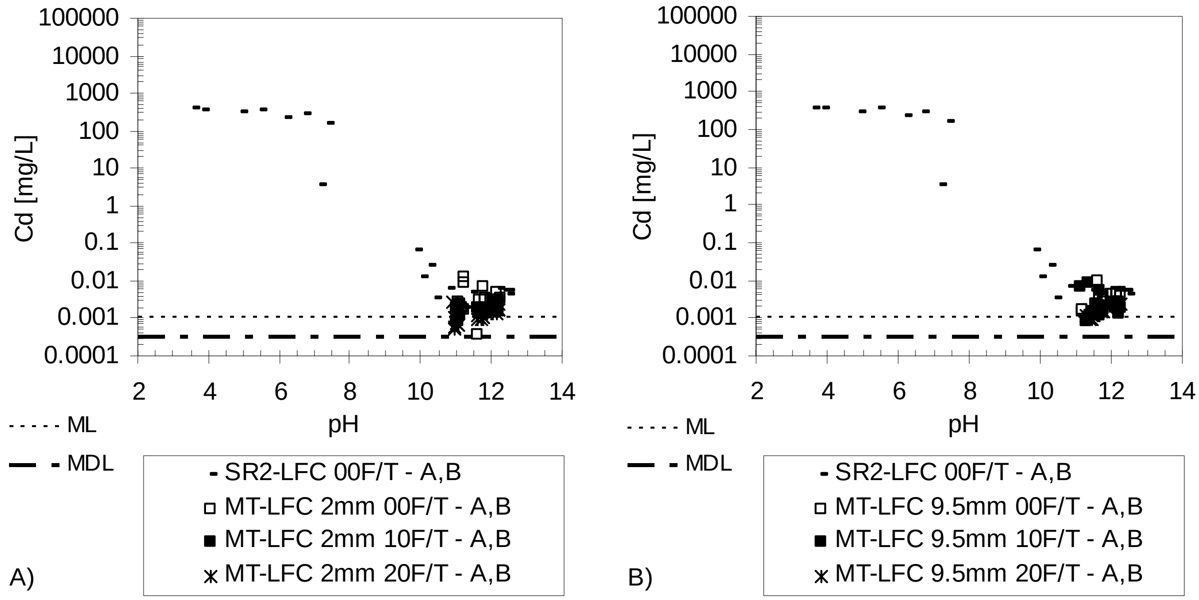


Figure 33. Cadmium concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.3.3. Copper release

The effect of F/T exposure on the release of copper from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 34A and Figure 34B, respectively. Copper concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 35.

The following general observations for copper were made:

- Poor reproducibility in the release of copper was observed for the baseline samples for both material gradations.
- F/T exposure decreased the release flux of copper during the initial 5 leaching intervals for both material gradations. This resulted in a decrease in the cumulative release of copper by as much as 28% for the less than 2 mm graded LFC material and 42% for the less than 9.5 mm graded LFC material after 500 hours of leaching. However, after ca. 100 hours of leaching, no significant difference in the release fluxes from the F/T cycle aged samples and the baseline samples was then observed.
- For both material gradations, no significant difference in the release of cadmium could be observed between the 10 and 20 F/T cycle exposures.
- Overall, for the baseline samples, a greater release of copper was observed from the less than 9.5 mm graded LFC material than from the less than 2 mm graded LFC material.
- In all cases, copper concentrations in leachates from mass transfer testing were close to or lower than those from batch testing at similar pH. In some instance, copper release might have been limited by saturation of the leachates.

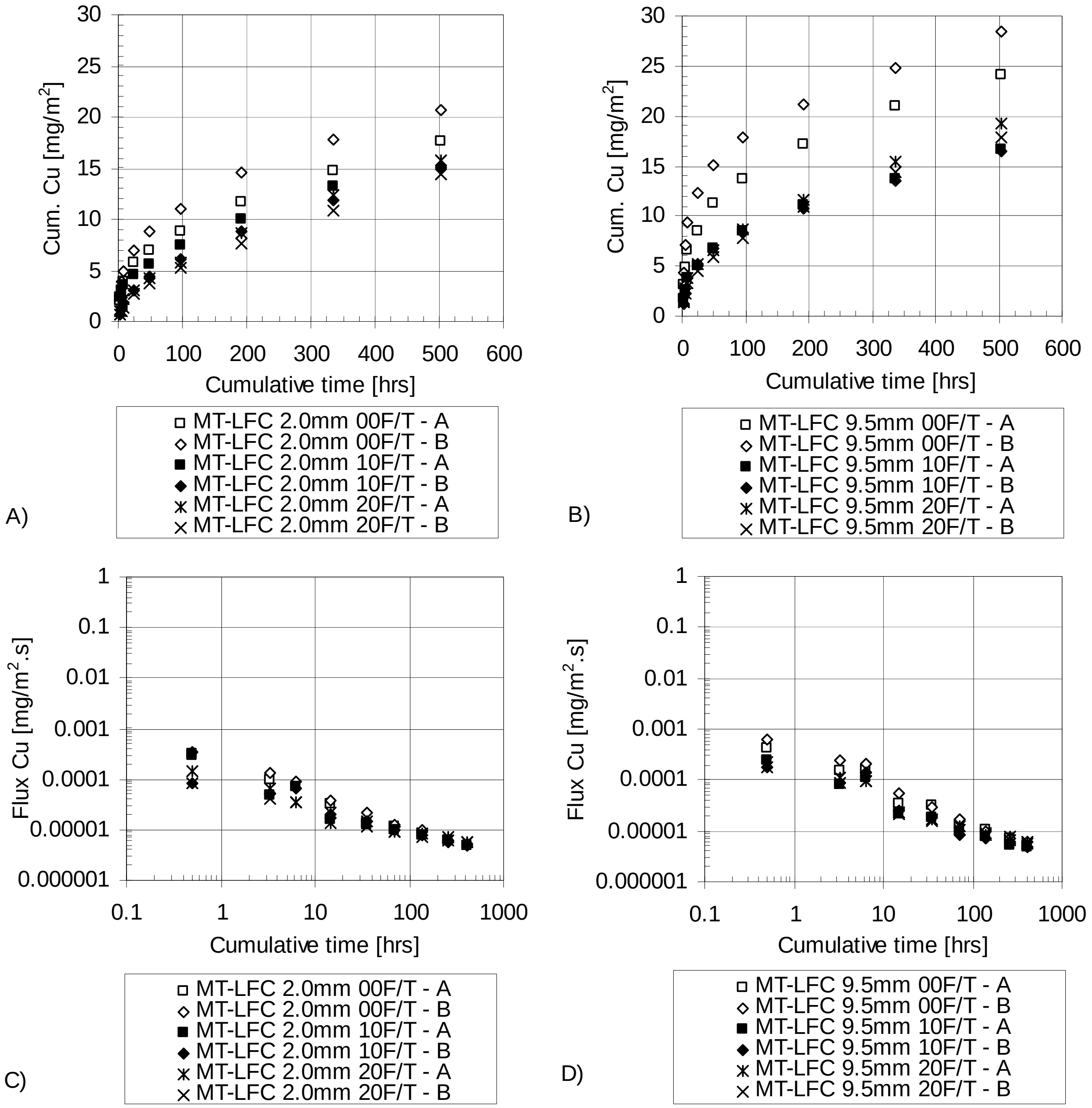


Figure 34. Copper release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

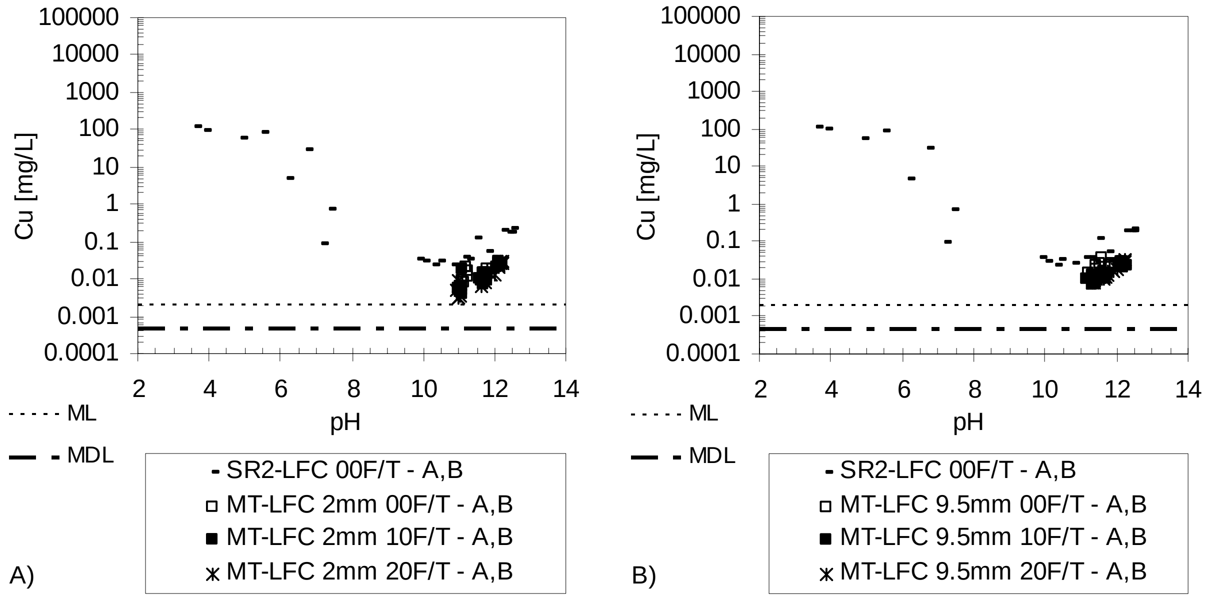


Figure 35. Copper concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.3.4. Lead release

The effect of F/T exposure on the release of lead from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 36A and Figure 36B, respectively. Lead concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 37.

The following general observations for lead were made:

- No significant effect of F/T exposure on the release of lead was observed for the less than 2 mm graded LFC material.
- For the less than 9.5 mm graded LFC material, exposure to F/T cycles resulted in a decrease in the release of lead. The reduction in the cumulative release of lead was as much as 35% after 500 hours of leaching.
- In all cases, lead concentrations in leachates from mass transfer testing were close to those from batch testing at similar pH, indicating that most likely lead had been limited by saturation of the leachates for most leaching intervals.

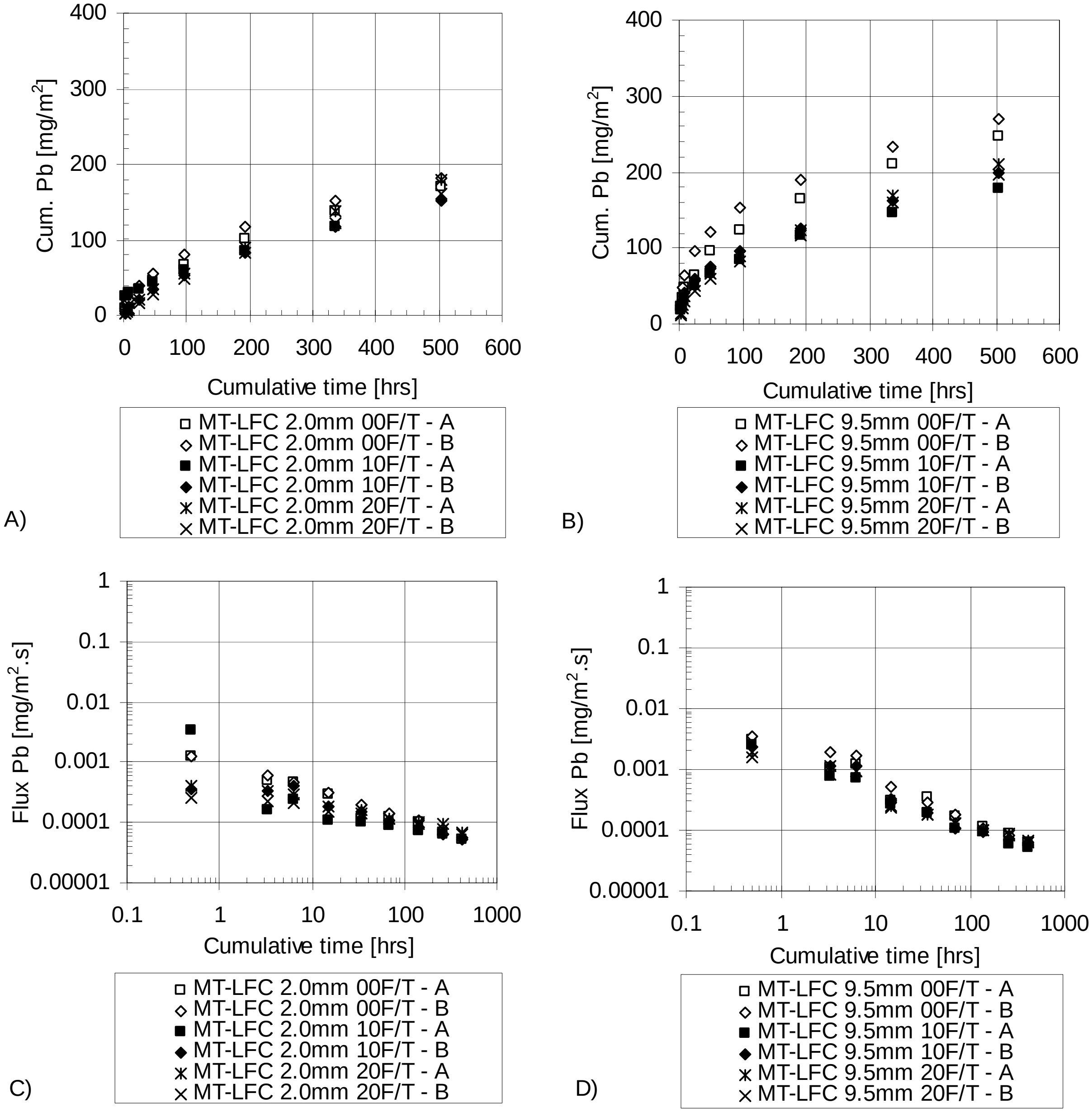


Figure 36. Lead release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

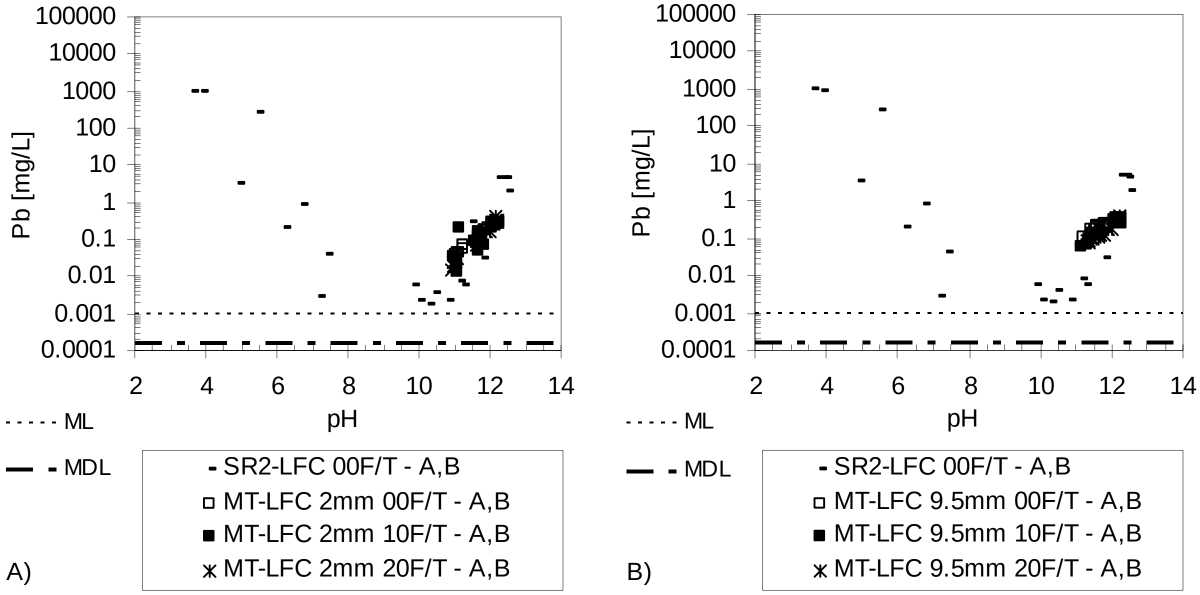


Figure 37. Lead concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.3.5. Zinc release

The effect of F/T exposure on the release of zinc from the less than 2 mm and less than 9.5 mm graded LFC materials is presented in Figure 38A and Figure 38B, respectively. Zinc concentrations as a function of pH from mass transfer testing compared to batch testing are shown in Figure 39.

The following general observations for zinc were made:

- Poor reproducibility in the release of zinc was observed for the baseline samples for both material gradations.
- Exposure to F/T cycles resulted in a decrease in the release of zinc for both material gradations. The reduction in the cumulative release of zinc was ca. 72% and ca. 70% after 500 hours of leaching for the less than 2 mm graded LFC material and less than 9.5 mm graded LFC material.
- No significant difference in the release of zinc was observed between the 10 and 20 F/T cycle aged samples for both material gradations.
- In all cases, zinc concentrations in leachates from mass transfer testing were close to or lower than those from batch testing at similar pH. In some instances, zinc release might have been limited by saturation of the leachates.

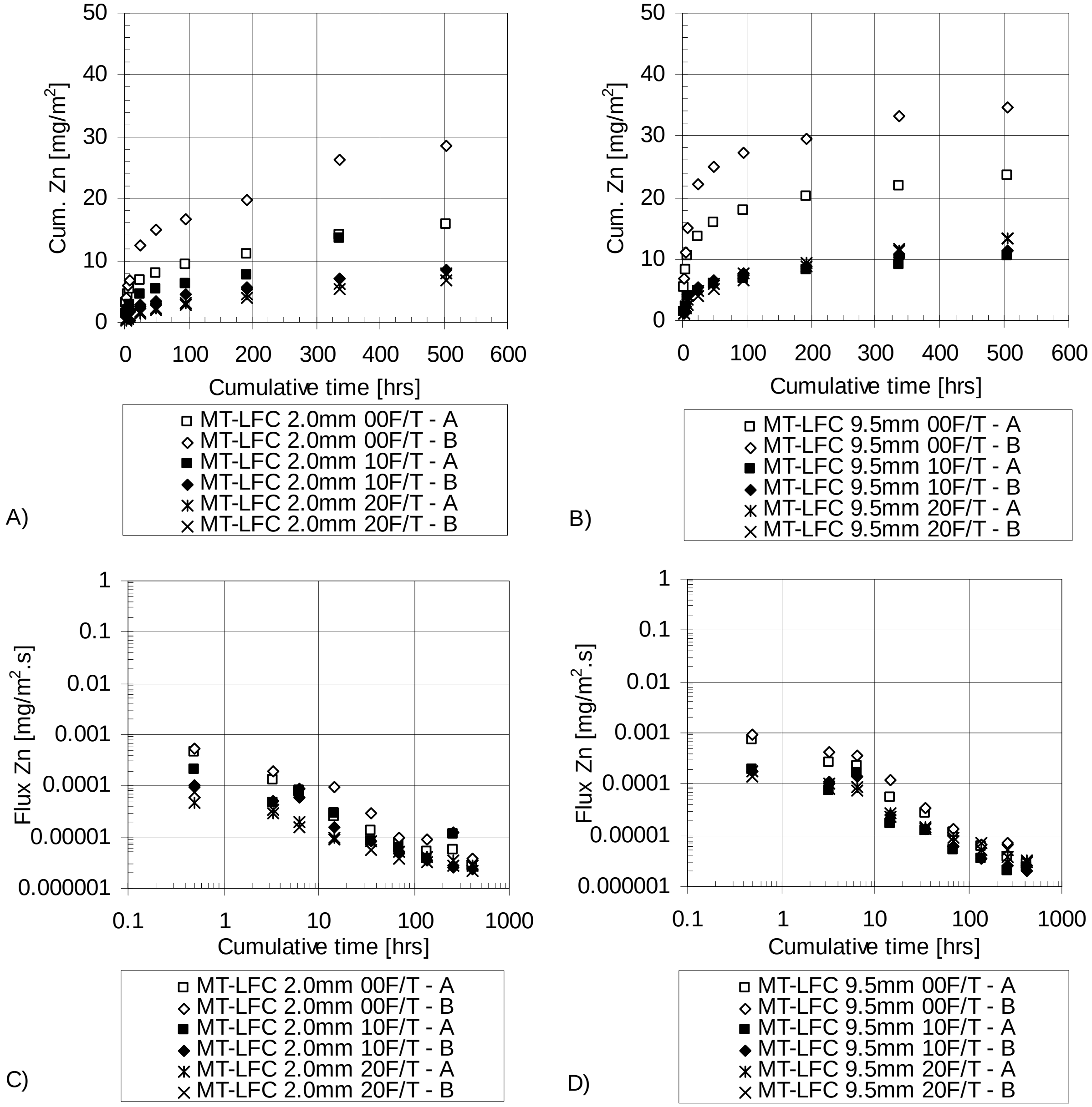


Figure 38. Zinc release after exposure to 0, 10, and 20 F/T cycles. A) and C) cumulative release and flux as a function of time for the less than 2 mm graded LFC material; B) and D) cumulative release and flux as a function of time for the less than 9.5 mm graded LFC material.

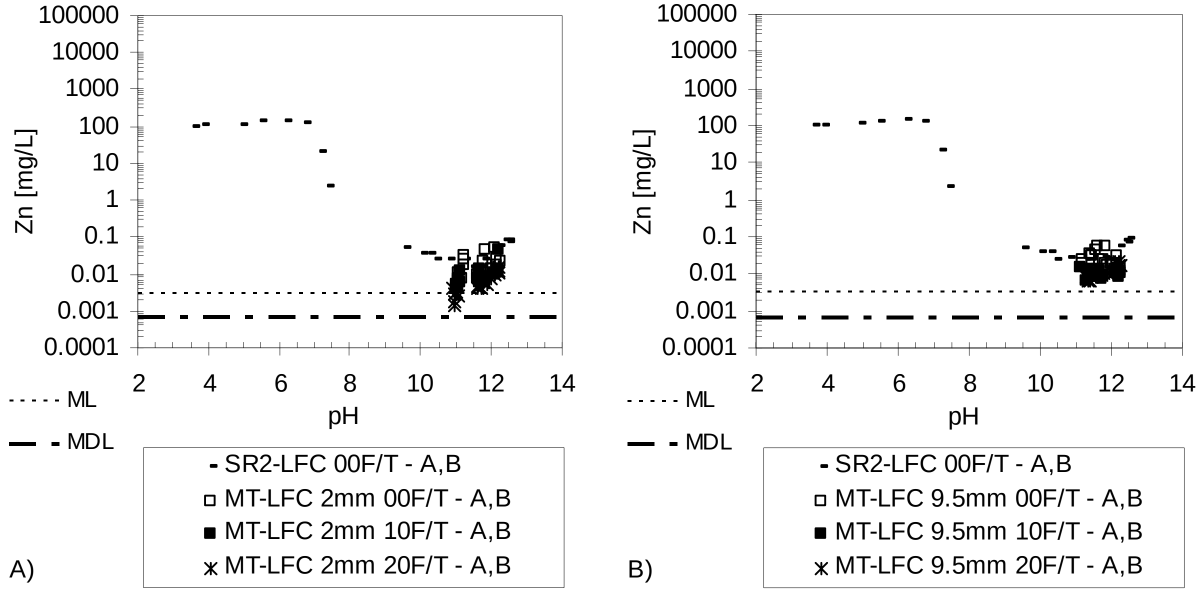


Figure 39. Zinc concentration as a function of pH from mass transfer testing compared to batch testing for A) the less than 2 mm graded LFC material and B) the less than 9.5 mm graded LFC material.

4.4.3.6. Conclusions

As with the major material constituents, F/T exposure decreased the release flux of all of the primary contaminants examined (i.e., arsenic, cadmium, copper, lead, and zinc), suggesting material consolidation during F/T exposure. A decrease in the release of arsenic, cadmium, copper, lead, and zinc of ca. 80%, 72%, 28%, and 72%, respectively was observed for the less than 2 mm graded LFC material. For the less than 9.5 mm graded LFC material, a decrease in the release of arsenic, cadmium, copper, lead, and zinc of ca. 80%, 60%, 42%, 35%, and 70% was observed. No significant effect of the number of F/T cycles on the release of copper, lead, and zinc was observed (similar release for 10 and 20 F/T cycle exposures). For cadmium, increased number of F/T cycles resulted in a further decrease in the release flux and cumulative release.

4.4.4. ANOVA analysis

ANOVA analysis was performed on the leachate pH and conductivity and cumulative release of major material constituents and primary contaminants obtained after 504 hours (21 days) of continuous leaching with periodic renewals. Twenty-one days of leaching were chosen for ANOVA analysis because it represented the greatest cumulative leaching time common to all samples.

A p-value of 0.05 for main and interaction effects was used as a cut-off. This indicates that if the calculated p-value was less than 0.05, the null hypothesis (no difference) was false and a difference was very likely to exist.

ANOVA analysis on leachate pH and conductivity

Material gradation and F/T cycles were not found to be statistically significant for the leachate pH (Table 7). For the leachate conductivity, F/T cycles provided a significant difference at a confidence level of 95%. Interactions between material gradation and F/T cycles were not statistically significant for the leachate pH and conductivity.

The main effects plots for the leachate conductivity showed an increase in conductivity with increasing number of F/T cycles (Figure 40).

Table 7. ANOVA analysis of main and interaction effects on measured leachate pH and conductivity after 504 hours of leaching.

Source	p-value		Conclusion
	pH	Conductivity	p-value of 0.05
Material gradation	0.396	0.670	Not significant
F/T cycles	0.091	**0.006**	Significant: conductivity
Material gradation*F/T cycles	0.643	0.824	Not significant

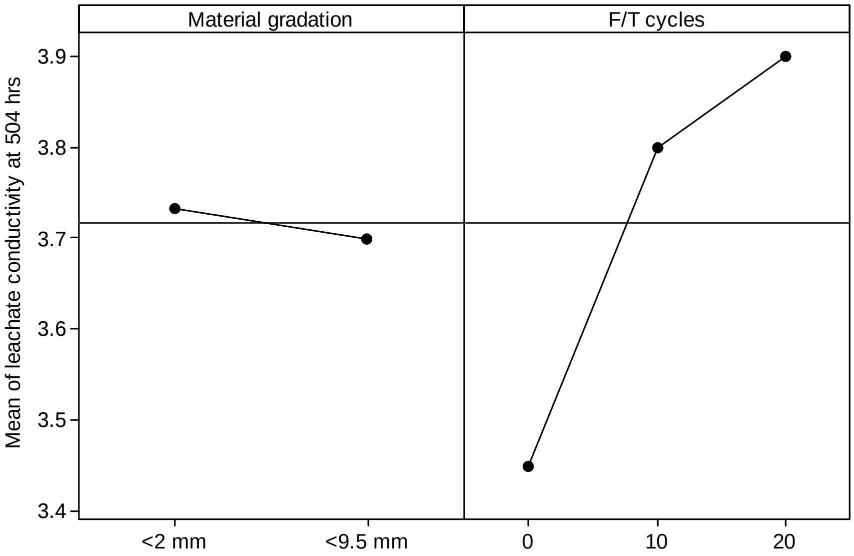


Figure 40. Main effects plots (data means) for leachate conductivity after 504 hours (21 days) of leaching.

ANOVA analysis on cumulative release of major material constituents

Table 8 shows the calculated p-values of main and interaction effects on the cumulative release of sodium, potassium, calcium, chloride, and sulfate obtained after 504 hours of continuous leaching with periodic renewals. The analysis showed that F/T cycles provided a significant difference in the cumulative release of all major material constituents examined at a confidence level of 95%. The material gradation was found to be statistically significant for all constituents (sodium, potassium, calcium, and chloride) but sulfate. The interactions between material gradation and F/T cycles were significant only for the cumulative release of calcium and sulfate.

The main effects plots for sodium, potassium, and chloride (Figure 41, Figure 42, and Figure 44) showed (i) an increase in the release when the material gradation changed from less than 2 mm to less than 9.5 mm and (ii) a decrease in the release with increasing number of F/T cycles. Two exceptions to the general observations are found in the main effects plots for calcium and sulfate (Figure 43 and Figure 45), which showed (i) a decrease in the release when the material gradation changed from less than 2 mm to less than 9.5 mm and (ii) a decrease in the release after exposure to 10 F/T cycles compared to the no F/T exposure case and an increase in the release after exposure to 20 F/T cycles compared to exposure to 10 F/T cycles, resulting in a lower release than that of the no F/T cycles case.

For calcium and sulfate, change in the cumulative release with the number of F/T cycles after 21 days of leaching depended on the material gradation (Figure 46 and Figure 47).

Table 8. ANOVA analysis of main and interaction effects on measured cumulative mass release of sodium, potassium, calcium, chloride, and sulfate after 504 hours (21 days) of leaching.

Source	p-value					Conclusion
	Na	K	Ca	Cl	SO_4^{2-}	p-value of 0.05
Material gradation	**0.001**	**0.003**	**0.000**	**0.004**	0.131	Significant: Na, K, Ca, Cl
F/T cycles	**0.006**	**0.017**	**0.000**	**0.000**	**0.000**	Significant: Na, K, Ca, Cl, SO_4^{2-}
Material gradation*F/T cycles	0.527	0.467	**0.000**	0.069	**0.000**	Significant: Ca, SO_4^{2-}

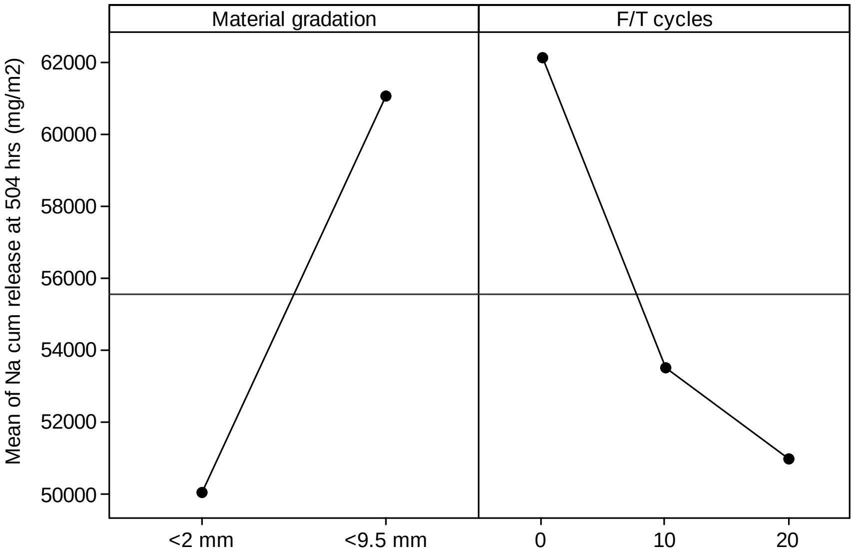


Figure 41. Main effects plots (data means) for sodium cumulative release after 504 hours (21 days) of leaching.

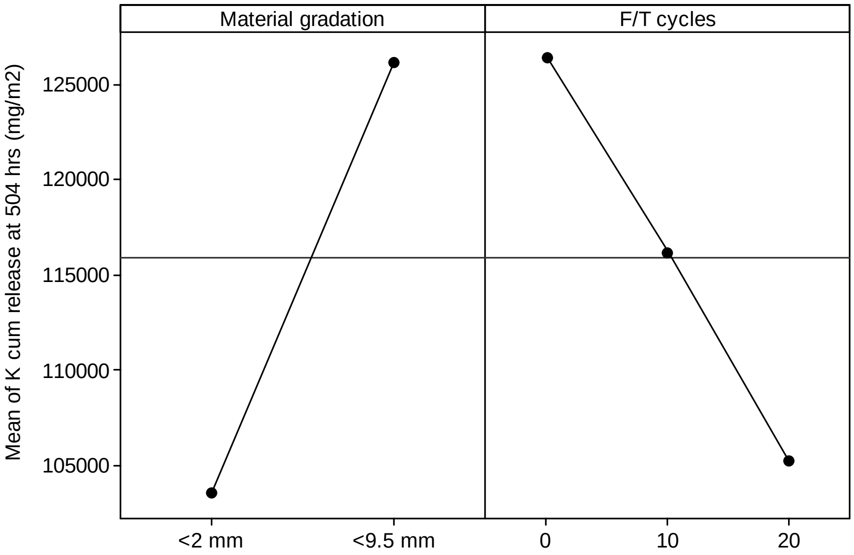


Figure 42. Main effects plots (data means) for potassium cumulative release after 504 hours (21 days) of leaching.

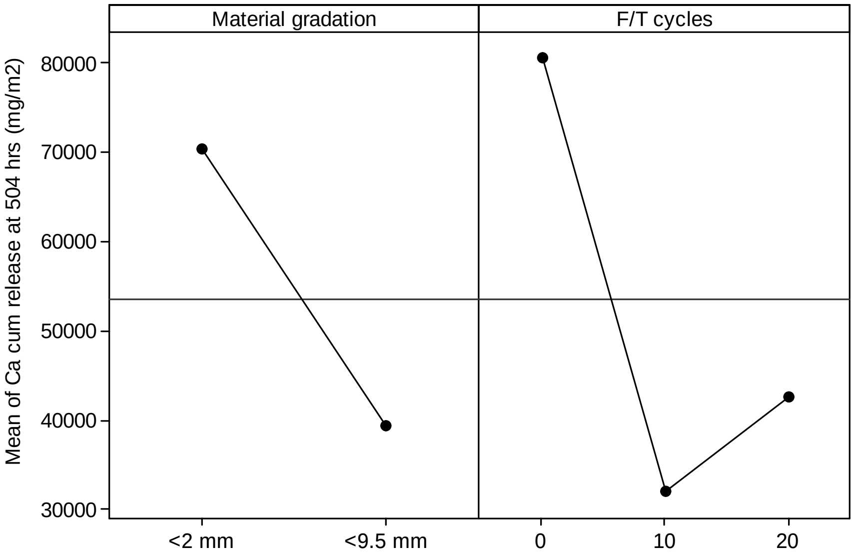


Figure 43. Main effects plots (data means) for calcium cumulative release after 504 hours (21 days) of leaching.

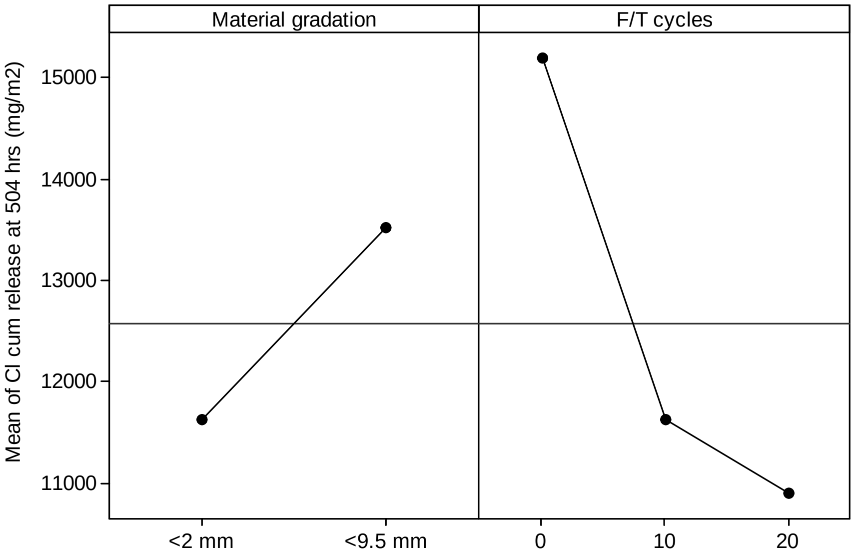


Figure 44. Main effects plots (data means) for chloride cumulative release after 504 hours (21 days) of leaching.

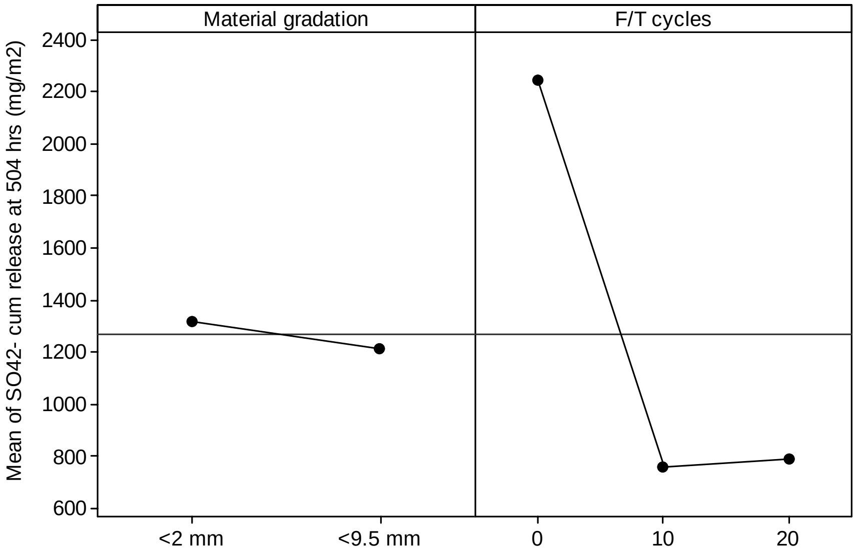


Figure 45. Main effects plots (data means) for sulfate cumulative release after 504 hours (21 days) of leaching.

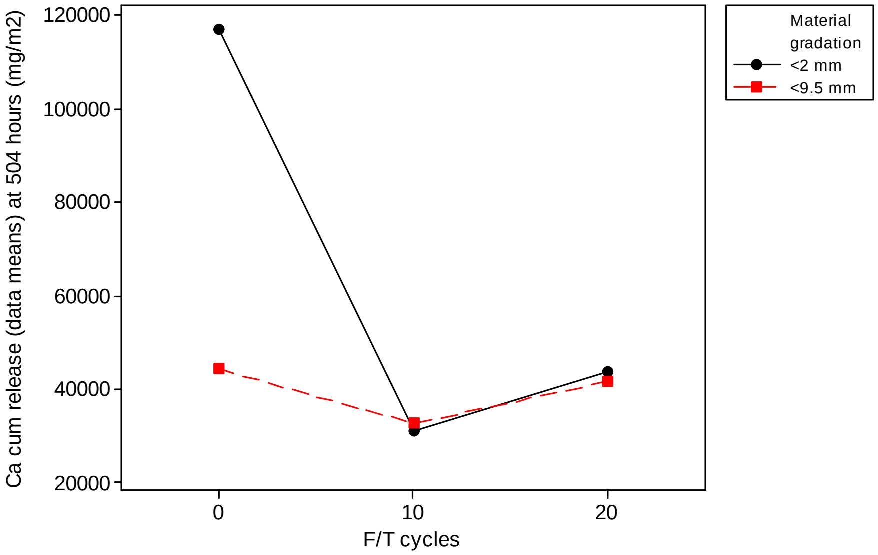


Figure 46. Interaction plots (data means) for calcium cumulative release after 504 hours (21 days) of leaching.

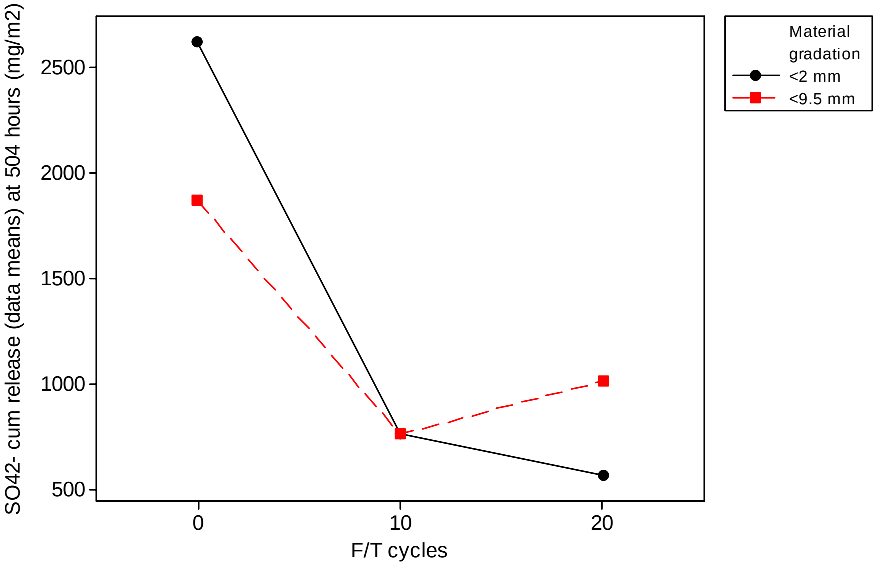


Figure 47. Interaction plots (data means) for sulfate cumulative release after 504 hours (21 days) of leaching.

ANOVA analysis on cumulative release of primary contaminants

Table 9 shows the calculated p-values of main and interaction effects on the cumulative release of arsenic, cadmium, copper, lead, and zinc obtained after 504 hours of continuous leaching with periodic renewals. The analysis showed that F/T cycles provided a significant difference in the cumulative release of all primary contaminants examined at a confidence level of 95%. The material gradation was found to be statistically significant only for copper and lead. Interactions between material gradation and F/T cycles were not found to be statistically significant for all primary contaminants examined.

The main effects plots showed similar behavior for all primary contaminants examined (Figure 48 to Figure 52): (i) an increase in the release when the material gradation changed from less than 2 mm to less than 9.5 mm and (ii) a decrease in the release with exposure to F/T cycles compared to the no F/T exposure case. For arsenic, copper, lead, and zinc the cumulative release at 21 days after exposure to 20 F/T cycles was similar to or greater than that obtained after exposure to 10 F/T cycles (but lower than for the no F/T exposure case).

Table 9. ANOVA analysis of main and interaction effects on measured cumulative mass release of arsenic, cadmium, copper, lead, and zinc after 504 hours (21 days) of leaching.

Source	p-value As	Cd	Cu	Pb	Zn	Conclusion p-value of 0.05
Material gradation	0.188	0.455	**0.015**	**0.001**	0.178	Significant: Cu, Pb
F/T cycles	**0.003**	**0.006**	**0.007**	**0.010**	**0.016**	Significant: As, Cd, Cu. Pb, Zn
Material gradation*F/T cycles	0.649	0.392	0.217	0.079	0.872	Not significant

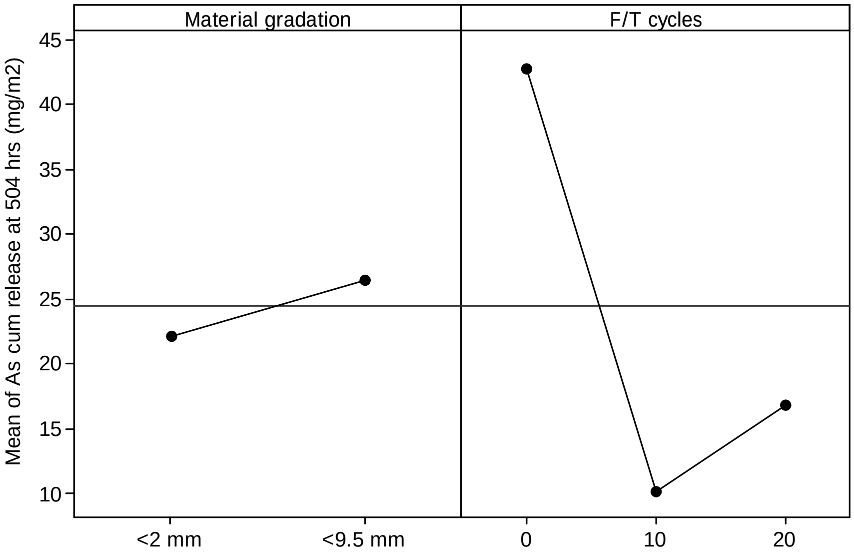


Figure 48. Main effects plots (data means) for arsenic cumulative release after 504 hours (21 days) of leaching.

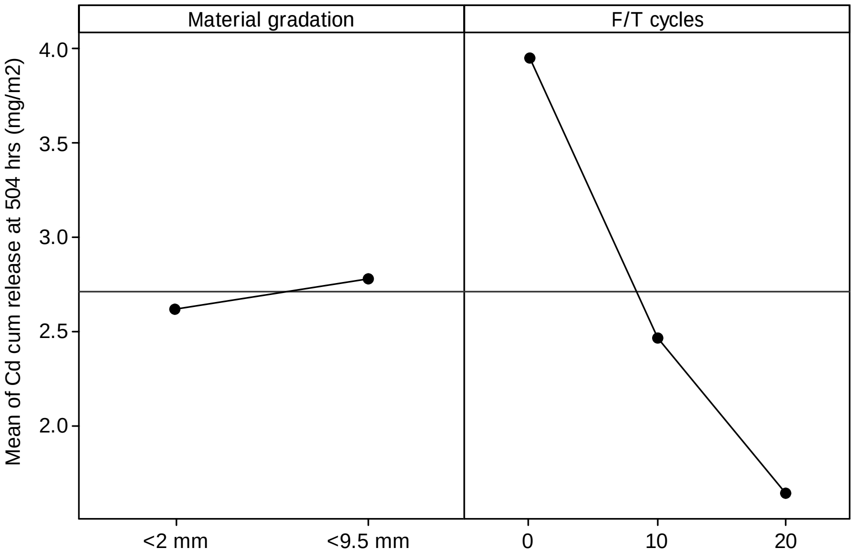


Figure 49. Main effects plots (data means) for cadmium cumulative release after 504 hours (21 days) of leaching.

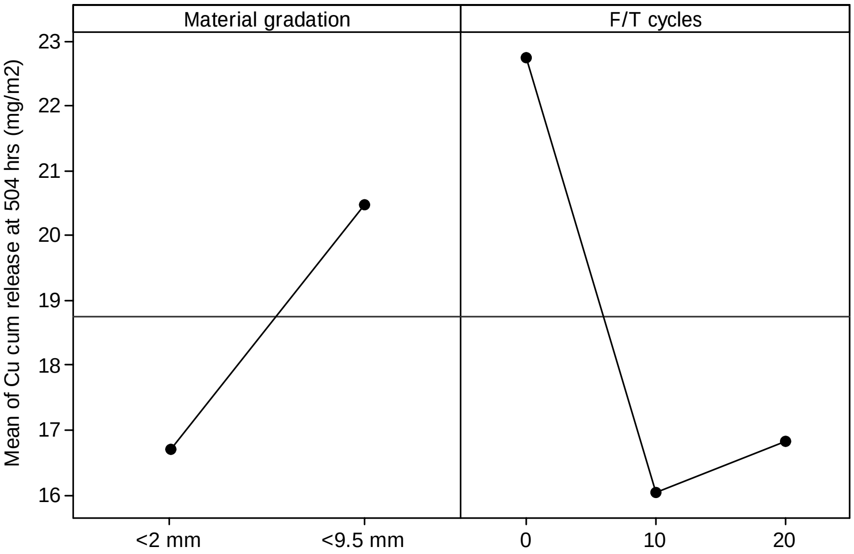


Figure 50. Main effects plots (data means) for copper cumulative release after 504 hours (21 days) of leaching.

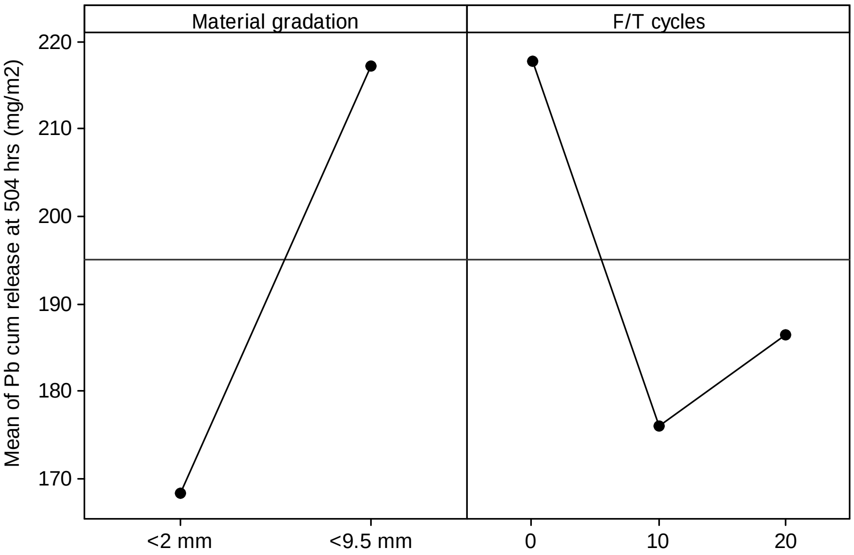


Figure 51. Main effects plots (data means) for lead cumulative release after 504 hours (21 days) of leaching.

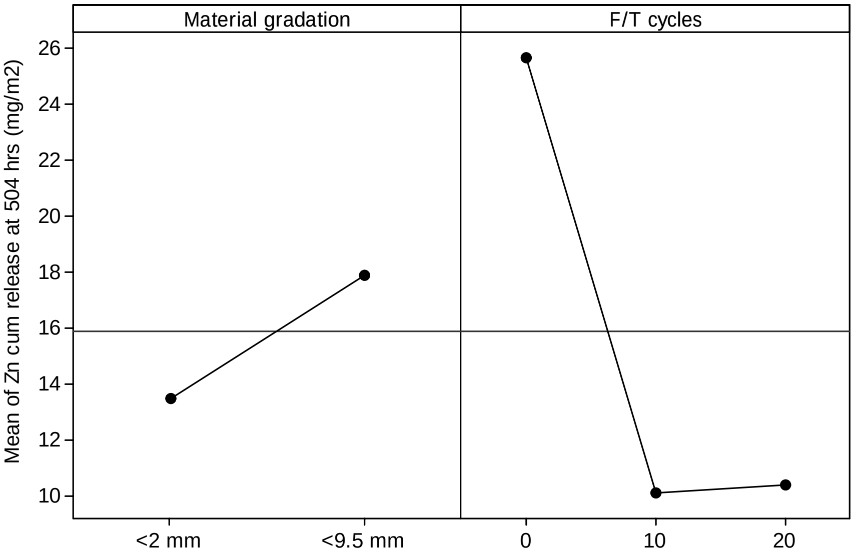


Figure 52. Main effects plots (data means) for zinc cumulative release after 504 hours (21 days) of leaching.

4.5. EFFECT OF F/T EXPOSURE ON FLOW PATTERN DURING PERCOLATION FLOW CONTROLLED SCENARIO

F/T exposure may affect flow patterns during percolation flow controlled scenario either by increasing cracks and creating preferential flow or by fine particle aggregation/consolidation leading to an overall increase or reduction of permeability. The flow pattern in the columns was examined based on the water flow exiting the columns and the transport behavior of bromide tracer.

4.5.1. Water flow

The output flow rate of each column as monitored based on the volume of leachate exiting the column is presented in Figure 53. Significant variation of the output flow rate as a function of time was observed with, in some instances, flow reduction by as much as an order of magnitude for the columns that had been exposed to 10 F/T cycles. Overall, the columns exposed to 10 F/T cycles showed an early breakthrough of the flow that was independent of the initial moisture content of the packed material (i.e., 7%, 15%, and 29%). This might have been the result of preferential flow and/or presence of cracks as a result of F/T exposure. However, further exposure to F/T cycles (i.e., 20 and 40 F/T) showed no significant difference in the time of initial breakthrough of the flow compared to that obtained for no F/T exposure, independent of the initial moisture content.

The average ouput flow rate indicated an overall reduction of the flow for the columns packed at 7% and 15% moisture content after exposure to F/T cycles with increased reduction as the number of F/T cycles increased (Figure 54). For the columns packed at the optimum moisture content (i.e., 29% moisture content), an increase in the average output flow rate was observed after exposure to 10 and 20 F/T cycles, while a reduction was observed after exposure to 40 F/T cycles (Figure 54).

The observed decrease in flow rate with F/T exposure was in agreement with the visual observation of particle aggregation and overall consolidation of the packed granular material (see section 4.3.1.2) and might have been the result of loose/fine particles blocking the flow path and/or self-cementing of the LFC material during thawing and subsequent permeation.

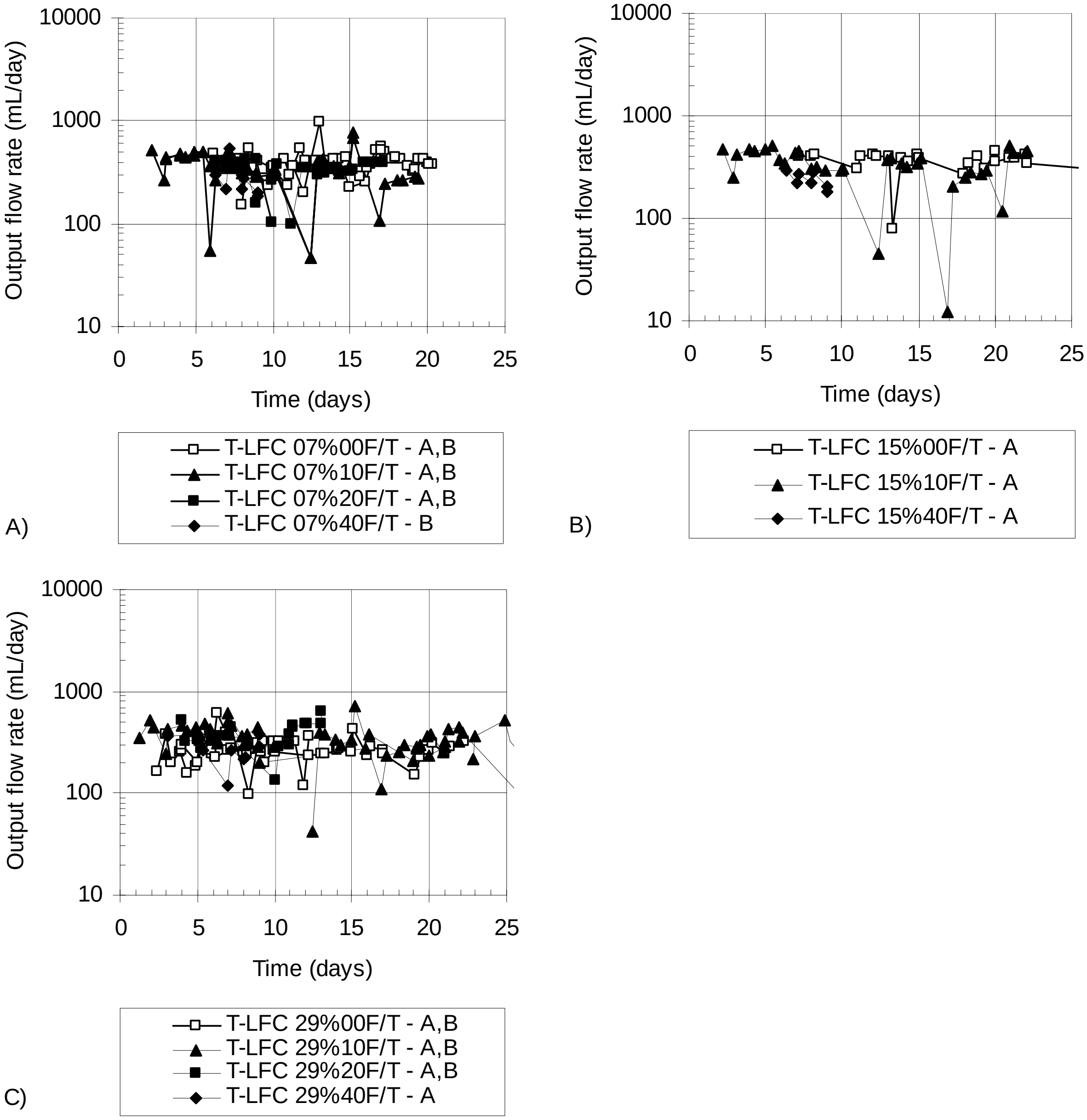


Figure 53. Output flow rate as a function of time after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content.

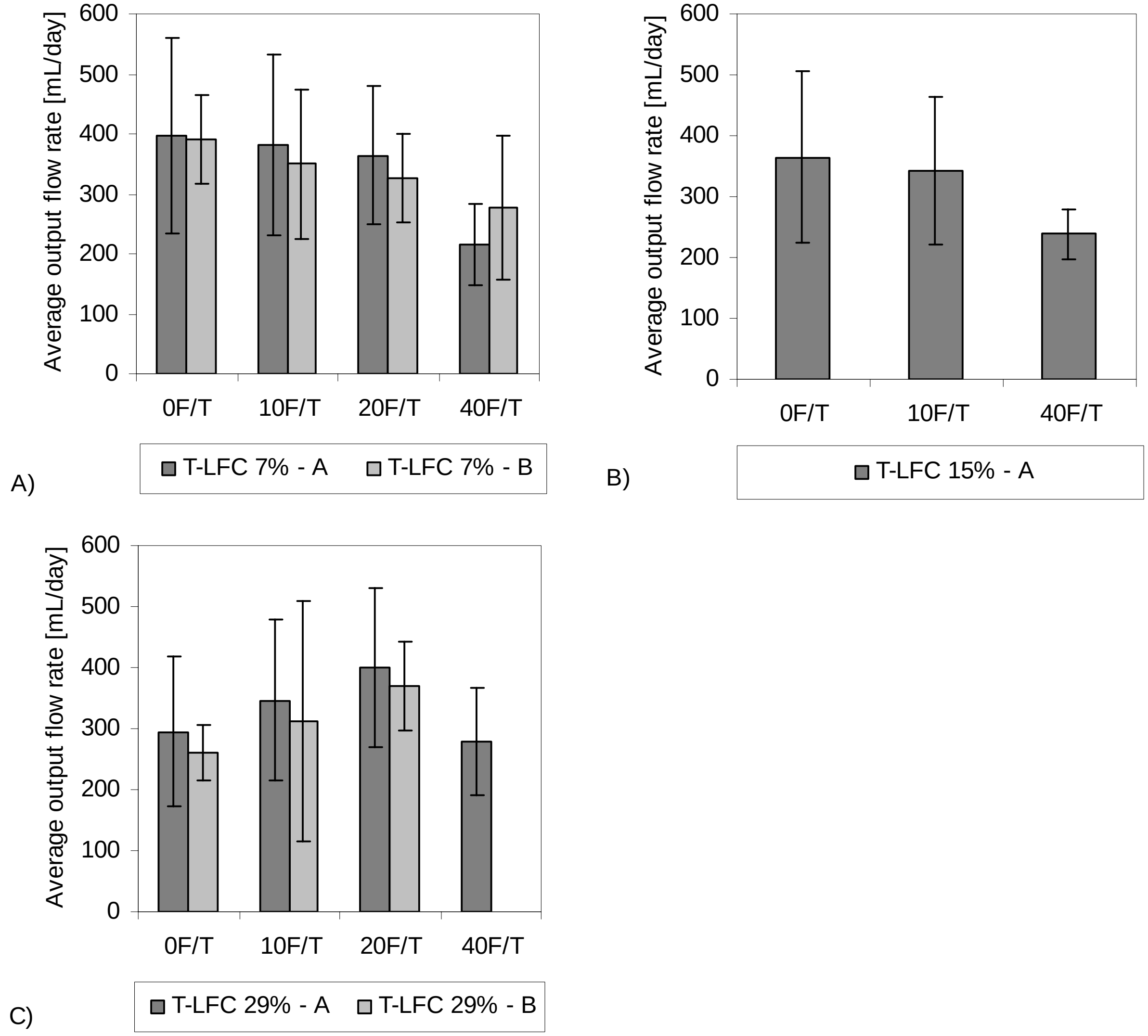


Figure 54. Average output flow rate after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content. Standard deviations are shown.

4.5.2. Transport of bromide

Bromide recovery for the columns that were not exposed to F/T cycles was overall greater after 20 days for the columns packed at the lowest moisture content (Figure 55). Bromide recovery after 20 days was ca. 60% for the columns packed at 7% moisture content, ca. 45% for that packed at 15% moisture content, and ca. 40% for that packed at the optimum moisture content (i.e., 29%). This is consistent with the respective initial porosity of the packed material (i.e., lower porosity obtained for material packed at the optimum moisture content).

Exposure to 10 F/T cycles resulted in a lower bromide recovery for the columns packed at 7% and 15% moisture content (i.e., less than 20% and 30%, respectively after 20 days), although an early breakthrough of the flow was observed (Figure 55). However, for the columns packed at the optimum moisture content, exposure to 10 F/T cycles resulted in a significantly greater bromide recovery (i.e., about 60% after 20 days) compared to that obtained for no F/T exposure.

In all cases, further exposure to F/T cycles (i.e., exposure to 20 and 40 F/T cycles) did not significantly affect bromide recovery and resulted in the same bromide recovery at 20 days as that obtained for no F/T exposure (i.e., ca. 60%, ca. 45%, and ca. 35% for the columns packed at 7%, 15%, and 29%, respectively).

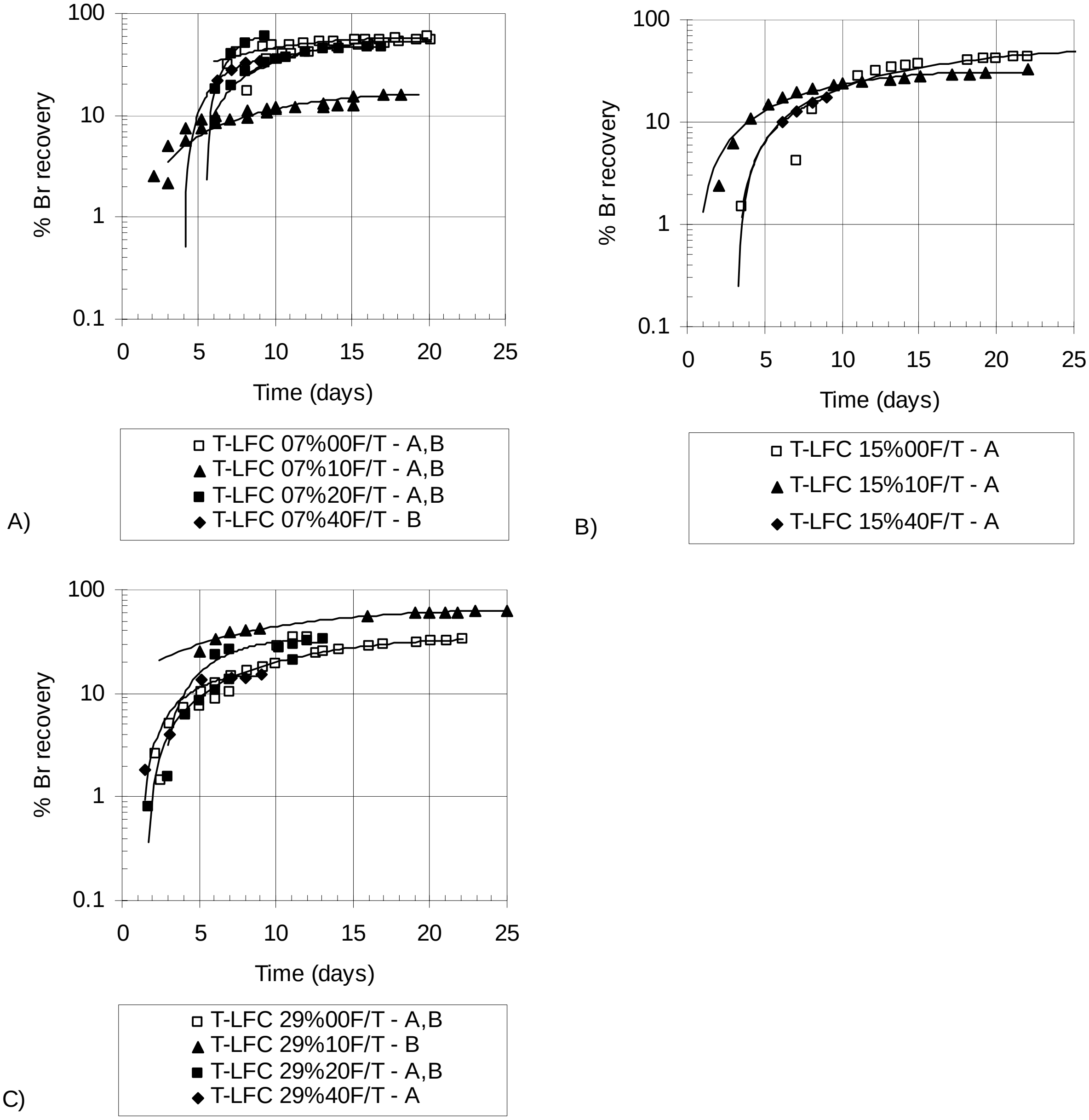


Figure 55. Percentage of bromide recovery after exposure to 0, 10, 20, and 40F/T cycles of the less than 9.5 mm graded LFC material packed at A) 7%, B) 15%, and C) 29% moisture content.

4.6. EFFECT OF F/T EXPOSURE ON CONSTITUENT LEACHING DURING PERCOLATION FLOW CONTROLLED (FLOW-THROUGH) SCENARIO

The following presents results of the effect of F/T exposure (0, 10, 20, and 40 F/T cycles; a cycle being 8 hours of freezing and 16 hours of thawing) for three moisture contents of the packed LFC material (i.e., 7%, 15%, and 29%) on (i) leachate pH and conductivity, (ii) release of major material constituents (i.e., sodium, potassium, calcium, chloride, and sulfate), and (iii) release of primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) during a percolation (flow-though) scenario.

4.6.1. Effect of F/T exposure on leachate pH and conductivity

The effect of F/T exposure on leachate pH and leachate conductivity of the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 56 and Figure 57, respectively.

The following general observations for the leachate pH were made:

- Leachate pH was not significantly affected by F/T exposure and initial moisture content at the time of the F/T cycles.
- Overall, a good reproducibility in the leachate pH was observed for all cases.
- The behavior of the leachate pH was similar for all cases with a slow decrease as the LS ratio increased (by as much as 2 pH units at an LS ratio of 10 L/kg). The leachate pH varied from 11.5 to 13.5.
- Leachate pH from column experiments was lower than that from batch experiments (i.e., SR003). The difference in pH between column and batch testing was more pronounced as the LS ratio increased (as much as 1 pH unit at the LS of 5 L/kg), except for the baseline columns packed at 29% moisture content for which a good agreement between batch and column testing was observed.

The following general observations for the leachate conductivity were made:

- For all cases, leachate conductivity decreased rapidly as LS ratio increased to 2 L/kg due to depletion of the soluble species (i.e., salts) and reached a plateau thereafter around a value of 6 mS/cm.
- Variability in leachate conductivity could be observed between the different levels of F/T exposure and within replicates at low LS ratios (i.e., LS ratios less than 0.2 L/kg). This was more pronounced for the columns packed at 7% and 15 % moisture content. However, no clear tendency resulting from F/T exposure could be observed.

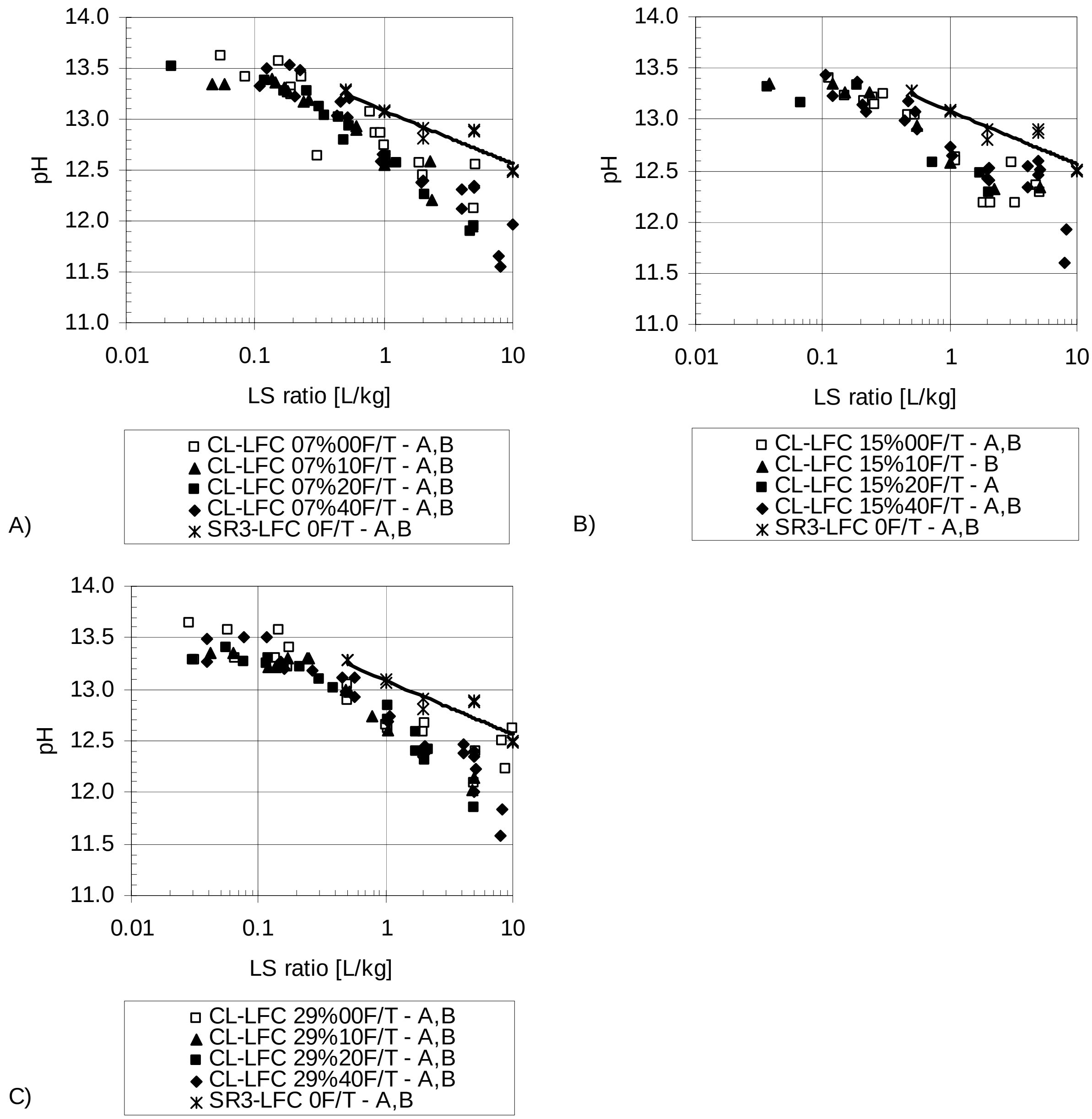


Figure 56. Leachate pH after exposure to 0, 10, 20, and 40 F/T cycles for the LFC material packed at A) 7% moisture content, B) 15% moisture content, and C) 29% moisture content (optimum moisture content).

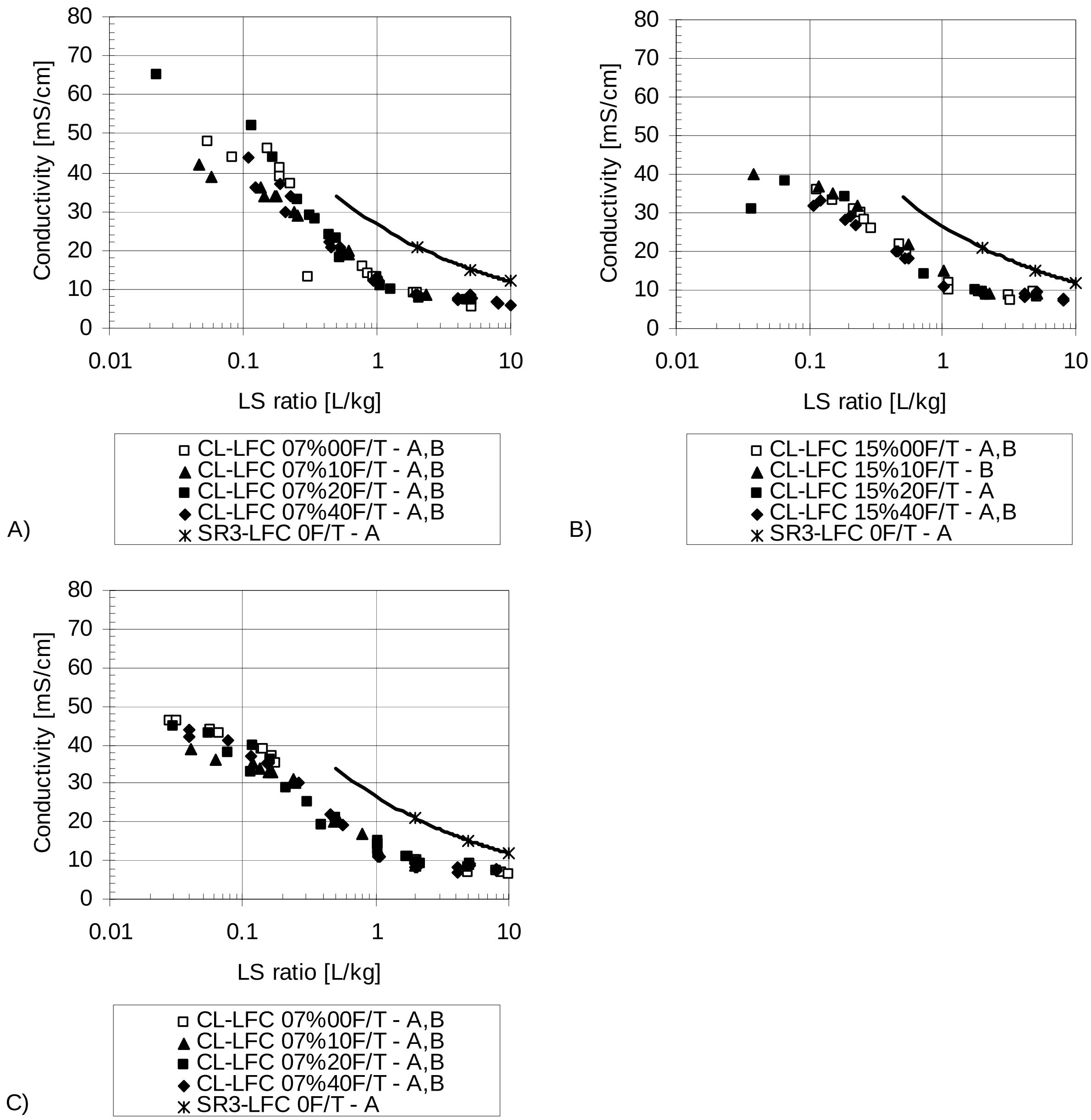


Figure 57. Leachate conductivity after exposure to 0, 10, 20, and 40 F/T cycles for the LFC material packed at A) 7% moisture content, B) 15% moisture content, and C) 29% moisture content (optimum moisture content).

4.6.2. Effect of F/T exposure on the release of major material constituents

For each constituent of concern, a common format is used for presenting the results. A set of four figures is used for each moisture content examined showing the different levels of F/T exposure. Figure A shows the concentration as a function of pH from column testing compared to batch testing (i.e., SR002.1). Figure B shows the concentration as a function of LS ratio from column testing compared to batch testing (i.e., SR003.1). Figure C shows the cumulative release as a function of LS ratio. Figure D shows the residuals of the cumulative release as a function of LS ratio relative to no F/T exposure (0 F/T cycles).

4.6.2.1. Sodium release

The effect of F/T exposure on the release of sodium for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 58, Figure 59, and Figure 60, respectively.

The following general observations for sodium were made:

- The release of sodium from the LFC material packed at 15% moisture content was the most significantly affected by F/T exposure, as observed from the residual plots.
- In all cases, the release of sodium from the columns exposed to 40 F/T cycles was similar to or lower than that from the baseline columns (0 F/T cycles) while the release of sodium from the columns exposed to 10 F/T cycles was greater, as indicated from the residual plots.
- Batch testing as a function of LS ratio was a conservative estimate of sodium release from column testing. Sodium concentrations in leachate from column testing were lower than that from batch testing at similar LS ratios (Figure 58B, Figure 59B, and Figure 60B). The difference was more pronounced as the LS ratio increased (as much as ca. 50 times lower at the LS of 10 L/kg). This result was consistent with a depletion of sodium occurring during column testing as the LS ratio increased, which was not the case during batch testing.
- On a cumulative mass basis, batch testing as a function of LS ratio was in good agreement with column testing (Figure 58C, Figure 59C, and Figure 60C).
- The cumulative release of sodium reached a plateau at an LS of ca. 2 L/kg. This plateau corresponded to the total amount of sodium added during the LFC material preparation (i.e., 0.29 wt% sodium chloride was added as source of tracer ions). This plateau was approximately 1300 mg/kg, 1100 mg/kg, and 1200 mg/kg, for the LFC material packed at 7%, 15%, and 29%, respectively.

LFC material packed at 7% moisture content

- The release of sodium from the 40 F/T cycle aged columns was overall slightly lower than that from the baseline columns and the 10 and 20 F/T cycle aged columns.
- At the LS ratio of 0.2 L/kg, the cumulative release of sodium was ca. 320 mg/kg for the 40 F/T cycles aged columns, while ca. 395 mg/kg, ca. 380 mg/kg, and ca. 465 mg/kg for the 0, 10 and 20 F/T cycle aged columns, respectively.

LFC material packed at 15% moisture content

- Exposure to 10 F/T cycles resulted in a greater release of sodium, while exposure to 20 and 40 F/T cycles resulted in a lower release of sodium compared to that obtained for no F/T exposure.
- At the LS ratio of 2 L/kg, the cumulative release of sodium was *ca*. 1375 mg/kg, ca. 1635 mg/kg, ca. 1110 mg/kg, and ca. 1085 mg/kg for the 0, 10, 20, and 40 F/T cycle aged columns.

LFC material packed at 29% moisture content (optimum moisture content)

- Exposure to 10 F/T cycles resulted in a slightly greater release of sodium.

- At the LS of 5 L/kg, the cumulative release of sodium was ca. *ca*. 1300 mg/kg, ca. 1910 mg/kg, ca. 1595 mg/kg, and ca. 1265 mg/kg for the 0, 10, 20, and 40 F/T cycle aged columns.

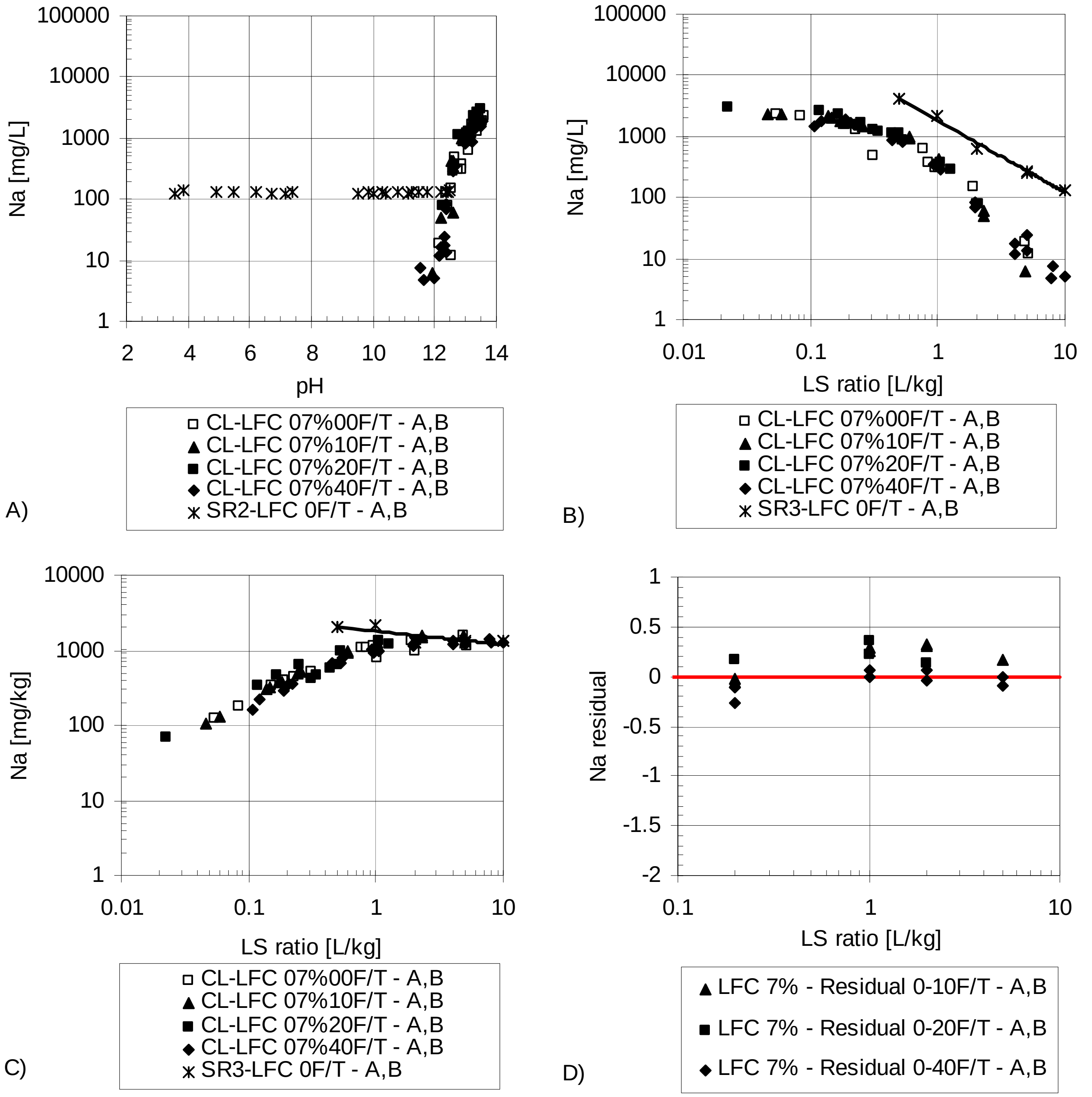


Figure 58. Sodium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

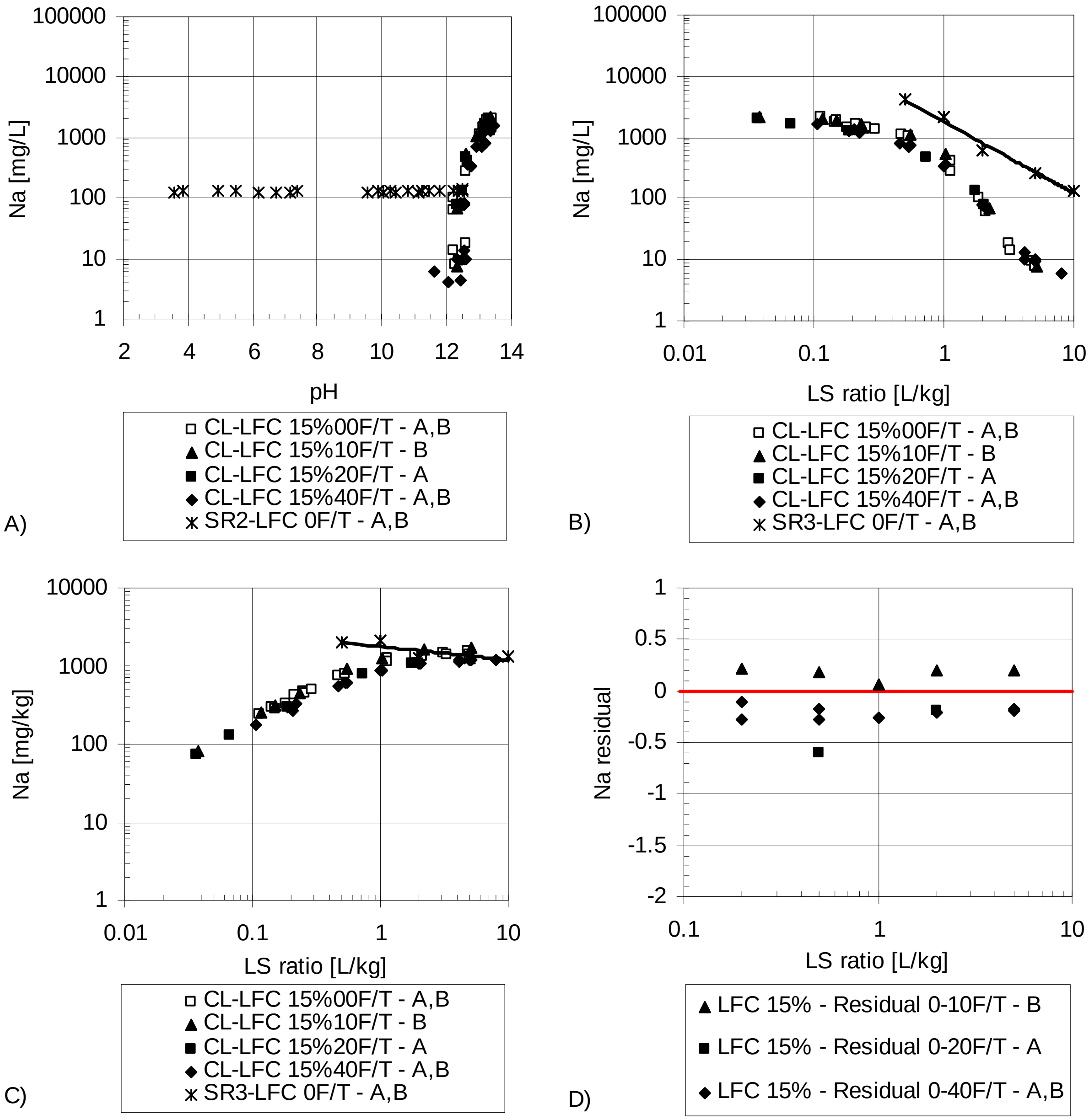


Figure 59. Sodium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

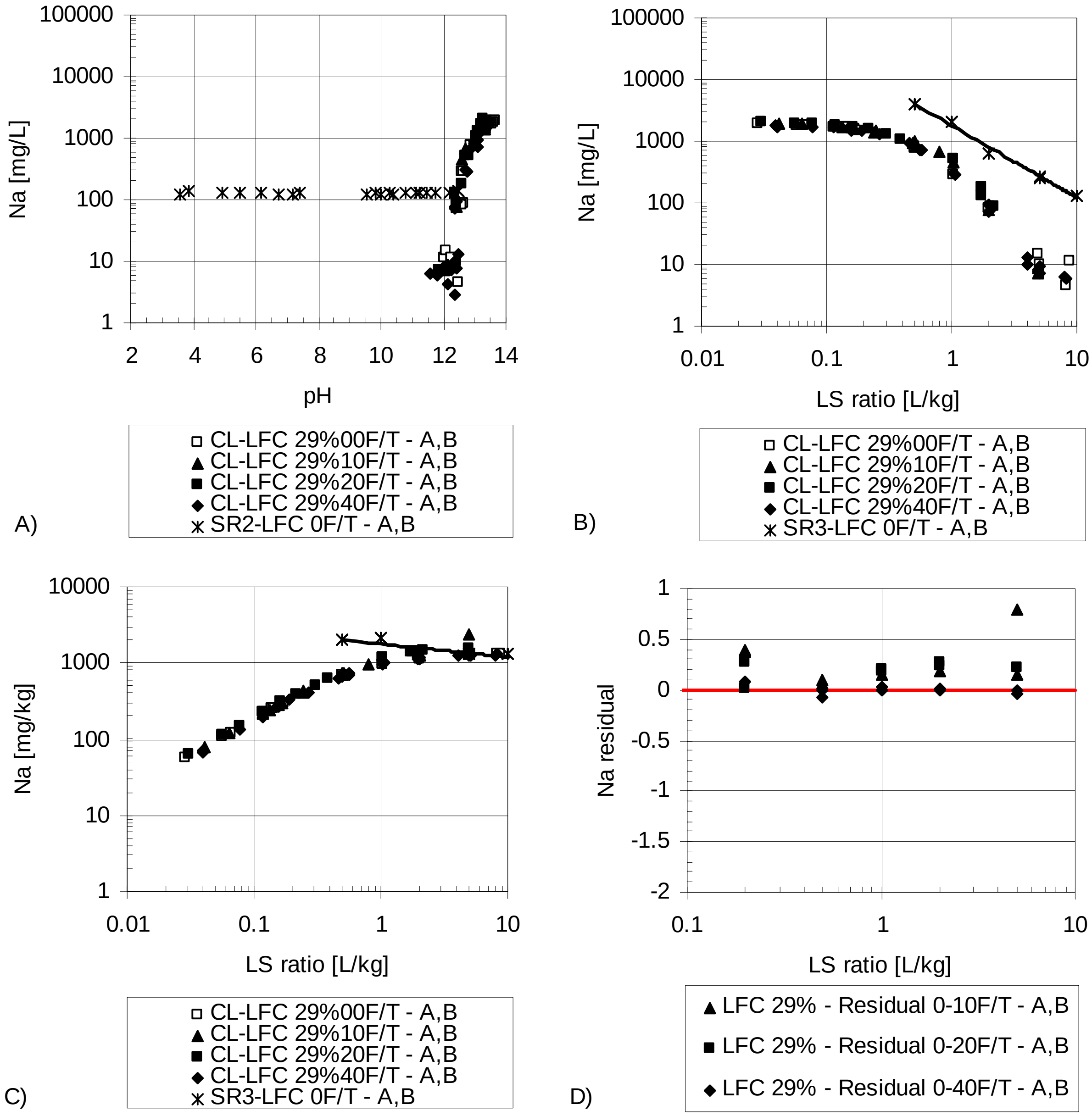


Figure 60. Sodium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.2.2. Potassium release

The effect of F/T exposure on the release of potassium for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 61, Figure 62, and Figure 63, respectively.

The following general observations for potassium were made:

- Exposure to 40 F/T cycles resulted in a lower release of potassium compared to no F/T exposure for the columns packed at 7% and 15% moisture content and no significant changes for the columns packed at 29% moisture content, as observed from the residual plots.
- A greater release of potassium was overall observed from the columns that had been exposed to 10 F/T cycles, independent of the initial moisture content at the time of F/T exposure.
- A greater variability in the cumulative release of potassium could be observed between the different levels of F/T aging and within replicates for the columns packed at 7 % and 15% moisture content than that packed at the optimum moisture content.
- As with sodium, for all cases, batch testing as a function of LS ratio was a conservative estimate of potassium release from column testing. Potassium concentrations in leachate from column testing were lower than that from batch testing at similar LS ratios (Figures Figure 61B, Figure 62B, and Figure 63B). The difference was more pronounced as the LS ratio increased (as much as ca. 4 times lower at the LS of 10 L/kg). This result was consistent with a depletion of potassium occurring during column testing as the LS ratio increased, which was not the case during batch testing.
- For all cases, on a cumulative mass basis, batch testing as a function of LS ratio was in good agreement with column testing (Figure 61C, Figure 62C, and Figure 63C).
- For all cases, the cumulative release of potassium reached a plateau for LS of ca. 2 L/kg. This plateau was around ca. 2700 mg/kg, ca. 2700 mg/kg, and ca. 3100 mg/kg, for the LFC material packed at 7%, 15%, and 29%, respectively.

LFC material packed at 7% moisture content

- Variability in the cumulative release of potassium could be observed between the different levels of F/T aging and within replicates.
- A poor replication in the cumulative release of potassium was obtained for the baseline columns (no F/T exposure).

LFC material packed at 15% moisture content

- The release of potassium from the 20 and 40 F/T cycle aged columns was lower than that from the baseline columns and the 10 F/T cycle aged columns.
- At the LS of 2 L/kg, the cumulative release of potassium was ca. 1985 mg/kg and ca. 1835 mg/kg for the 20 and 40 F/T cycle aged columns, while ca. 2660 mg/kg and ca. 3070 mg/kg for the 0 and 10 F/T cycle aged columns, respectively.

LFC material packed at 29% moisture content (optimum moisture content)

- The release of potassium from the 10 and 20 F/T cycle aged columns was greater than that from the baseline columns and the 40 F/T cycle aged columns over the entire range of LS ratios examined (ca. 1.4 times greater at the LS ratio of 2 L/kg).

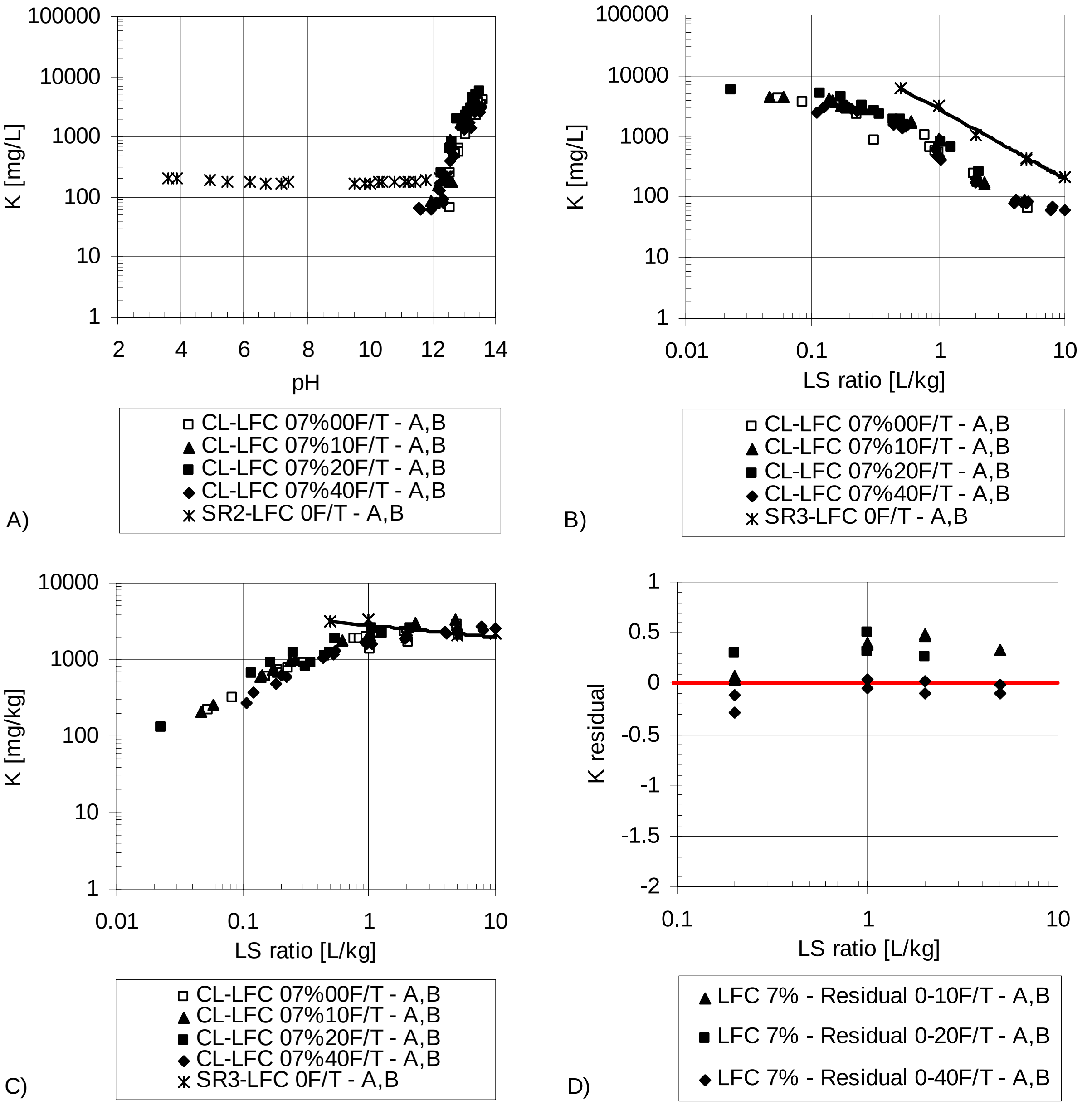


Figure 61. Potassium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

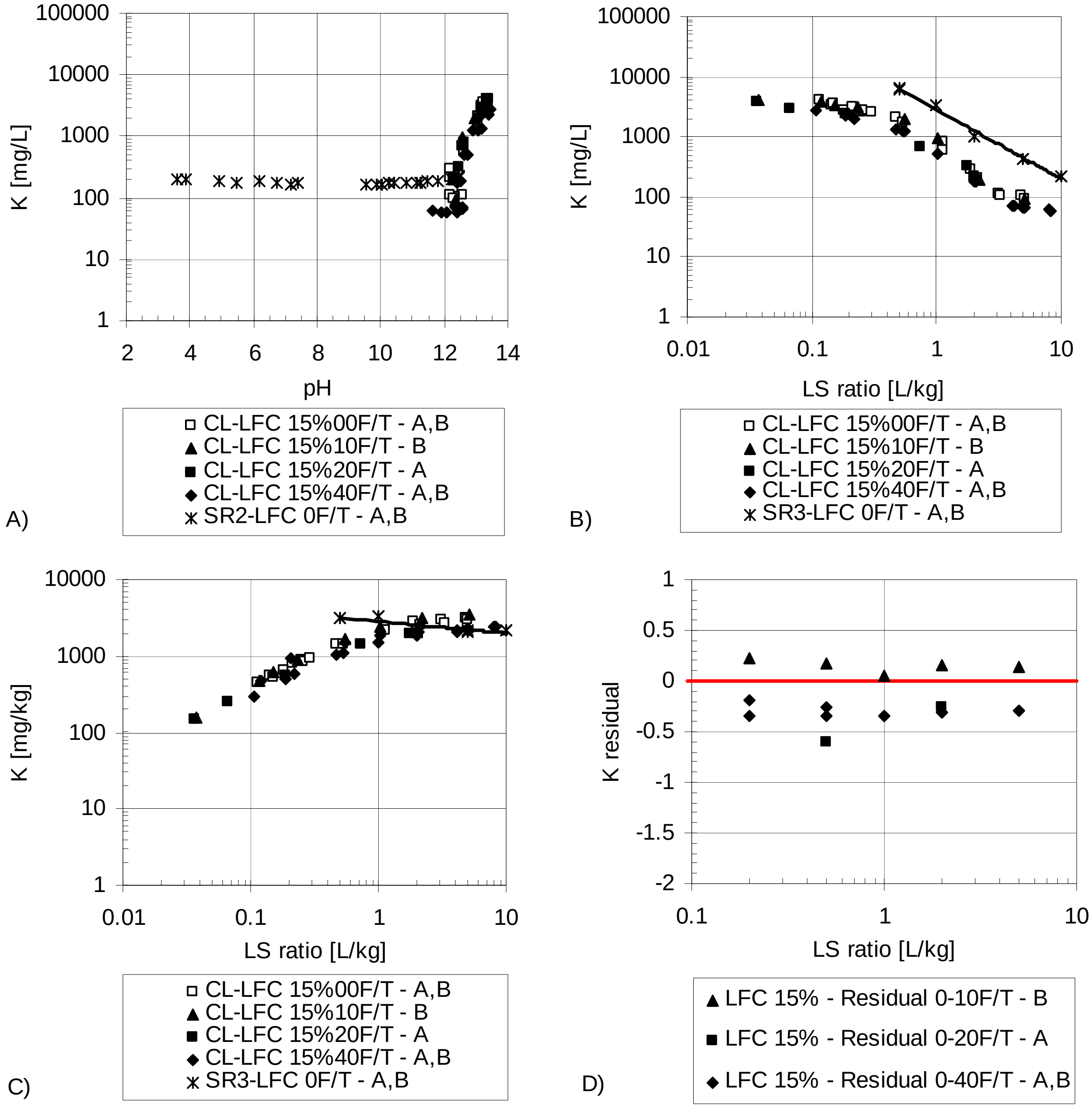


Figure 62. Potassium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

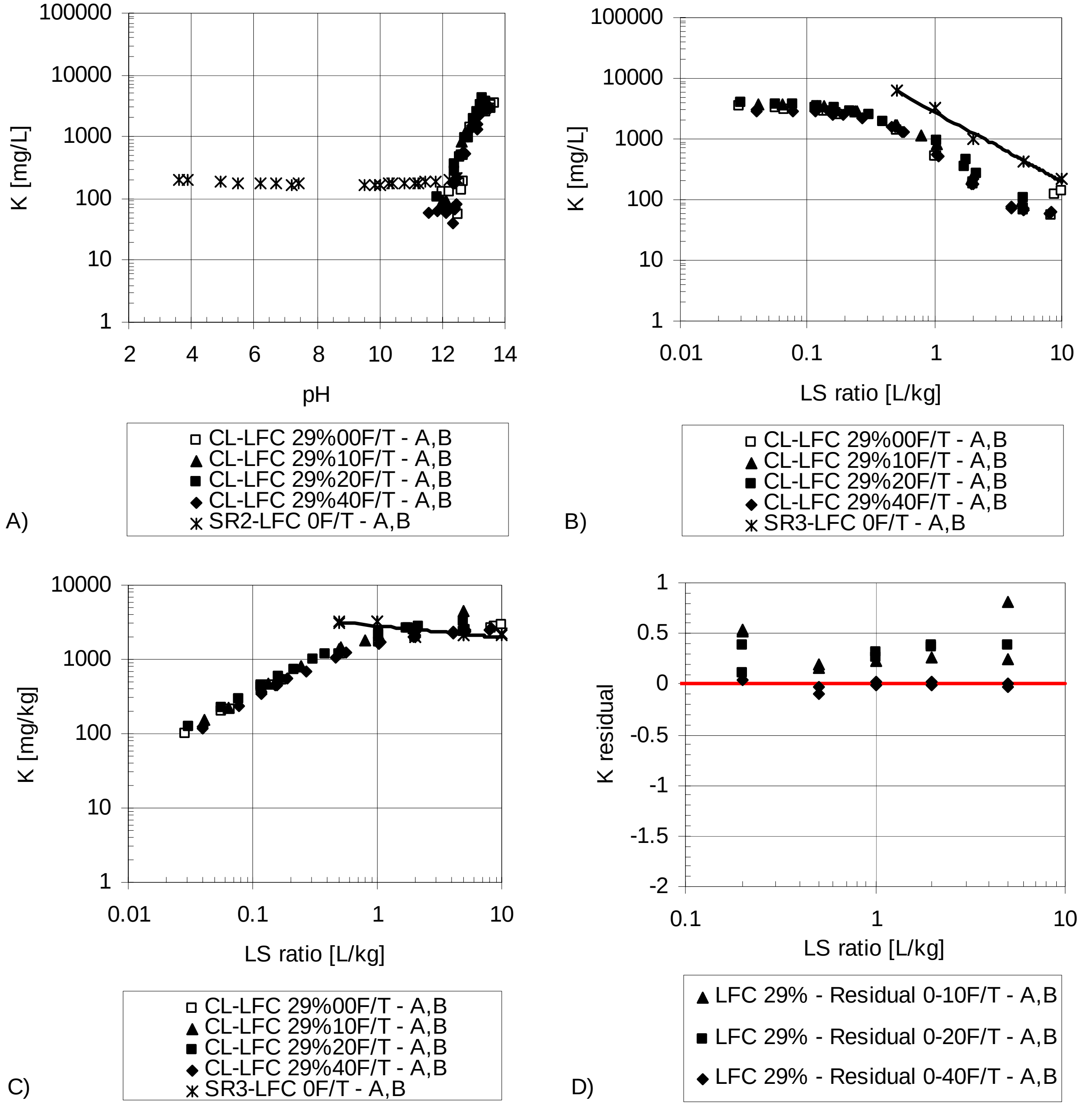


Figure 63. Potassium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.2.3. Calcium release

The effect of F/T exposure on the release of calcium for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 64, Figure 65, and Figure 66, respectively.

The following general observations for calcium were made:

- A great variability in the cumulative release of calcium was observed between the different levels of F/T exposure and within replicates for the columns packed at 7 % and 15% moisture content. The variability was much greater for LS ratios less than 2 L/kg.
- Overall, exposure to 40 F/T cycles resulted in a lower release of calcium (by as much as 4 times) for the columns packed at 7% and 15% moisture content.
- For all cases, on a cumulative mass basis, calcium release from batch testing at the LS ratios of 0.5, 1, and 2 L/kg was slightly lower (as much as 2.5 times) than that from column testing at the same LS ratios.

LFC material packed at 7% moisture content

- For LS ratios less than 1 L/kg, a lower cumulative release of calcium was observed for the 40 F/T cycle aged columns compared to the baseline columns and the 10 and 20 F/T cycle aged columns (by as much as ca. 4 times lower).

LFC material packed at 15% moisture content

- For LS ratios less than 2 L/kg, the cumulative release of calcium from the 20 and 40 F/T cycle aged columns was overall lower than that from the 0 and 10 F/T cycle aged columns (by as much as ca. 2 times lower).

LFC material packed at 29% moisture content (optimum moisture content)

- No clear tendency could be observed between the different levels of F/T aging for the LFC material packed at 29% moisture content.

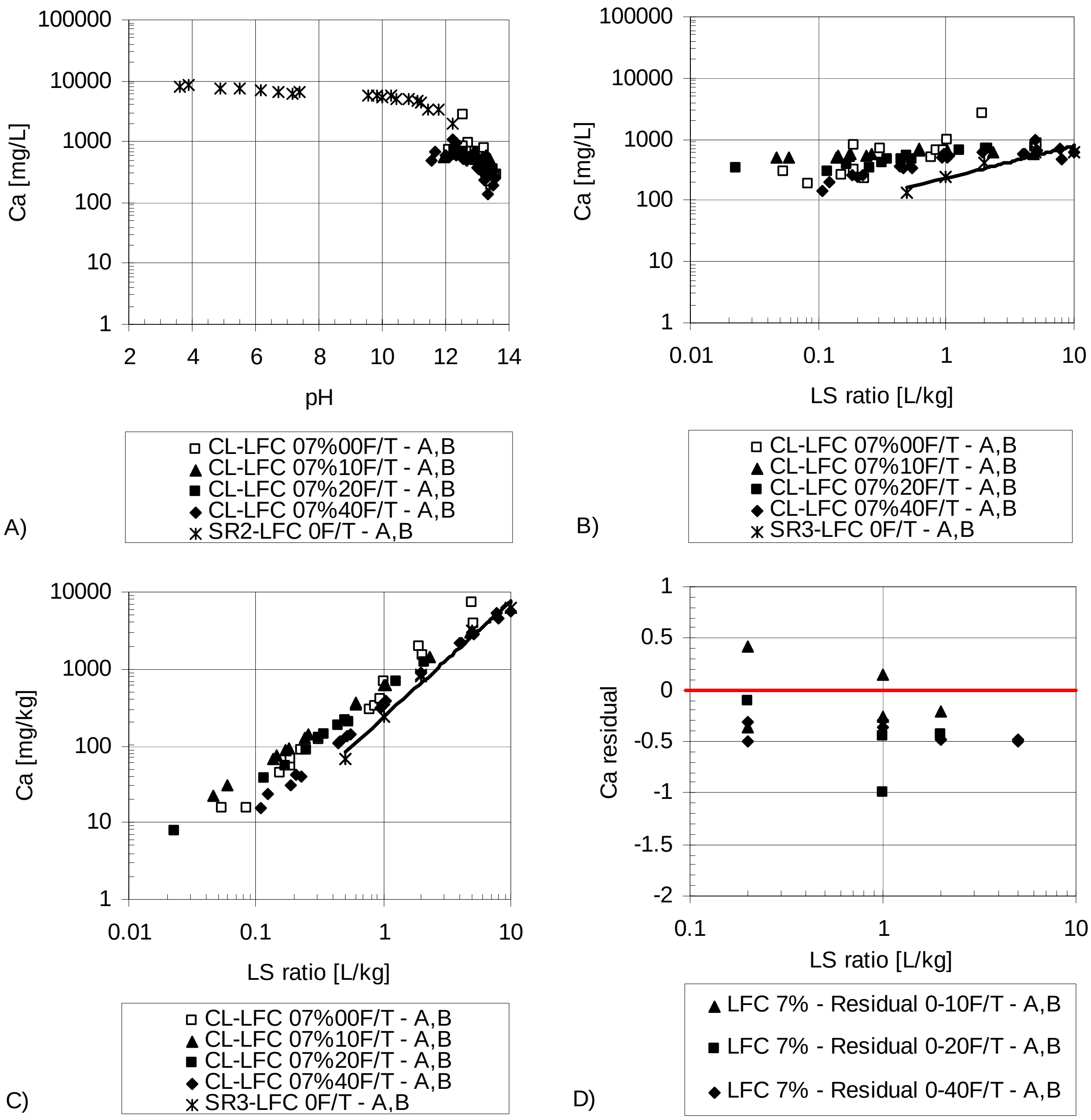


Figure 64. Calcium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

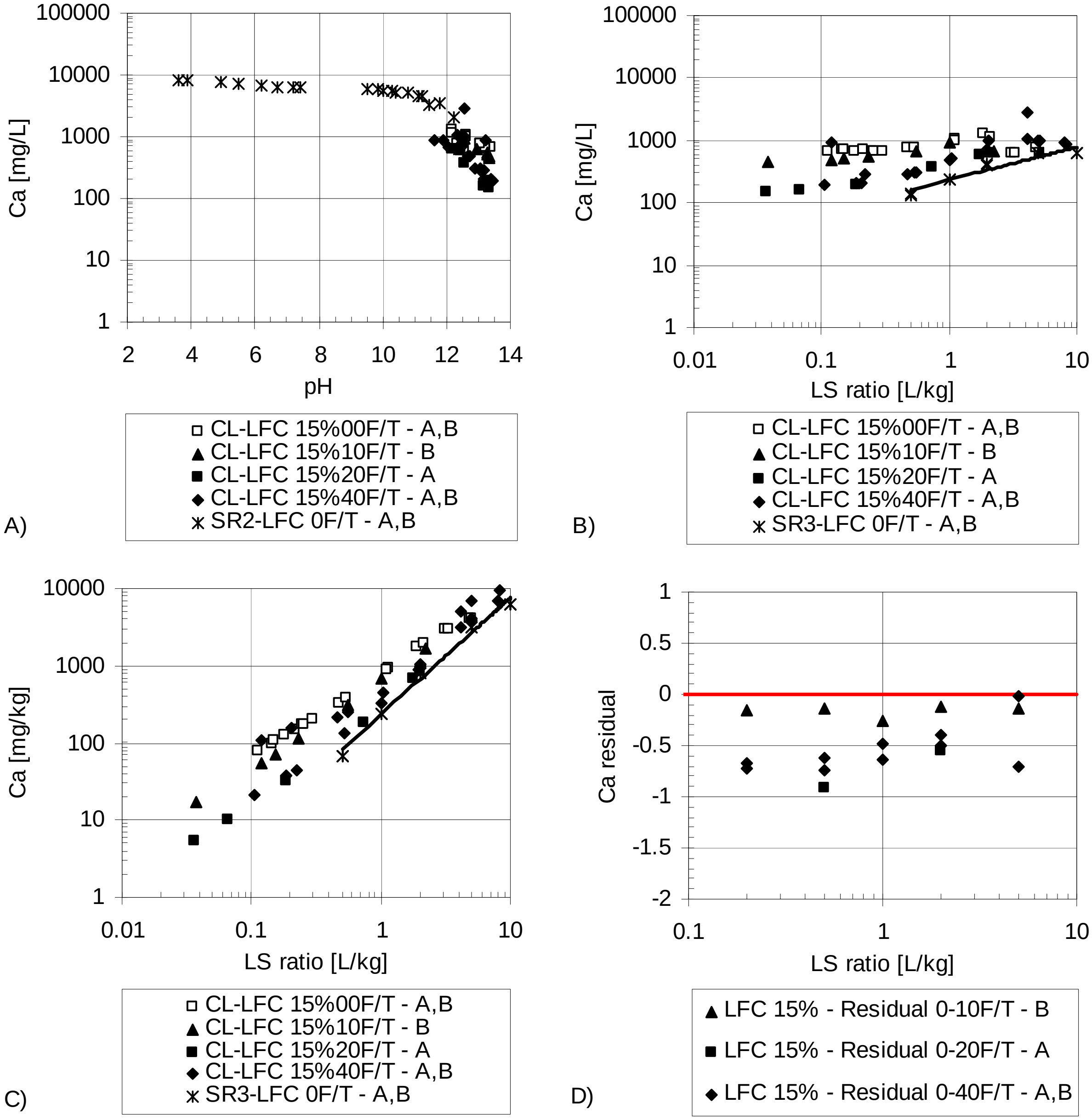


Figure 65. Calcium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

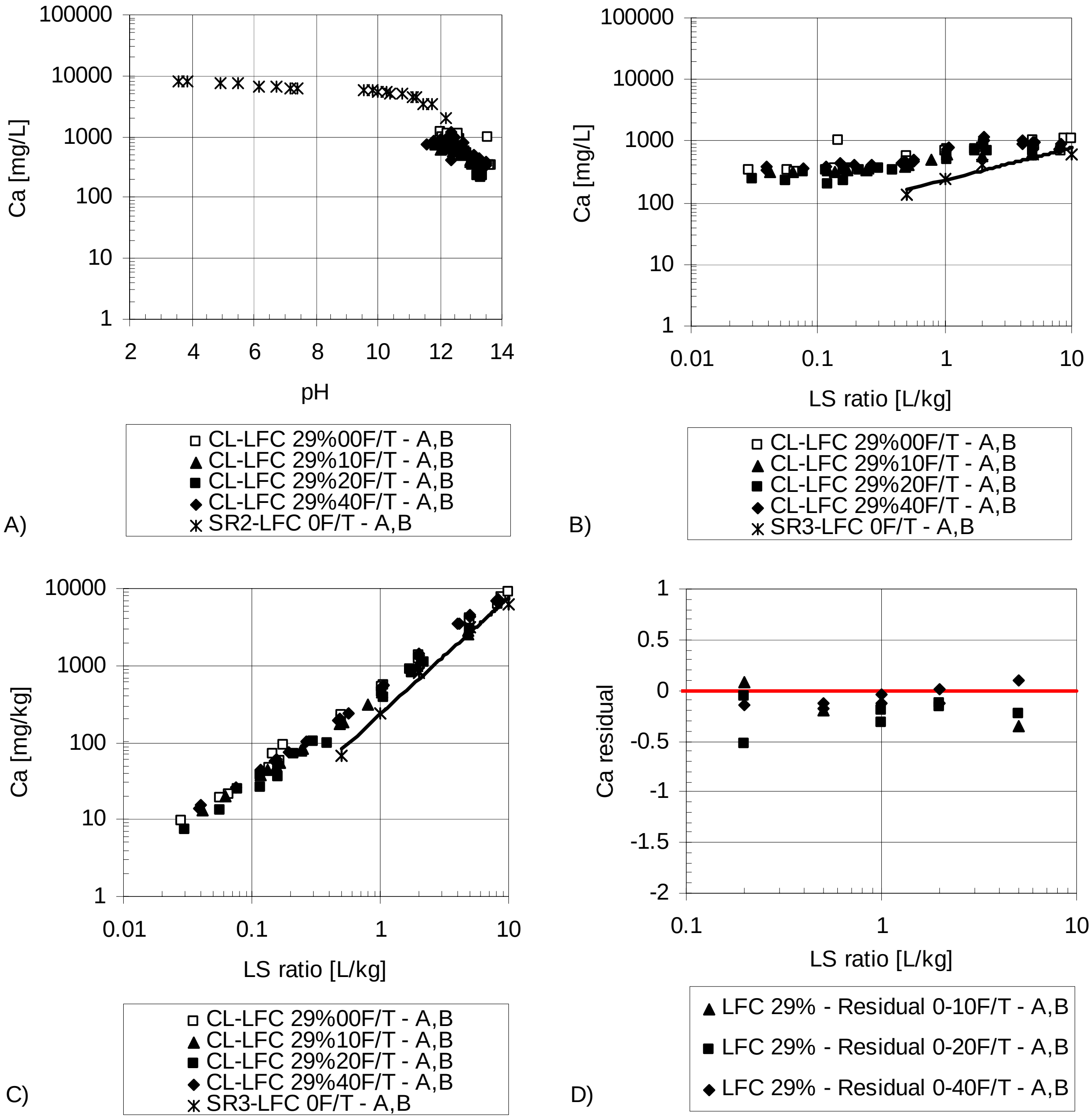


Figure 66. Calcium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.2.4. Chloride release

The effect of F/T exposure on the release of chloride for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 67, Figure 68, and Figure 69, respectively.

The following general observations for chloride were made:

- As with sodium and potassium, for all cases, the cumulative release of chloride reached a plateau at an LS ratio of ca. 2 L/kg. This plateau was ca. 585 mg/kg (with values ranging from 460 mg/kg to 720 mg/kg), ca. 550 mg/kg (with values ranging from 355 mg/kg to 720 mg/kg), and ca. 450 mg/kg (with values ranging from 355 to 610 mg/kg) for the columns packed at 7%, 15%, and 29%, respectively.
- Exposure to 40 F/T cycles resulted in a lower release of chloride for the columns packed at 15% moisture content.

LFC material packed at 7% moisture content

- Poor replication was observed for the baseline and the 20 F/T cycle aged columns.
- No clear tendency on the effect of F/T exposure could be observed.

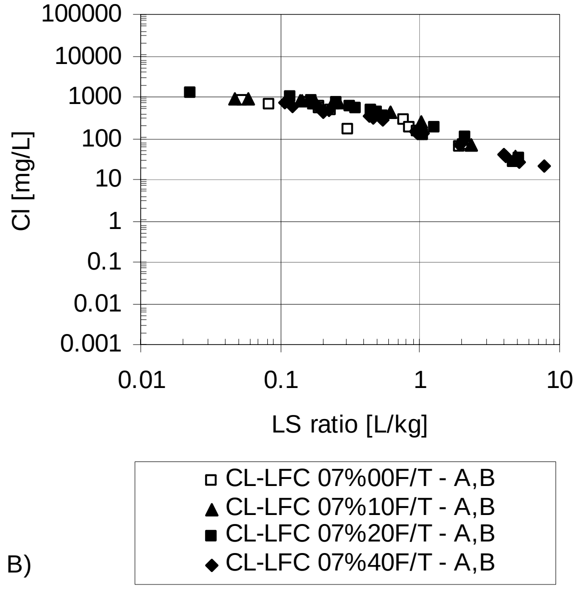
LFC material packed at 15% moisture content

- Exposure to F/T cycles resulted in a lower release of chloride over the entire range of LS ratios examined.
- The release of chloride from the 40 F/T cycle aged columns was lower than that from the baseline columns and the 10 and 20 F/T cycle aged columns (by approximately two times at any given LS ratio).

LFC material packed at 29% moisture content (optimum moisture content)

- Exposure to F/T cycles resulted in an initial greater release of chloride compared to that from the baseline columns (by as much as an order of magnitude for LS ratios less than 0.5 L/kg).

A) Not available



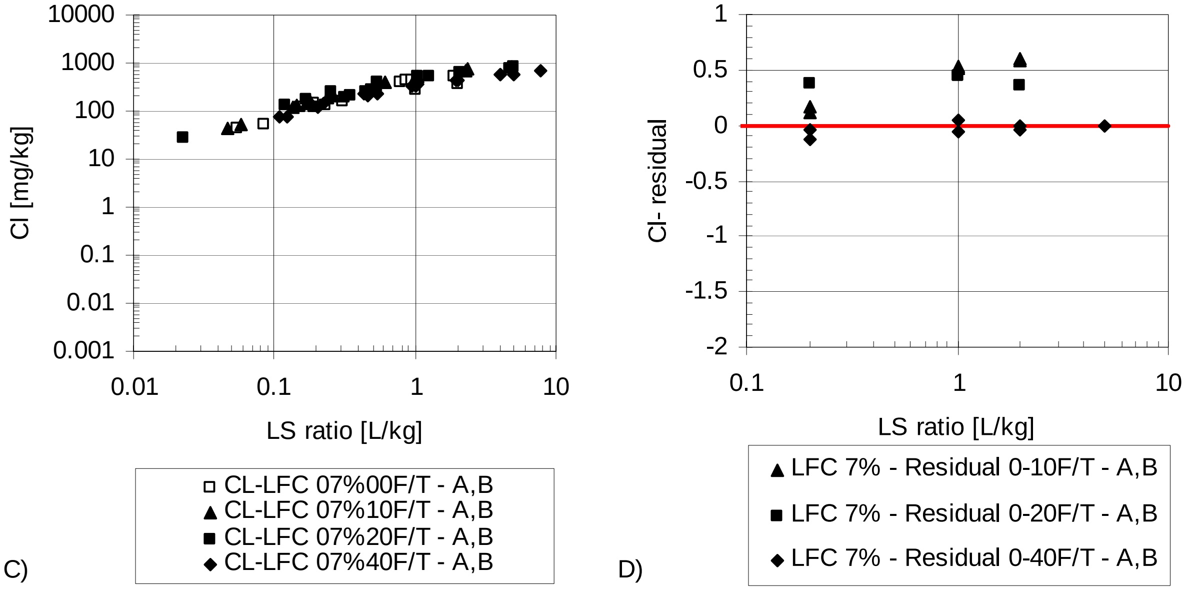


Figure 67. Chloride release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

A) Not available

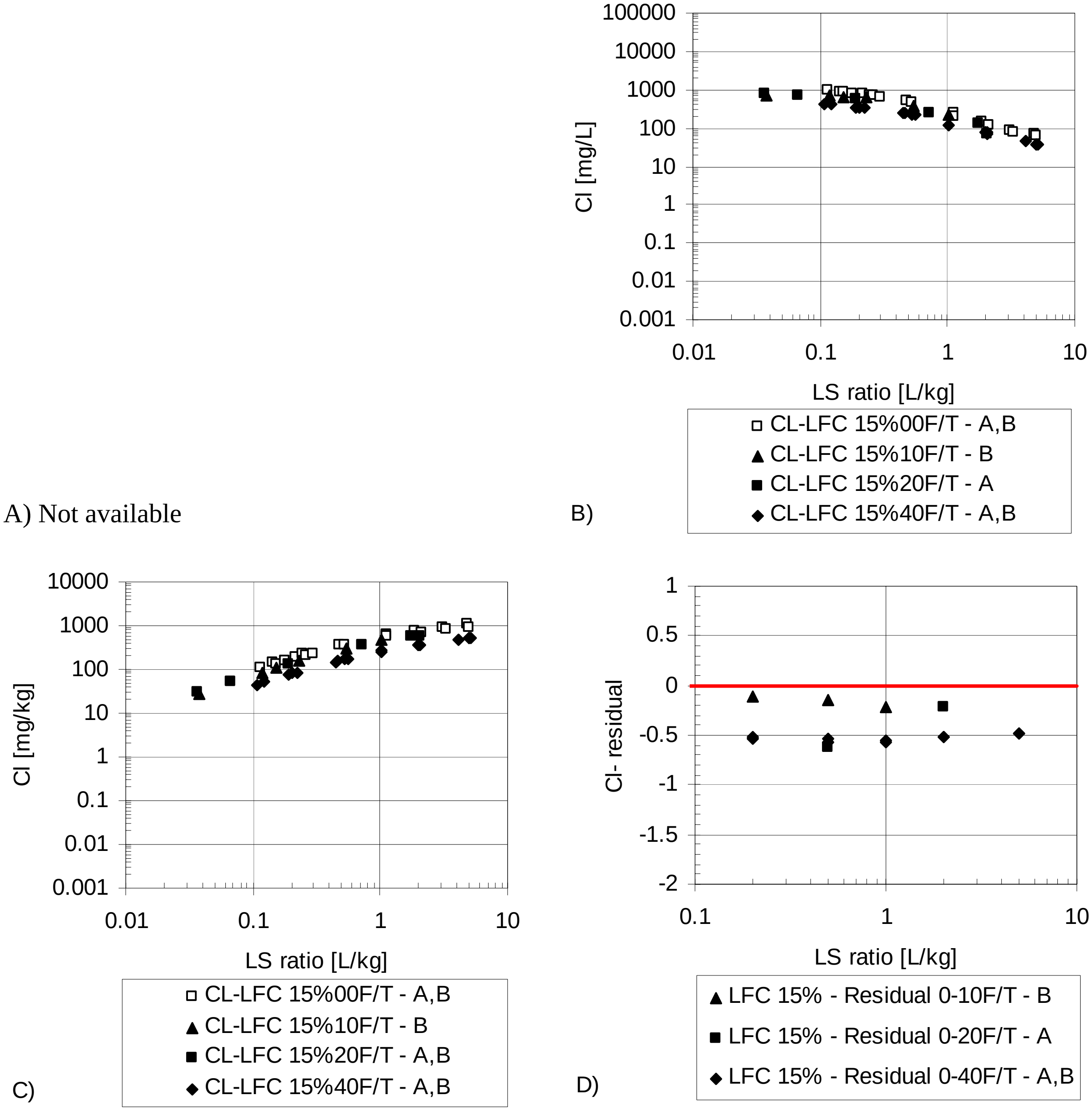
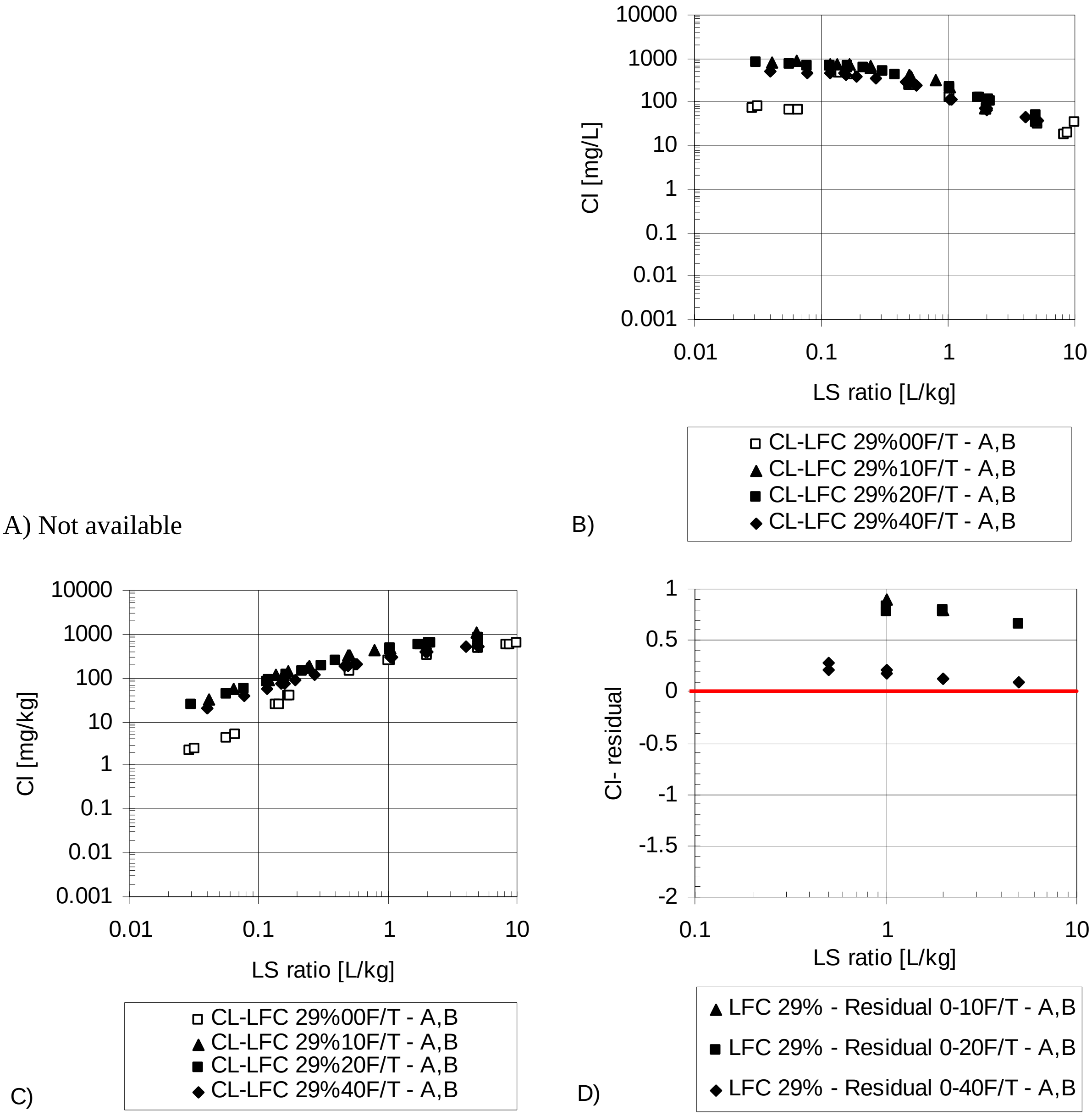


Figure 68. Chloride release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).



A) Not available

B)

C)

D)

Figure 69. Chloride release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.2.5. Sulfate release

The effect of F/T exposure on the release of sulfate for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 70, Figure 71, and Figure 72, respectively.

The following general observations for sulfate were made:

- Exposure to F/T cycles resulted in a lower release of sulfate compared to no F/T exposure for the columns packed at 7% and 15% moisture content, as shown by the residual plots.
- For all cases, the cumulative release of sulfate reached a plateau at an LS ratio of ca. 2 L/kg. This plateau was ca. 170 mg/kg (with values ranging from 100 mg/kg to 285 mg/kg), ca. 65 mg/kg (with values ranging from 28 mg/kg to 130 mg/kg), and ca. 45 mg/kg (with values ranging from 30 to 65 mg/kg) for the columns packed at 7%, 15%, and 29%, respectively.

LFC material packed at 7% moisture content

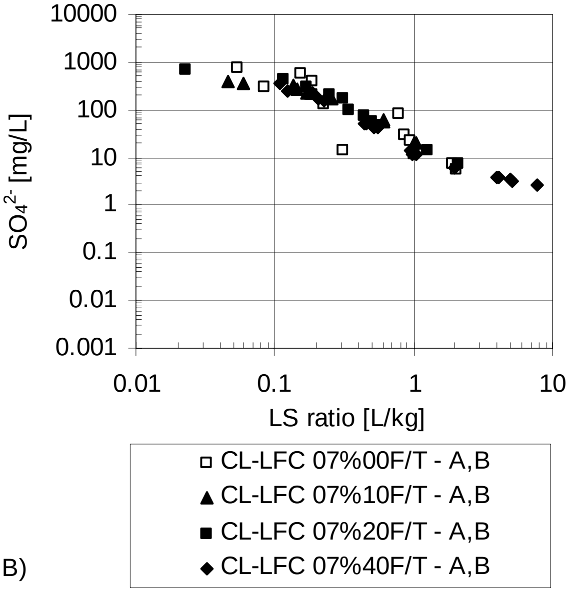
- Poor reproducibility in the cumulative release of sulfate was observed for the baseline columns and the 20 F/T cycle aged columns.
- As with potassium release, variability in the cumulative release of sulfate could be observed between the different levels of F/T aging and within replicates.
- No clear tendency of the effect of F/T aging on the cumulative release of sulfate could be observed.

LFC material packed at 15% moisture content

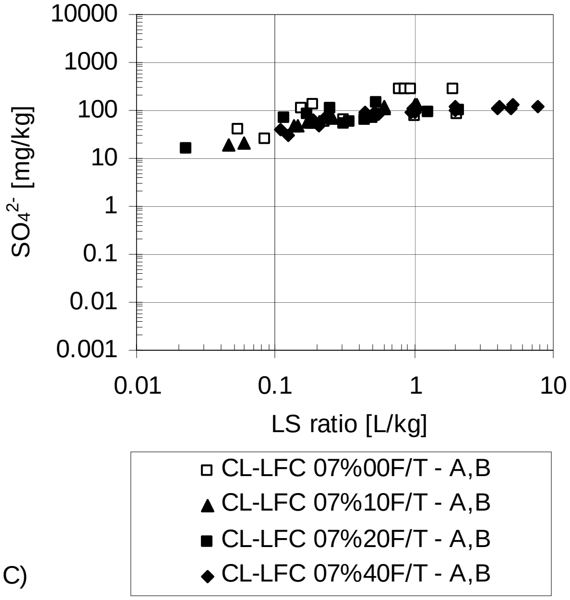
- The cumulative release of sulfate from the 40 F/T cycle aged columns was less than that from the 10 and 20 F/T cycle aged columns, which was less than that from the baseline columns.
- At the LS of 1 L/kg, the cumulative release of sulfate was ca. 25 mg/kg for the 40 F/T cycle aged columns, while ca. 125 mg/kg and ca. 60 mg/kg for the baseline columns and the 10 and 20 F/T cycle aged columns.

LFC material packed at 29% moisture content (optimum moisture content)

- The cumulative release of sulfate from the 40 F/T cycle aged columns was less than that from the baseline columns over the entire range of LS ratios examined.



A) Not available



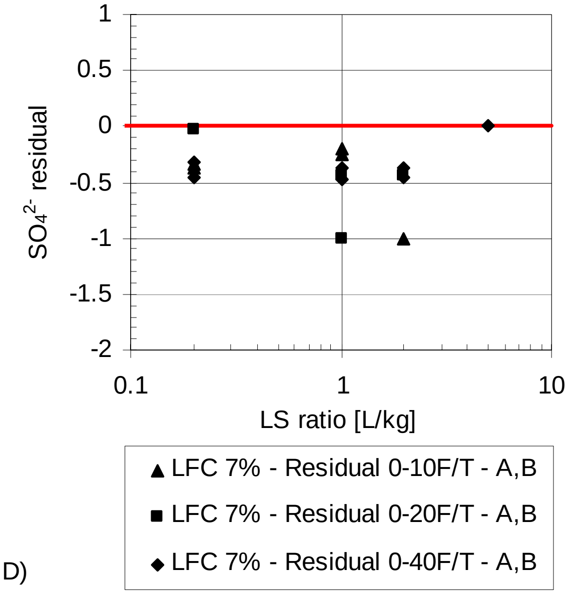


Figure 70. Sulfate release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

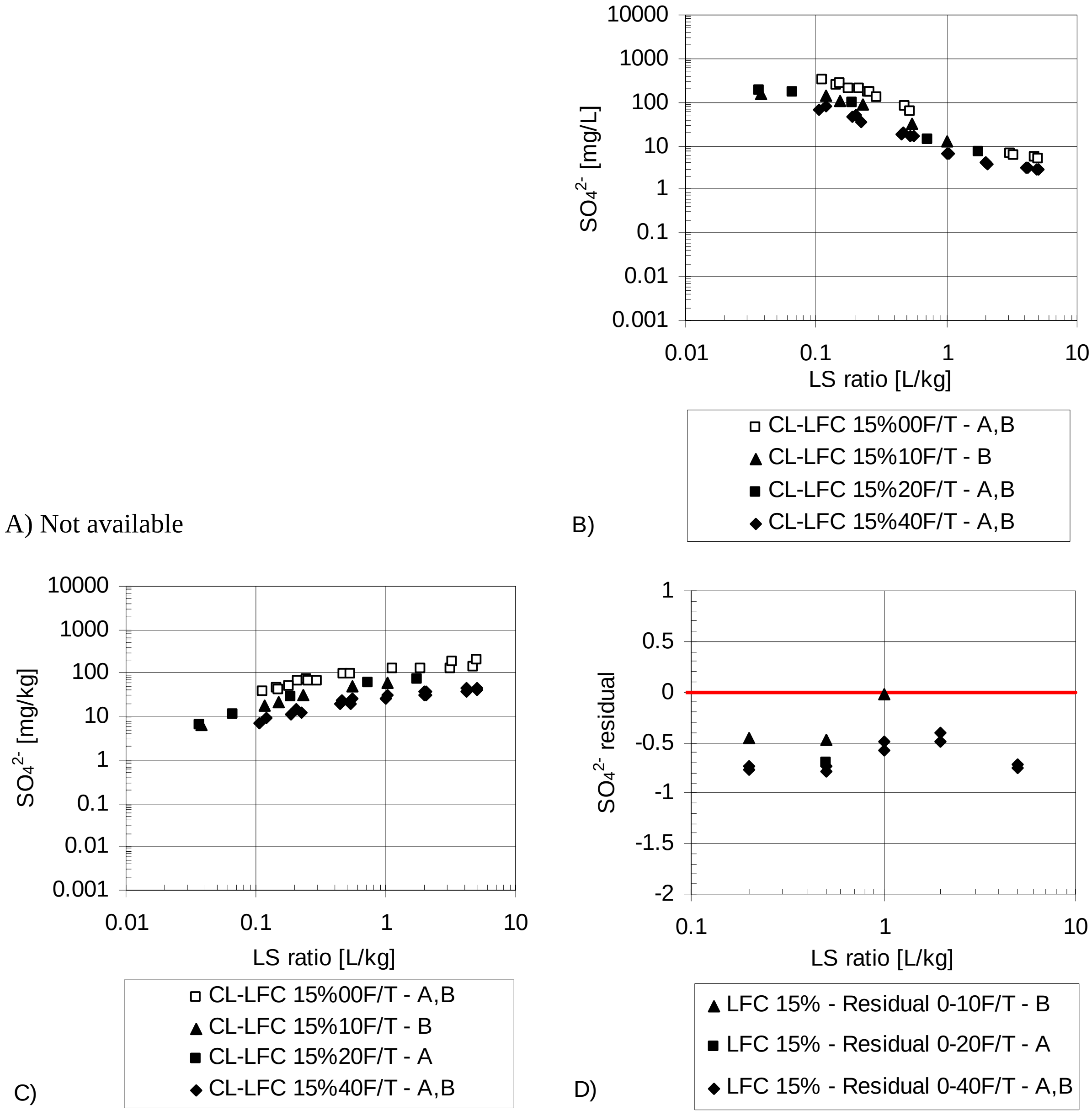


Figure 71. Sulfate release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

A) Not available

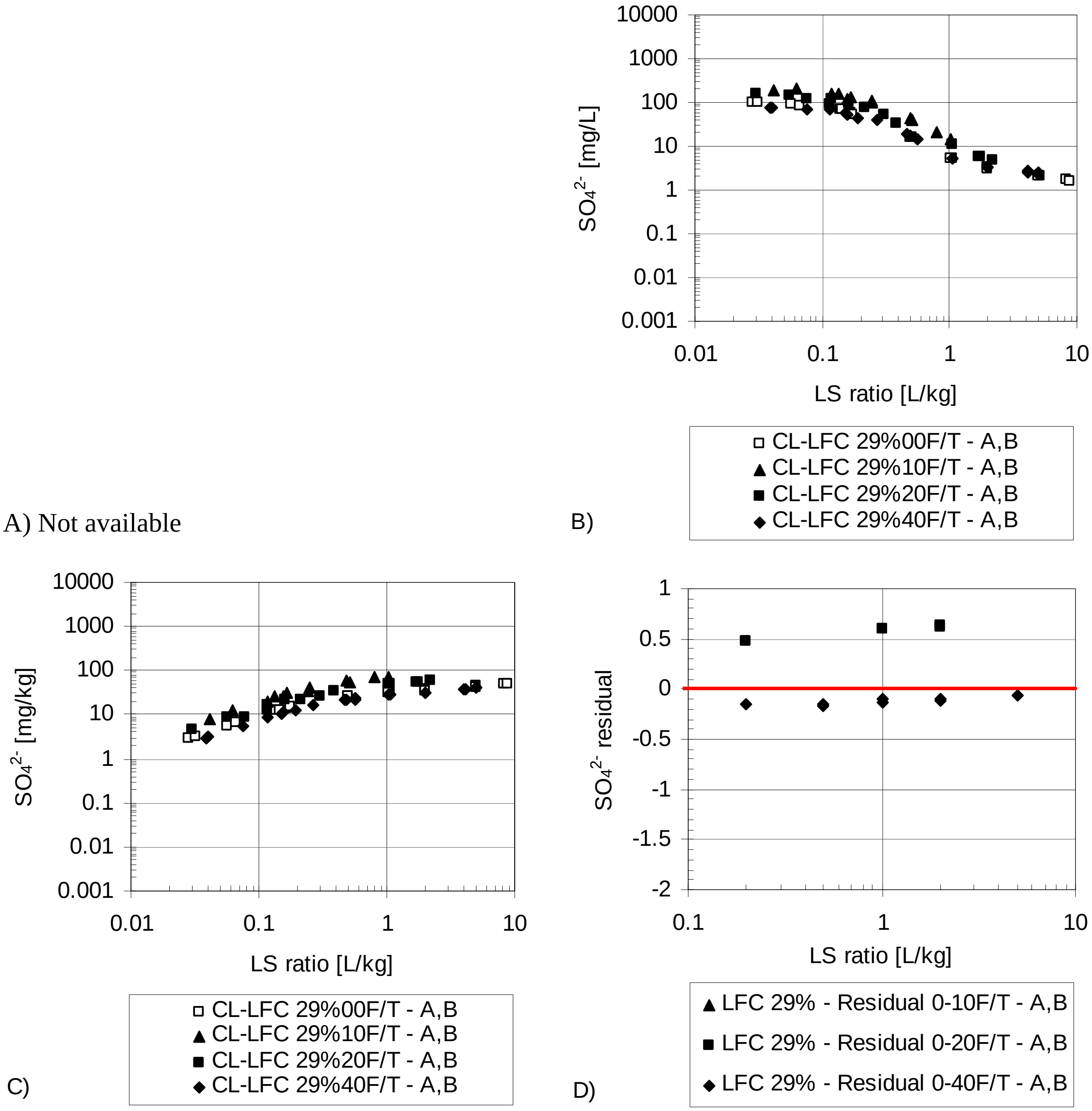


Figure 72. Sulfate release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.2.6. Conclusions

Exposure to F/T cycles had overall the greatest effect on the leaching of major material constituents when the LFC material was packed at a moisture content that was ca. 52% (i.e., 15% moisture content) of the value of the optimum moisture content. The greatest variability in the release could be observed between the different levels of F/T exposure and within replicates when the LFC material was packed at a moisture content that was ca. 24% (i.e., 7% moisture content) of the value of the optimum moisture content. The least effect of F/T exposure was observed when the LFC material was packed at the optimum moisture content.

Overall, as the number of F/T cycles increased, the release of the major material constituents showed an initial increase generally after exposure to 10 F/T cycles and in some cases after exposure to 20 F/T cycles compared to the no F/T cycles cases, followed by a decrease generally after exposure to 20 and 40 F/T cycles, suggesting consolidation of the LFC material during F/T exposure. The continued decrease after 40 F/T cycles resulted in a release less than the no F/T exposure cases. These results are in agreement with the behavior of the flow rate and visual observation of particle aggregation and overall consolidation of the packed granular material (see section 4.3.1.2).

4.6.3. Effect of F/T exposure on the release of primary contaminants

For each contaminant of concern, a common format is used for presenting the results. A set of four figures is used for each moisture content examined showing the different levels of F/T exposure. Figure A shows the concentration as a function of pH from column testing compared to batch testing (i.e., SR002.1). Figure B shows the concentration as a function of LS ratio from column testing compared to batch testing (i.e., SR003.1). Figure C shows the cumulative release as a function of LS ratio. Figure D shows the residuals of the cumulative release as a function of LS ratio relative to no F/T exposure (0 F/T cycles).

4.6.3.1. Arsenic release

The effect of F/T exposure on the release of arsenic for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 73, Figure 74, and Figure 75, respectively.

The following general observations for arsenic were made:

- A great variability in the cumulative release of arsenic was observed between the different levels of F/T exposure and within replicates for the columns packed at 7% and 15% moisture content.
- Arsenic concentration in the leachate from column testing was less than or close to the solubility of arsenic for most cases. Concentrations of arsenic greater than the solubility of arsenic obtained from the SR003 test were, however, observed for a small number of leachates from the 10 F/T cycle aged columns packed at 7% and 15% moisture content. This behavior was not observed in the leachates from the columns packed at the optimum moisture content (i.e., 29%). These anomalous data points could have been experimental outliers or could indicate that changes in the material chemistry had occurred, which were not observed during batch testing. Further investigations are warranted.
- On a cumulative mass basis, batch testing was in good agreement overall with column testing except for the columns packed at 7% and 15% moisture content that were exposed

to 10 F/T cycles for which batch testing underestimated the release by as much as 2 orders of magnitude.

LFC material packed at 7% moisture content

- Overall, a good replication was obtained except for the baseline columns and the columns that had been exposed to 20 F/T cycles. These columns showed, respectively, as much as one order of magnitude difference in the cumulative release over the entire range of LS ratios examined between the two replicates.
- The greatest arsenic release was observed for the columns that had been exposed to 10 F/T cycles with ca. 0.94 mg/kg released at the LS of 5 L/kg, compared to less than 0.3 mg/kg released for the baseline columns and columns that had been exposed to 20 and 40 F/T cycles.

LFC material packed at 15% moisture content

- A good replication was obtained where replicates were available.
- No significant difference in the cumulative release of arsenic could be observed between the baseline columns and the columns that had been exposed to 20 and 40 F/T cycles with less than 0.3 mg/kg of arsenic released at the LS of 5 L/kg.
- A much greater arsenic release was, however, observed after an LS ratio of 0.1 L/kg for the columns that had been exposed to 10 F/T cycles (however, this result is only based on one replicate).

LFC material packed at 29% moisture content (optimum moisture content)

- Poor replication was obtained for the columns that had been exposed to 20 FT cycles.
- No significant effect of F/T exposure was overall observed on the release of arsenic from the LFC material packed at 29% moisture content, as shown by the residual plots.
- For all cases, arsenic concentrations in leachate from column testing were lower than that from batch testing at similar LS ratios. This could indicate that arsenic equilibrium may not have been obtained in the columns and could be the result of a lower ionic strength in the column leachate compared to the batch studies due to prior release of highly soluble species (at LS of 0.5 L/kg, ca. 60% of sodium has been released from the column).

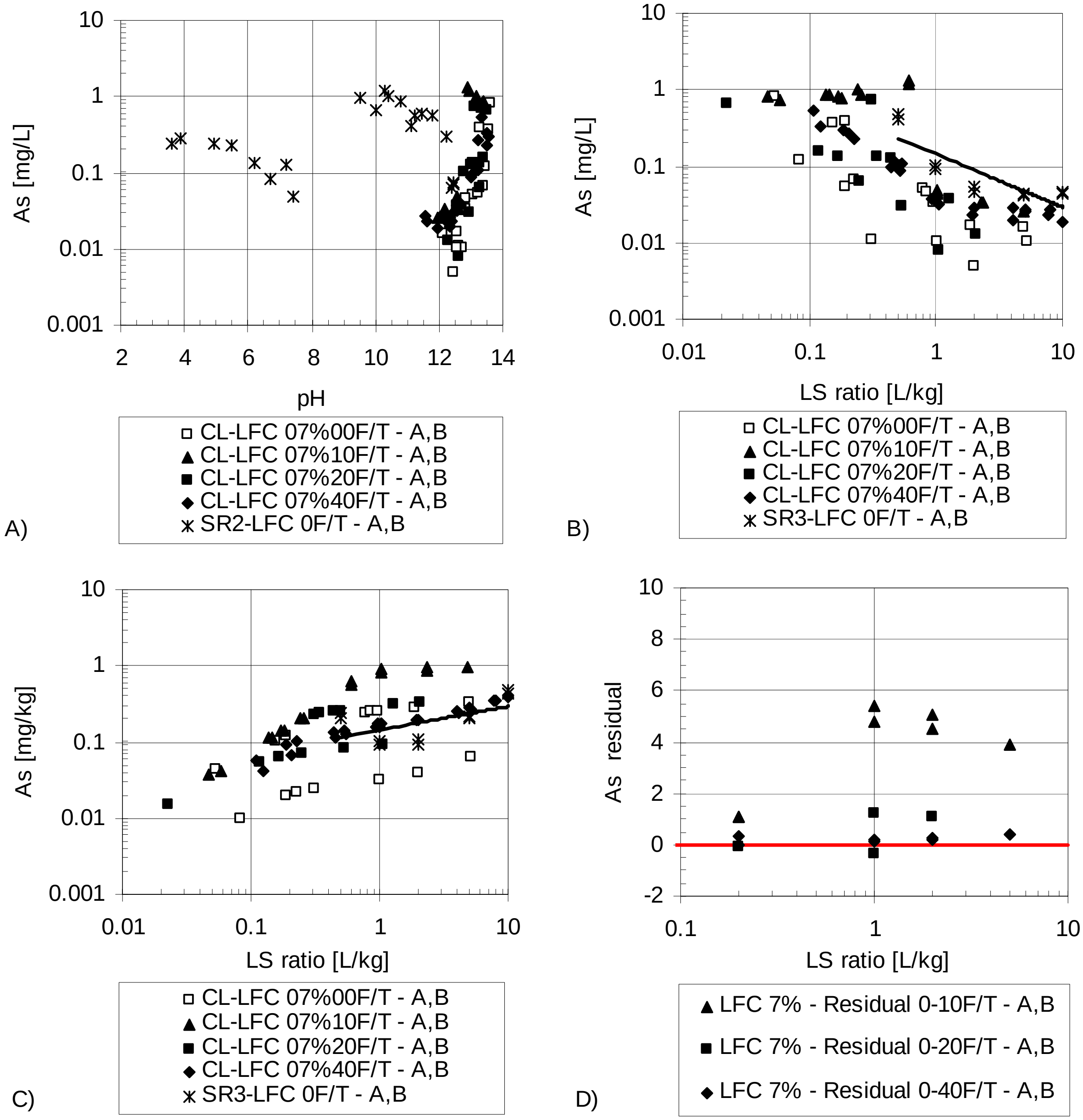


Figure 73. Arsenic release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

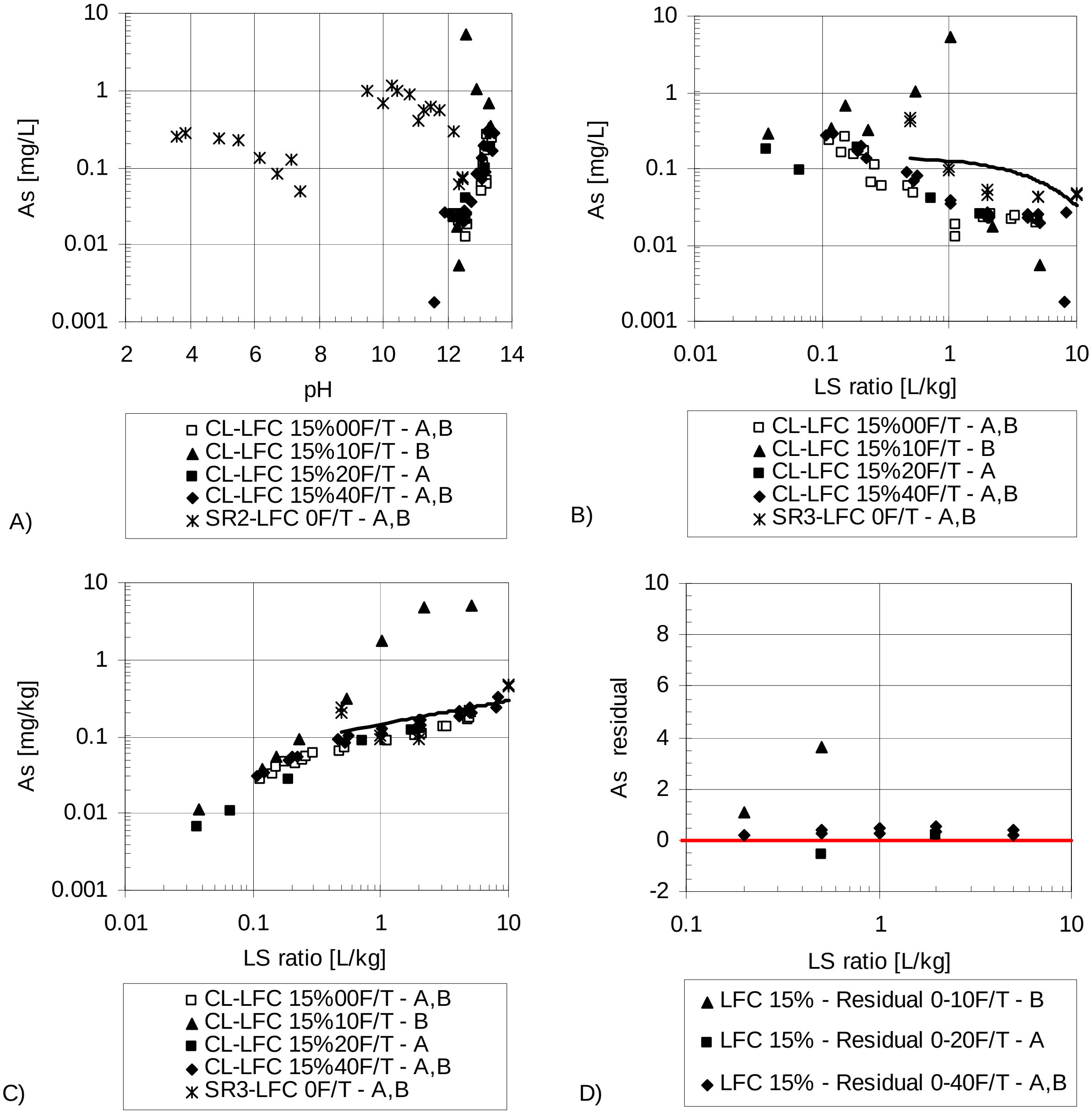


Figure 74. Arsenic release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

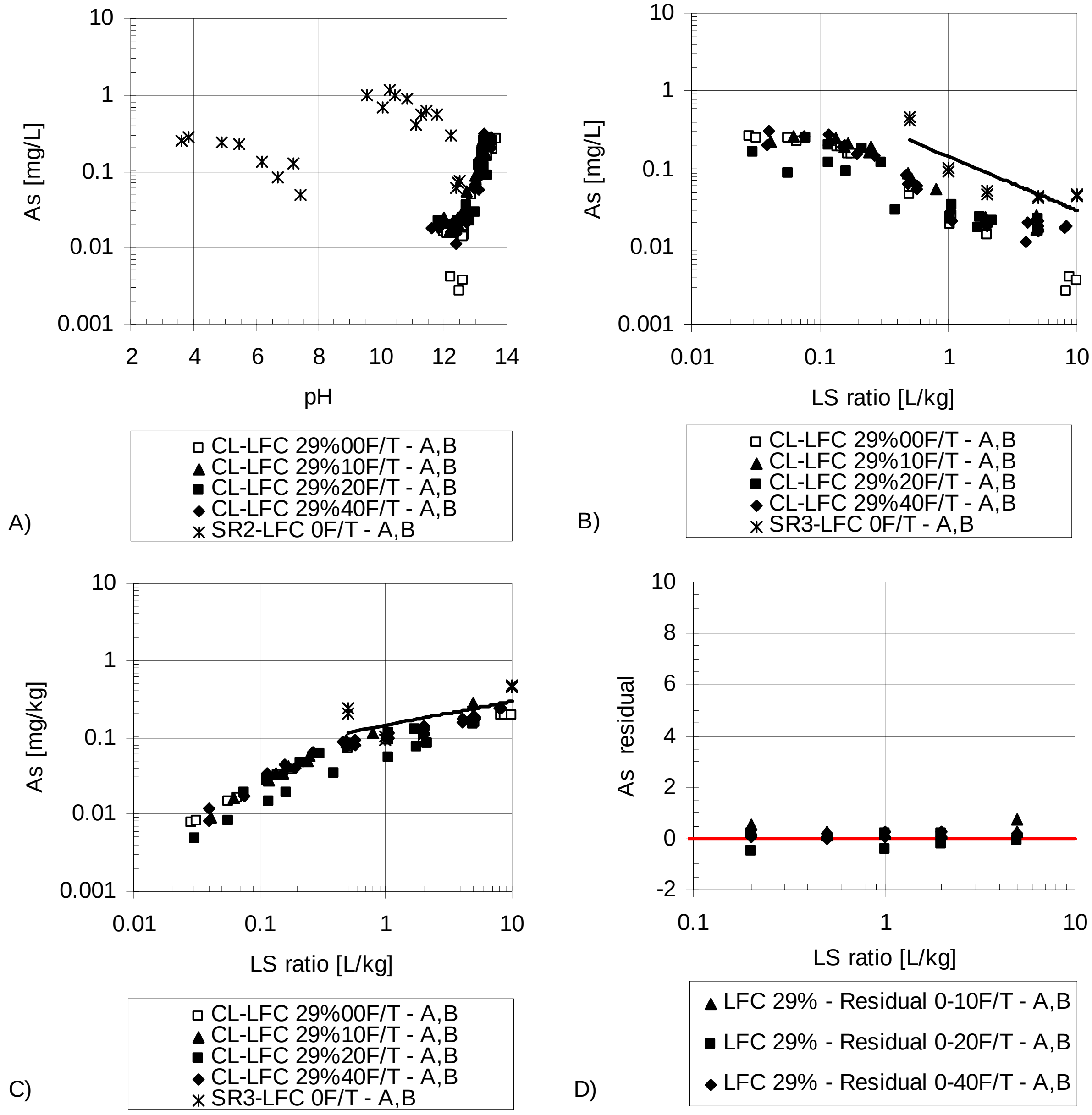


Figure 75. Arsenic release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.3.2. Cadmium release

The effect of F/T exposure on the release of cadmium for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 76, Figure 77, and Figure 78, respectively.

The following general observations for cadmium were made:

- No clear tendency of the effect of F/T exposure on the release of cadmium could be observed.
- Cadmium concentration in the leachate from column testing was less than or close to the solubility of cadmium for most cases.
- Batch testing as a function of LS ratio (SR003 test) was a conservative estimate of column testing.

LFC material packed at 7% moisture content

- Poor replication was observed for the baseline columns.
- A great variability in the cumulative release of cadmium was observed between the different levels of F/T exposure and within replicates.
- Overall, exposure to 10 F/T cycles resulted in a lower release of cadmium, while exposure to 40 F/T cycles resulted in a greater release of cadmium, as shown by the residual plots. This is in contrast with all previous observations.

LFC material packed at 15% moisture content

- Exposure to 10 F/T cycles resulted in an increase in the release of cadmium over the entire range of LS ratios examined compared to the baseline columns.
- Exposure to 40 F/T cycles resulted in an initial increase in the release of cadmium for LS ratios less than 1 L/kg and a subsequent decrease in the release of cadmium for greater LS ratios compared to the baseline columns.
- At the LS of 5 L/kg, the cadmium release was ca. 0.03 mg/kg for the 10 F/T cycle aged columns, while ca. 0.019 mg/kg for the 20 and 40 F/T cycle aged columns.

LFC material packed at 29% moisture content (optimum moisture content)

- For LS ratios less than 5 L/kg, the cumulative release of cadmium from the 10 and 20 F/T cycle aged columns was less than that from the 0 and 40 F/T cycle aged columns (by as much as 2 times).
- For LS ratios greater than 5 L/kg, no significant difference in the cumulative release of cadmium could be observed between the different levels of F/T exposure.

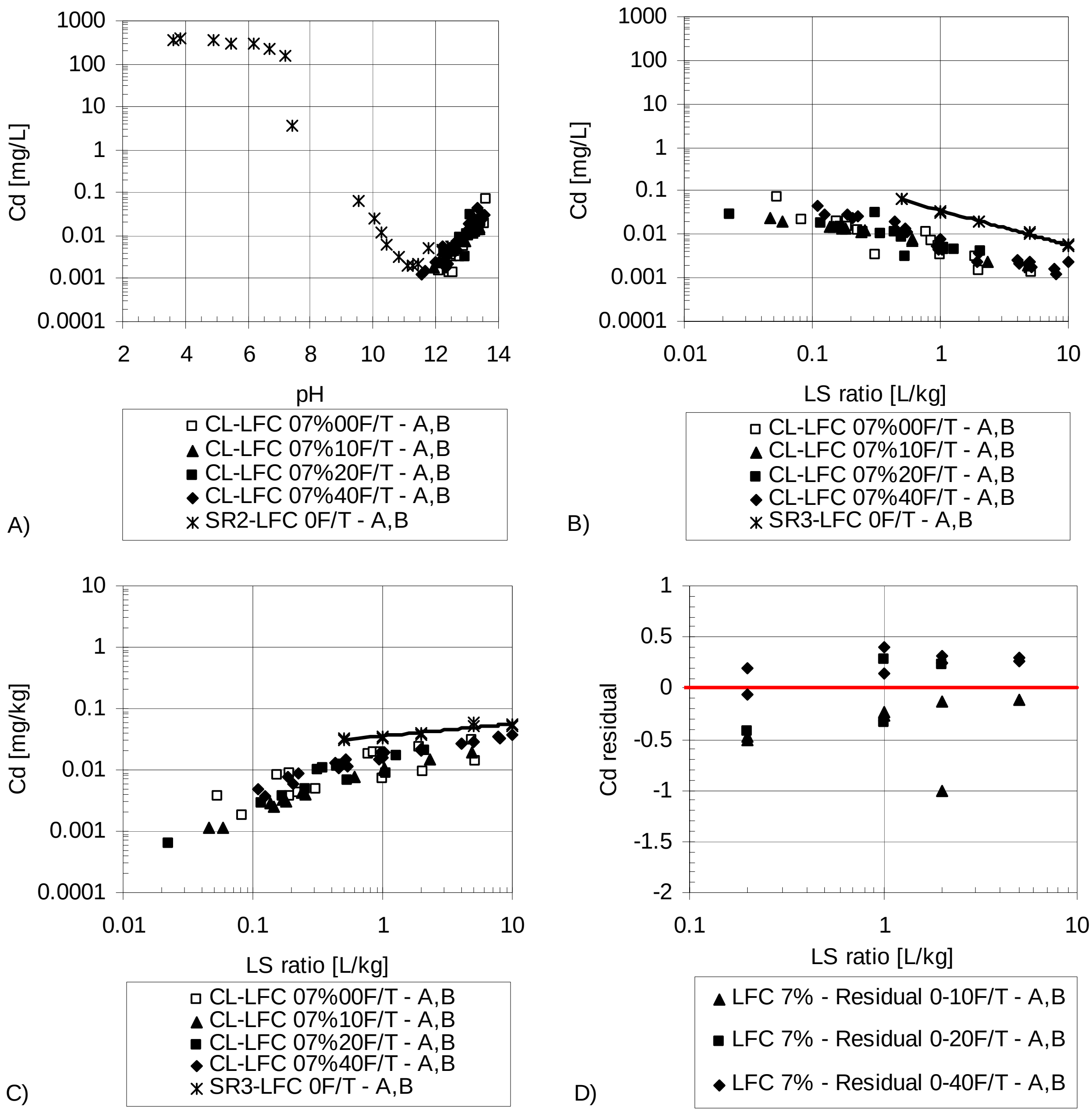


Figure 76. Cadmium release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

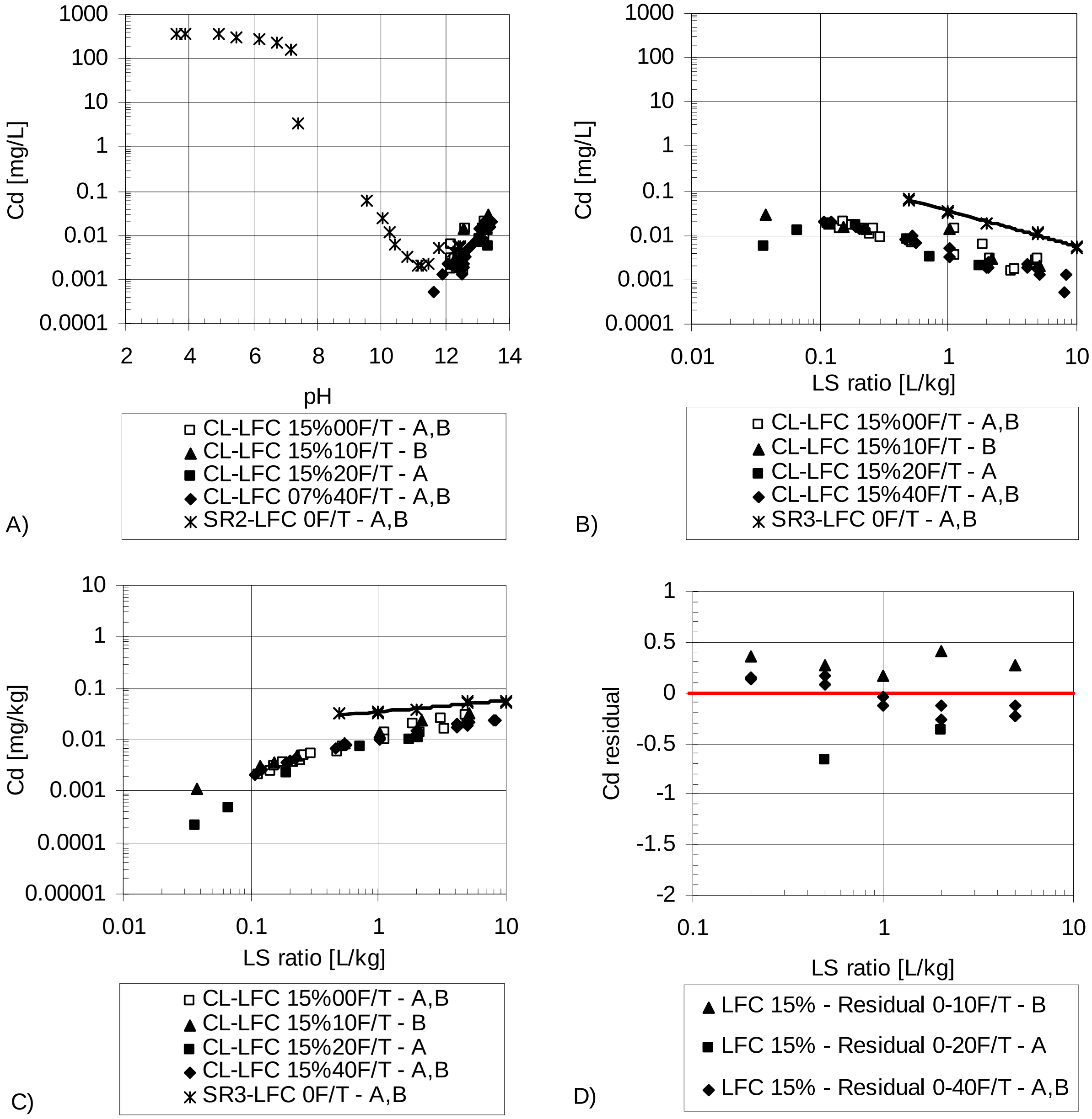


Figure 77. Cadmium release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

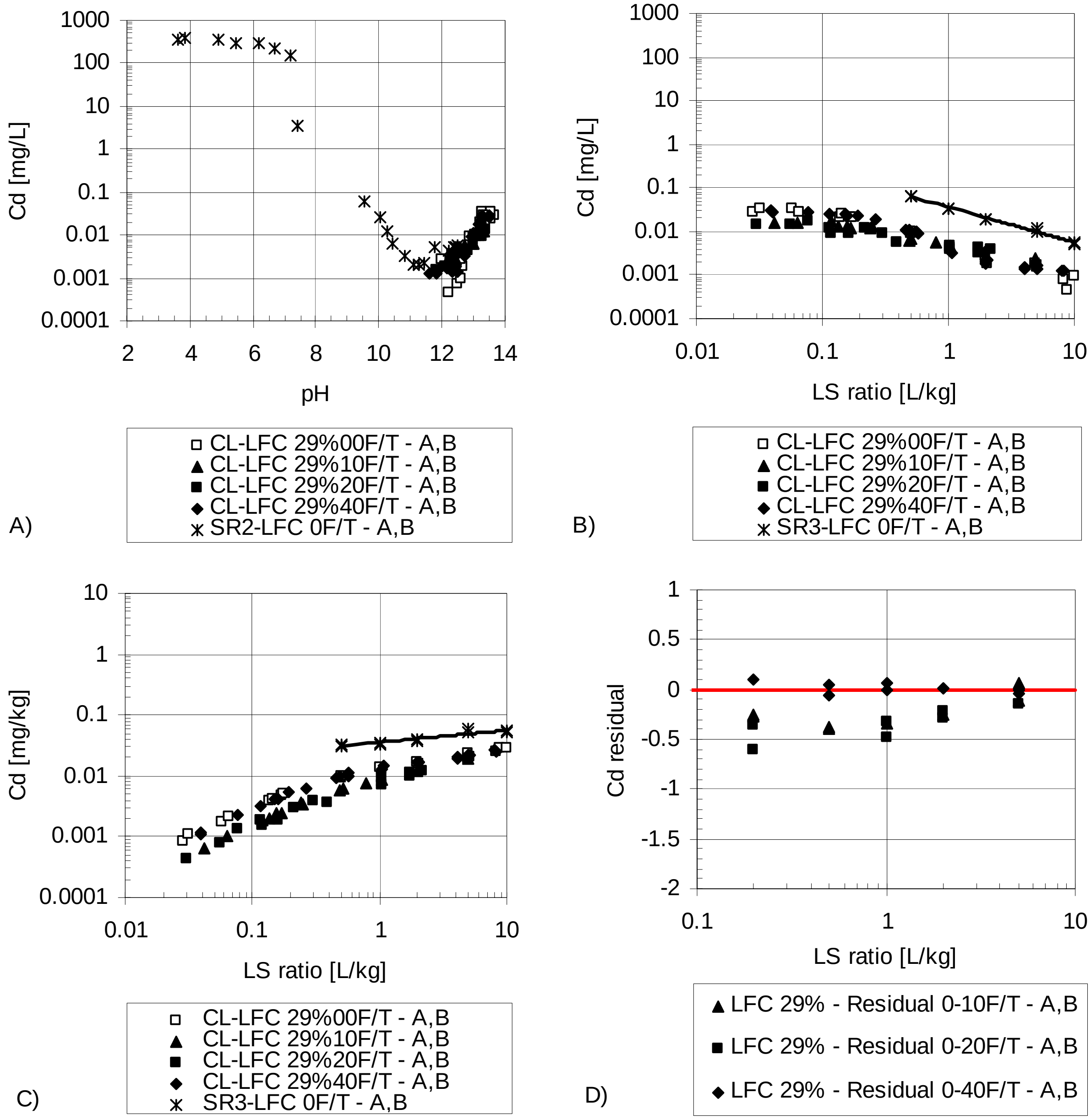


Figure 78. Cadmium release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.3.3. Copper release

The effect of F/T exposure on the release of copper for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 79, Figure 80, and Figure 81, respectively.

The following general observations for copper were made:

- Greater variability in the cumulative release of copper was observed for the columns packed at 7% and 15% moisture content compared to that packed at the optimum moisture content.
- Overall, for all cases, exposure to 40 F/T cycles resulted in a decrease in the release of copper, suggesting consolidation of the material.
- Copper concentration in the leachate from column testing was less than or close to the solubility of copper for most cases.
- Batch testing as a function of LS ratio (SR003 test) was a conservative estimate of column testing.

LFC material packed at 7% moisture content

- Exposure to 40 F/T cycles decreased the release of copper compared to no F/T exposure over the entire range of LS ratios examined.
- The greatest release of copper was observed from the 20 F/T cycle aged columns.
- At the LS of 2 L/kg, the cumulative release of copper was ca. 1.3 mg/kg for the 20 F/T aged columns and less than 0.8 mg/kg, 0.7 mg/kg, and 0.5 mg/kg for the 0, 10, and 40 F/T cycle aged columns, respectively.

LFC material packed at 15% moisture content

- Exposure to 10 F/T cycles increased the release of copper compared to no F/T exposure over the entire range of LS ratios examined.
- Exposure to 40 F/T cycles decreased the release of copper compared to no F/T exposure over the entire range of LS ratios examined.
- At the LS of 2 L/kg, the cumulative release of copper was ca. 0.9 mg/kg for the 10 F/T cycle aged columns (only 1 replicate available) and ca. 0.5 mg/kg for the 40 F/T cycle aged columns, while ca. 0.6 mg/kg and ca. 0.7 mg/kg for the 20 F/T cycle aged and baseline columns.

LFC material packed at 29% moisture content (optimum moisture content)

- Exposure to 40 F/T cycles decreased the release of copper compared to no F/T exposure, as shown by the residual plots.

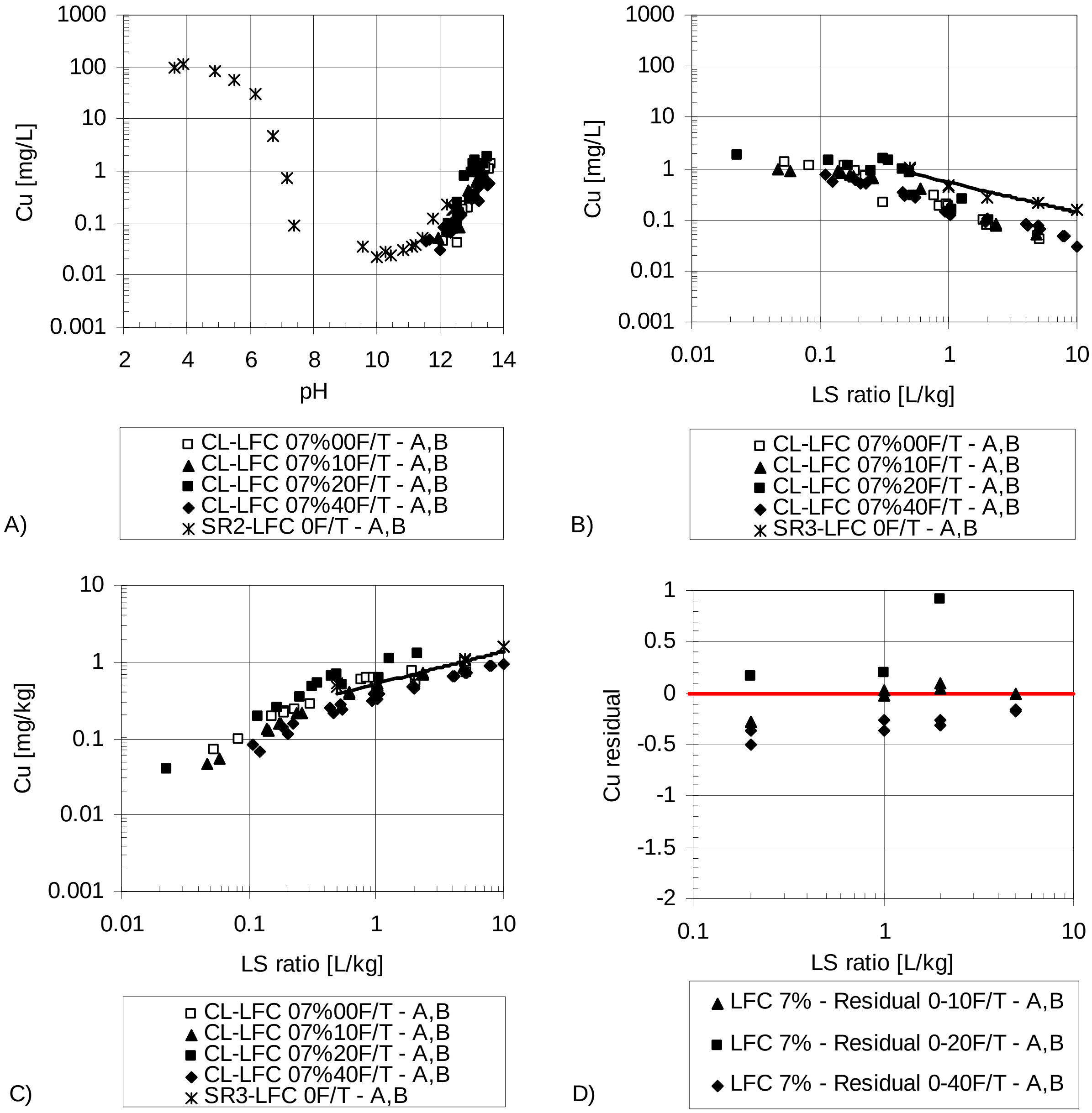


Figure 79. Copper release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

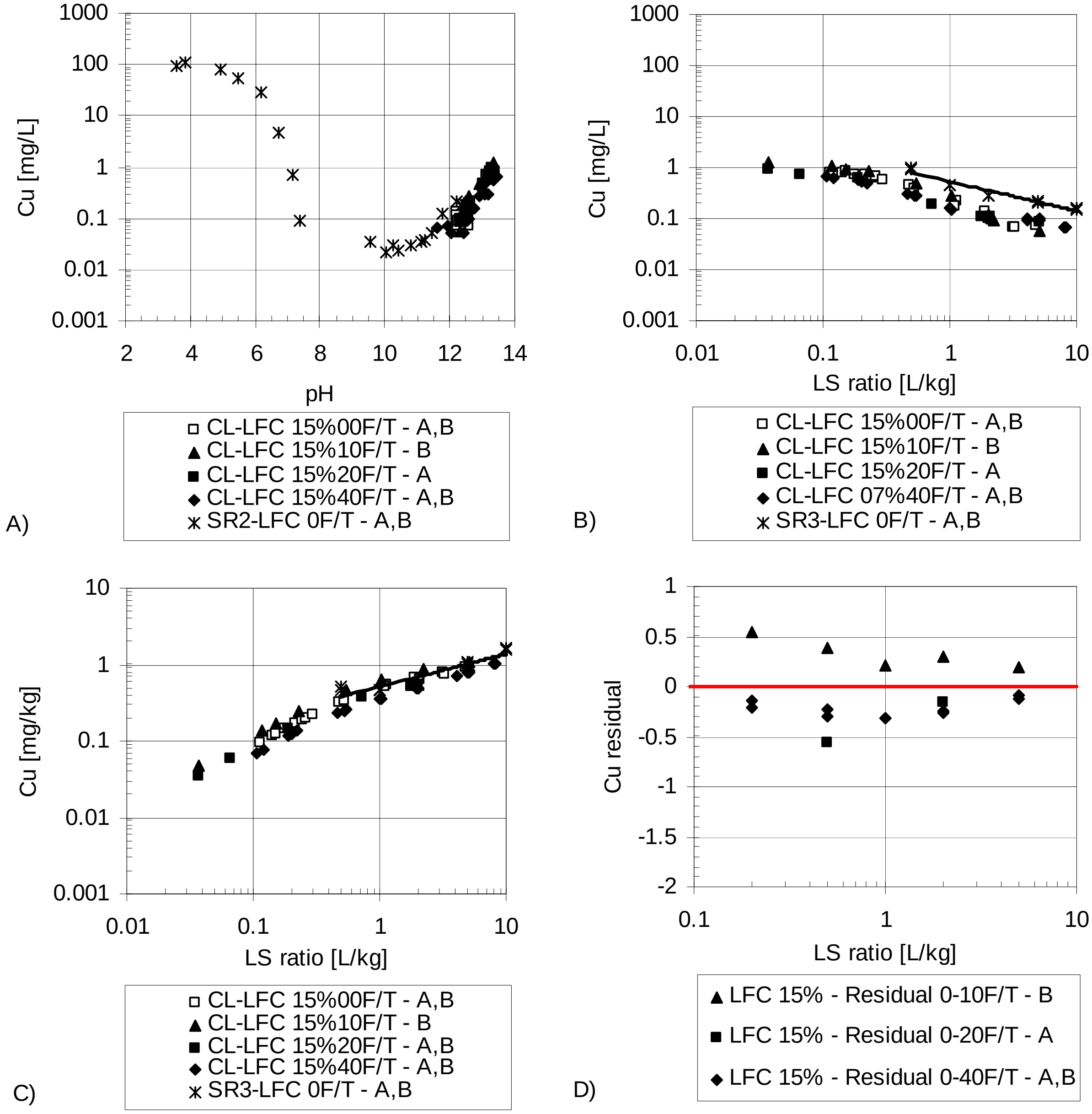


Figure 80. Copper release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

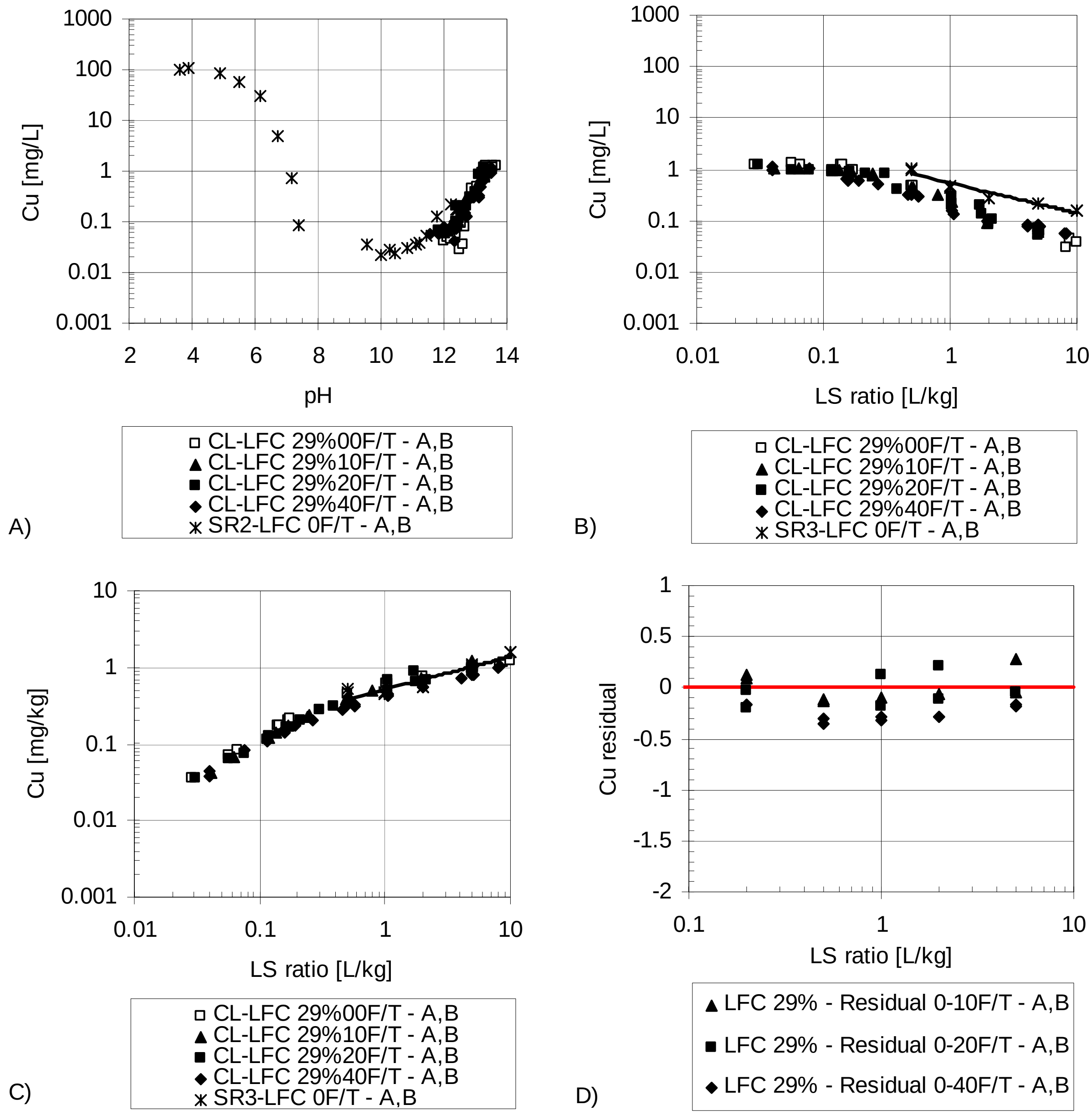


Figure 81. Copper release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.3.4. Lead release

The effect of F/T exposure on the release of lead for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 82, Figure 83, and Figure 84, respectively.

The following general observations for lead were made:

- Overall, no significant effect of F/T exposure on the release of lead was observed.
- Lead concentration in the leachate from column testing was close to the solubility of lead for all cases.
- Batch testing as a function of LS ratio (SR003 test) was a conservative estimate of column testing.

LFC material packed at 7% moisture content

- No significant difference in the release of lead could be observed between the different levels of F/T exposure.
- At the LS of 2 L/kg, the cumulative release of lead was ca. 6.7 mg/kg, ca. 8.7 mg/kg, ca. 8.0 mg/kg, and ca. 7.9 mg/kg, for the baseline and 10, 20, and 40 F/T cycle aged columns, respectively.

LFC material packed at 15% moisture content

- Poor replication was observed for the 40 F/T cycle aged columns.
- For one replicate, exposure to 40 F/T cycles resulted in an initial decrease in the release of lead (by as much as 7 times) for LS ratios less than 1 L/kg, compared to no F/T exposure.
- For LS ratios greater than 1 L/kg, no significant difference in the release of lead between the different levels of F/T exposure could be observed.

LFC material packed at 29% moisture content (optimum moisture content)

- No significant effect of F/T exposure on the release of lead could be observed, as shown by the residual plots.

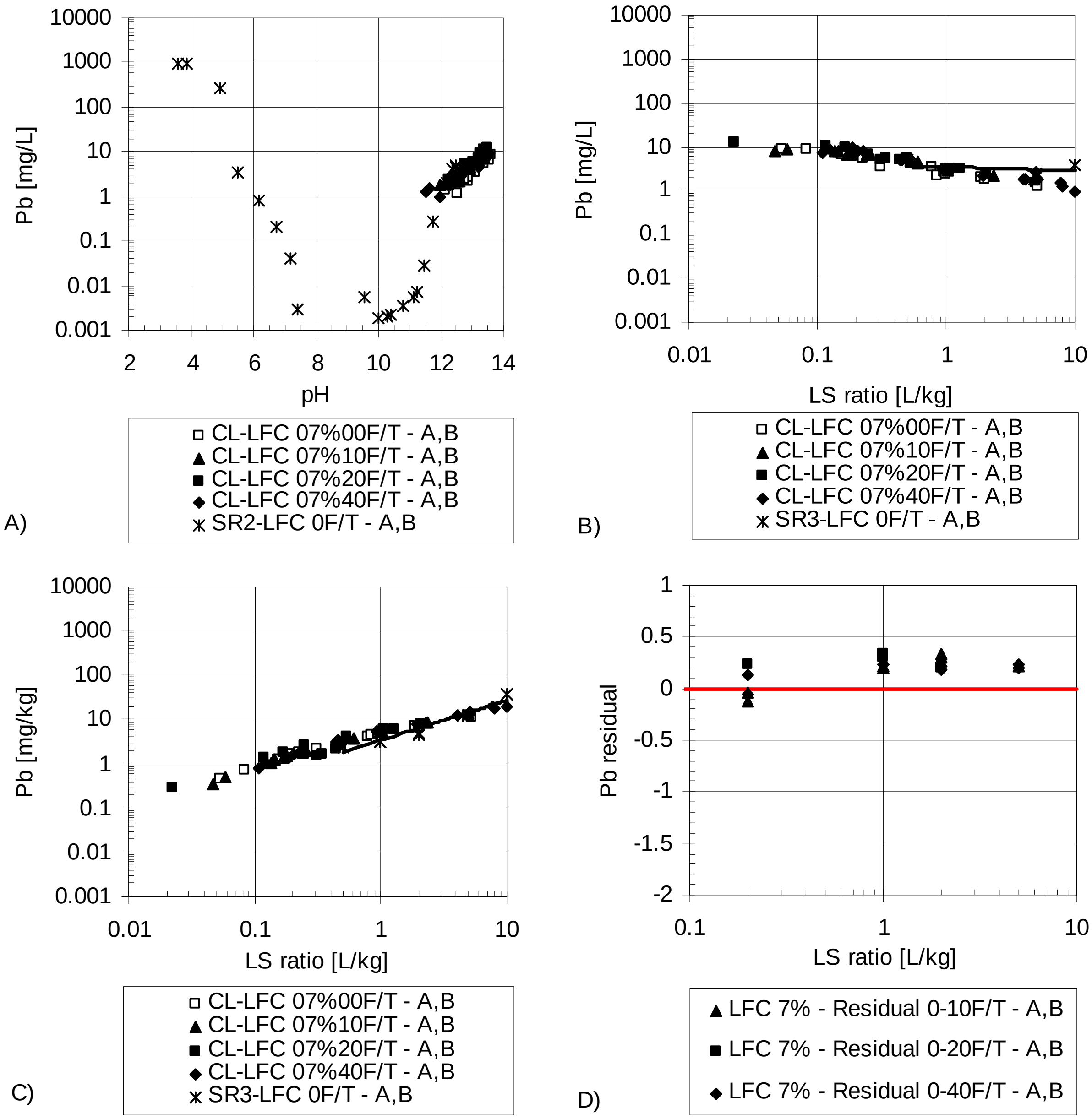


Figure 82. Lead release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

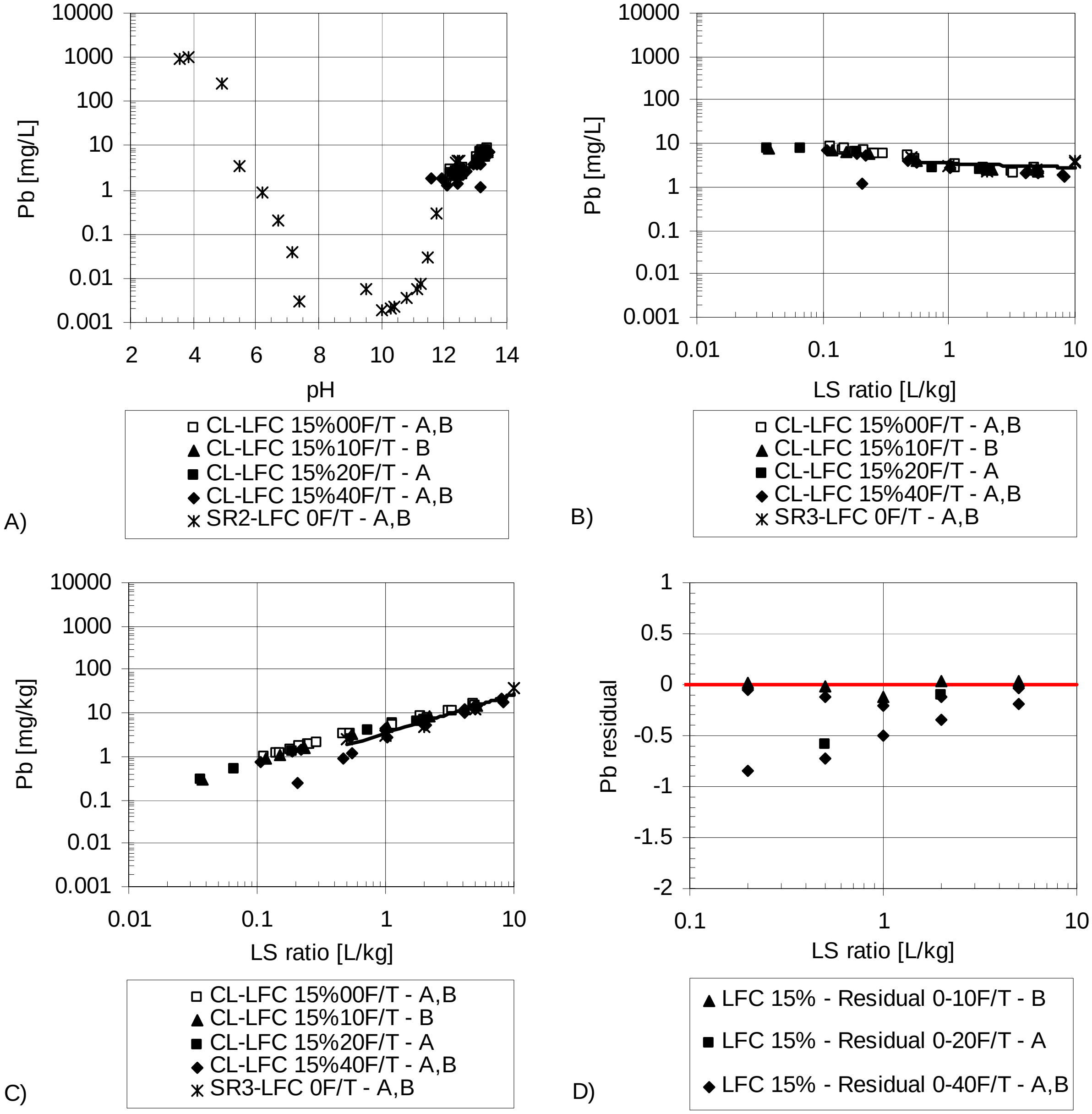


Figure 83. Lead release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

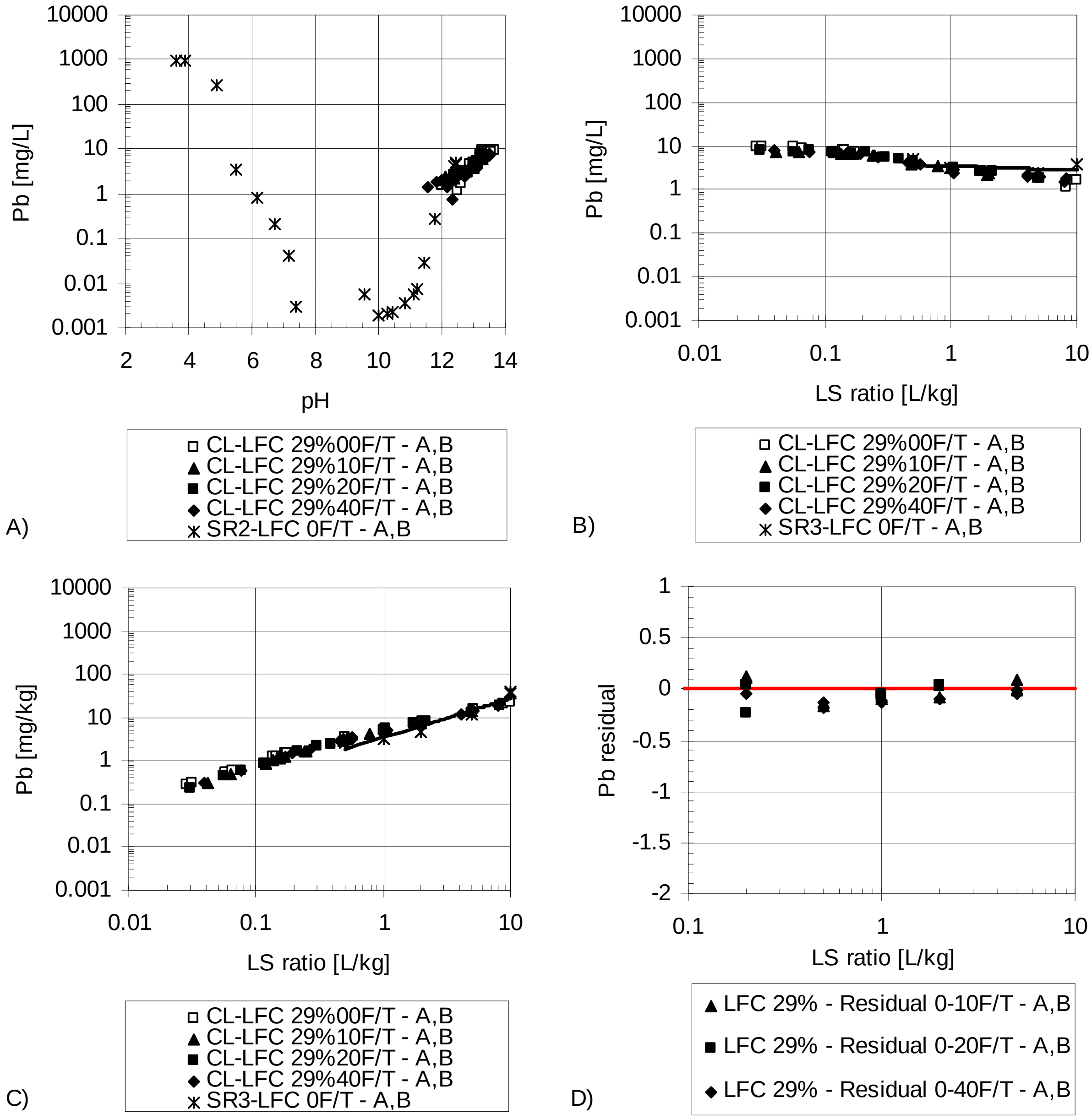


Figure 84. Lead release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.3.5. Zinc release

The effect of F/T exposure on the release of zinc for the LFC material packed at 7%, 15%, and 29% moisture content is presented in Figure 85, Figure 86, and Figure 87, respectively.

The following general observations for zinc were made:

- The greatest effect of F/T exposure on the release of zinc was observed when the LFC material was packed at 7% and 15% moisture content. For the LFC material packed at 15% moisture content, exposure to 10 F/T cycles resulted in an increase in the release of zinc compared to no F/T exposure while exposure to 20 and 40 F/T cycles resulted in a decrease in the release, suggesting material consolidation during F/T exposure. No clear tendency of the effect of F/T exposure could be observed, however, for the LFC material packed at 7% moisture content.
- Zinc concentration in the leachate from column testing was close to the solubility of zinc for all cases.
- Batch testing as a function of LS ratio (SR003 test) was a conservative estimate of column testing.

LFC material packed at 7% moisture content

- Variability in the cumulative release of zinc was observed between the different levels of F/T exposure and within replicates.
- For LS ratios less than 5 L/kg, the cumulative release of zinc from the 20 F/T cycle aged columns was greater (by as much as 3 times) than that from the 0, 10, and 40 F/T cycle aged columns.

LFC material packed at 15% moisture content

- Exposure to 10 F/T cycles resulted in an increase in the release of zinc compared to that obtained from the baseline columns, while exposure to 20 and 40 F/T cycles resulted in a decrease in the release of zinc, as shown by the residual plots.
- At the LS of 2 L/kg, the cumulative release of zinc was ca. 0.32 mg/kg, ca. 0.40 mg/kg, ca. 0.20 mg/kg, and ca. 0.15 mg/kg, for the 0, 10, 20, and 40 F/T cycle aged columns, respectively.

LFC material packed at 29% moisture content (optimum moisture content)

- No effect of F/T exposure on the release of zinc was observed.

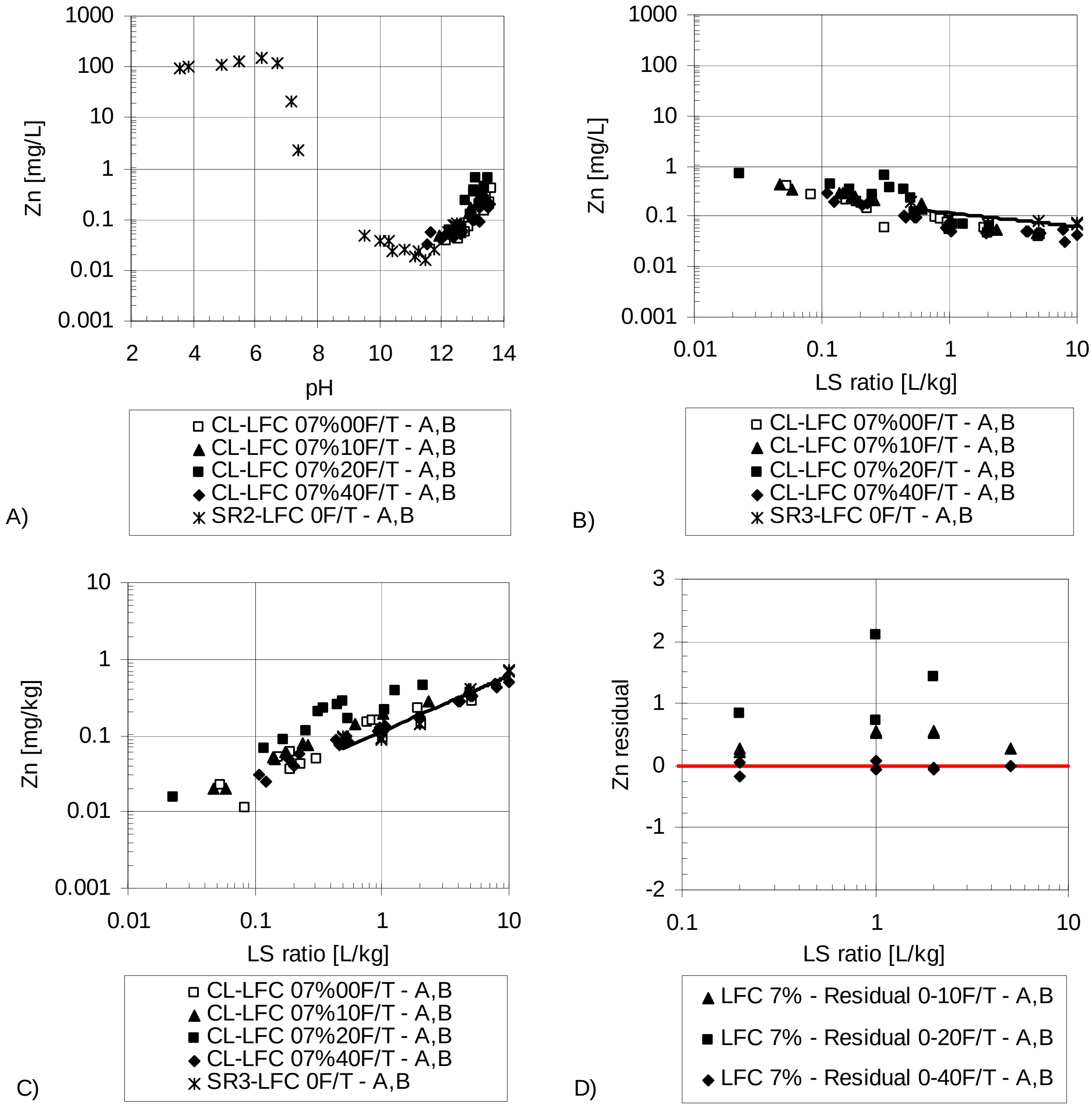


Figure 85. Zinc release from the LFC material packed at 7% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

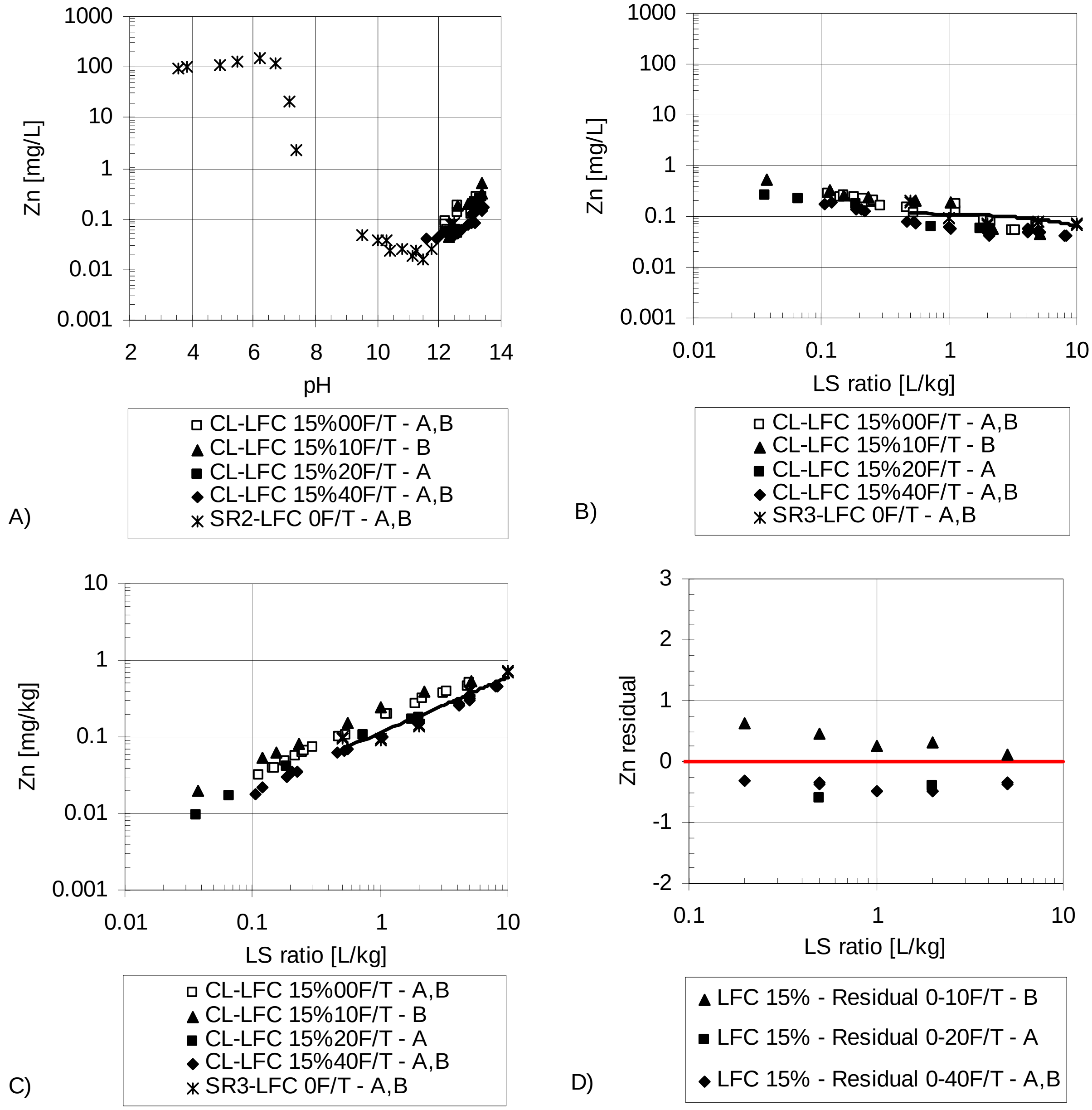


Figure 86. Zinc release from the LFC material packed at 15% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

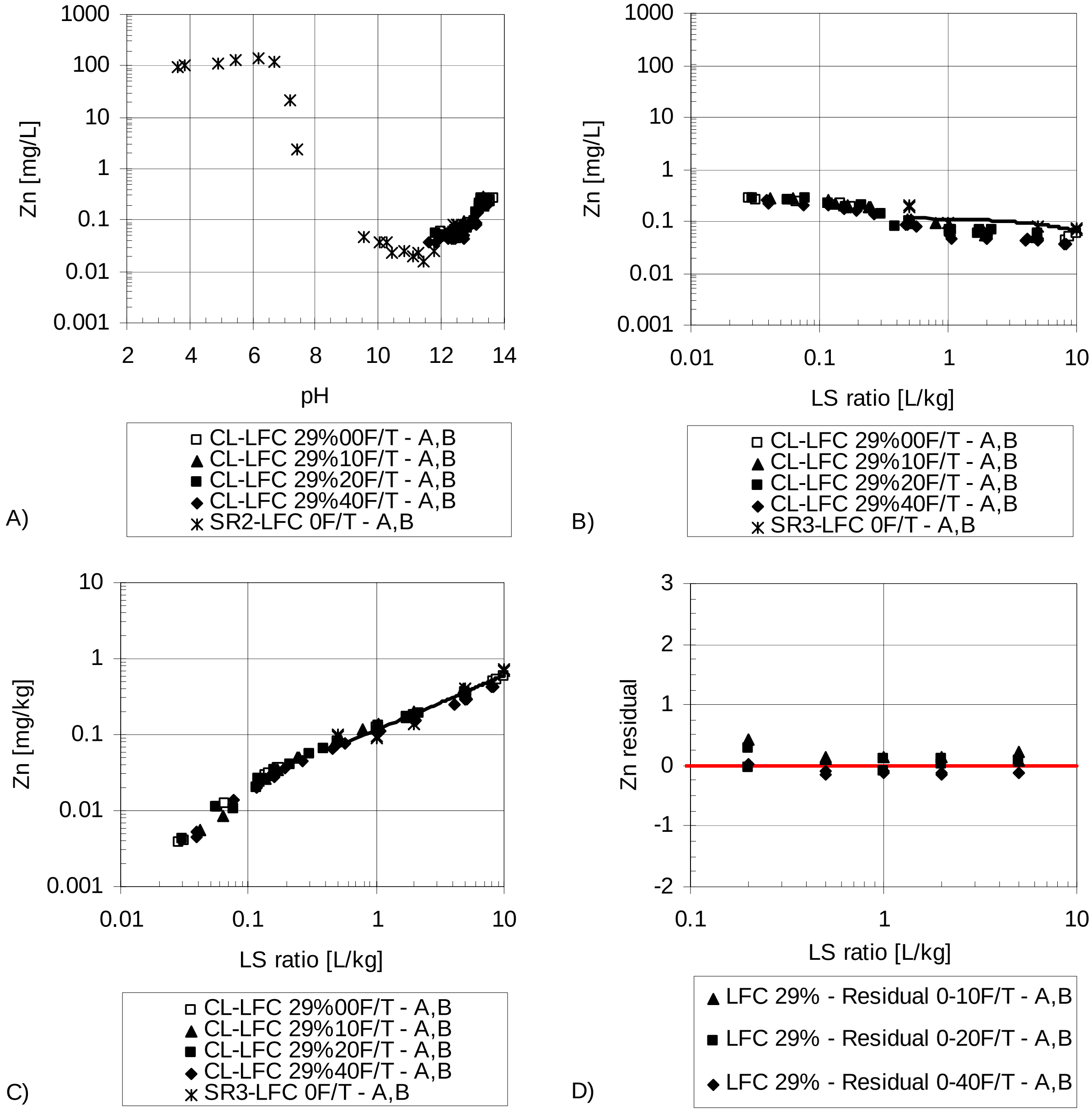


Figure 87. Zinc release from the LFC material packed at 29% moisture content after exposure to 0, 10, 20, and 40 F/T cycles. A) Concentration as a function of pH from column testing compared to batch testing. B) Concentration as a function of LS ratio from column testing compared to batch testing. C) Cumulative release as a function of LS ratio. D) Residuals of the cumulative release as a function of LS ratio as determined relative to no F/T exposure (0 F/T cycles).

4.6.3.6. Conclusions

Exposure to F/T cycles had overall the greatest effect on the leaching of primary contaminants when the LFC material was packed at a moisture content that was lower than that of the optimum moisture content (i.e., 7% and 15%, which represented ca. 24% and 52% of the value of the optimum moisture content).

Overall, as with the major material constituents, as the number of F/T cycles increased, the release of the primary contaminants showed an initial increase generally after exposure to 10 F/T cycles and in some cases after exposure to 20 F/T cycles compared to the no F/T cycles case, followed by a decrease generally after exposure to 20 and 40 F/T cycles. The continued decrease after 40 F/T cycles resulted in a release less than the no F/T exposure cases.

4.6.4. ANOVA analysis

ANOVA analysis was performed on the leachate pH and conductivity and the cumulative release of major material constituents (i.e., sodium, potassium, and calcium) and primary contaminants (arsenic, cadmium, copper, lead, and zinc) obtained at an LS of 2 L/kg. This LS ratio was chosen for ANOVA analysis because it represented the greatest LS ratio common to all samples. Assuming an infiltration rate of 20 cm/year, this LS ratio[4] corresponded to ca. 3 years of continuous infiltration into an RCA layer of 20 cm with a density of 1.4 g/cm^3, while to ca. 30 years for an infiltration rate of 2 cm/year.

A p-value of 0.05 for main and interaction effects was used as a cut-off. This indicates that if the calculated p-value was less than 0.05, the null hypothesis (no difference) was false and a difference was very likely to exist.

ANOVA analysis on leachate pH and conductivity

Moisture content of the packed material and exposure to F/T cycles did not provided any statistically significant difference in leachate pH at a confidence level of 95% (Table 10).
For leachate conductivity, the moisture content of the packed material provided a significant difference at a confidence level of 95% (Table 10). The interactions between moisture content and F/T cycles were statistically significant only for leachate conductivity.

Table 10. ANOVA analysis of main and interaction effects on measured leachate pH and conductivity at LS of 2 L/kg.

Source	p-value		Conclusion
	pH	Conductivity	p-value of 0.05
Moisture content	0.277	**0.008**	Significant: conductivity
F/T cycles	0.299	0.071	Not significant
Moisture content*F/T cycles	0.102	**0.036**	Significant: conductivity

---

[4] For field scenarios, LS is directly a function of time, infiltration rate and material depth according to

$$LS_{site}\,[L/kg] = 10\,[L/cm\text{-}m^2]\,\frac{\inf\,[cm/year]\cdot t_{year}}{\rho[kg/m^3]\cdot H_{fill}[m]}$$

ANOVA analysis on cumulative release of major material constituents

Table 11 shows the calculated p-values of main and interaction effects on the release of sodium, potassium, and calcium at an LS of 2 L/kg. The analysis showed that F/T cycles provided a significant difference in the cumulative release of sodium, potassium, and calcium at a confidence level of 95%. The moisture content of the packed material was not found to be statistically significant. Interactions between moisture content and number of F/T cycles were found to be significant for the release of potassium and calcium but not for the release of sodium.

The main effects plots for sodium, potassium, and calcium release at an LS of 2 L/kg are shown in Figure 88, Figure 89, and Figure 90, respectively. The plots showed that sodium and potassium release (i) decreased slightly when the moisture content of the packed material changed from 7 to 29% and (ii) increased after exposure to 10 F/T cycles and decreased thereafter with increasing number of F/T cycles (20 and 40 F/T cycles), resulting in a lower release of sodium and potassium after exposure to 40 F/T cycles compared to no F/T exposure. For calcium, the main effects plots showed a decrease in the release as the number of F/T cycles increased from 0 to 40 F/T cycles.

For potassium and calcium, change in the release at an LS of 2 L/kg with the number of F/T cycles depended on the moisture content of the packed material at the time of freezing (Figure 91 and Figure 92). The interaction plots showed that interactions between moisture content and number of F/T cycles were greater for the moisture content of 15%.

The boxplot of sodium, potassium, and calcium release at an LS of 2 L/kg (Figure 93) indicated that the release of potassium had the greatest range.

Table 11. ANOVA analysis of main and interaction effects on measured cumulative mass release of sodium, potassium, and calcium at LS of 2 L/kg.

Source	p-value Na	 K	 Ca	Conclusion p-value of 0.05
Moisture content	0.906	0.914	0.161	Not significant
F/T cycles	**0.003**	**0.000**	**0.000**	Significant: Na, K, Ca
Moisture content*F/T cycles	0.073	**0.012**	**0.005**	Significant: K, Ca

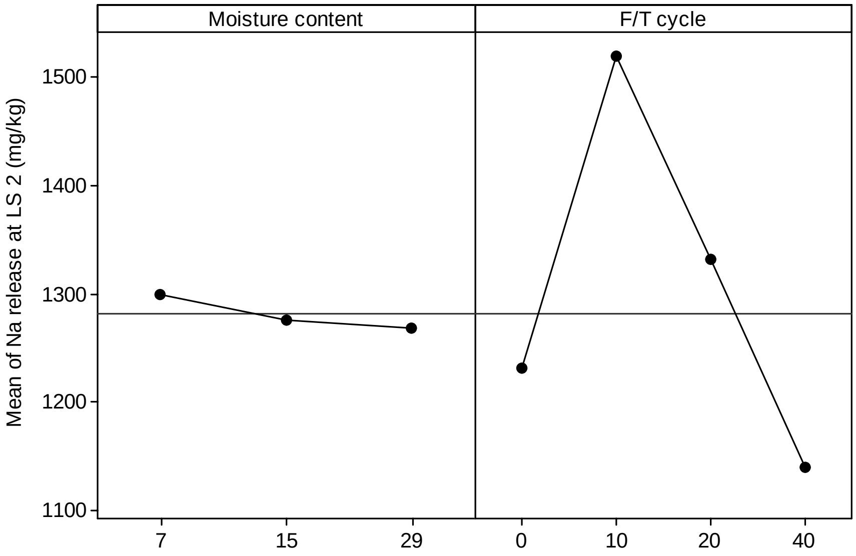


Figure 88. Main effects plots (data means) for sodium release at LS 2 L/kg.

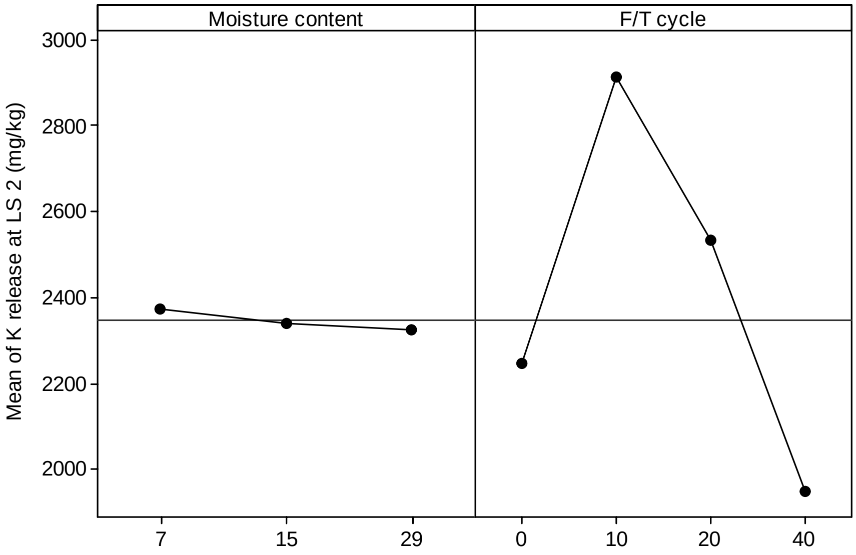


Figure 89. Main effects plots (data means) for potassium release at LS 2 L/kg.

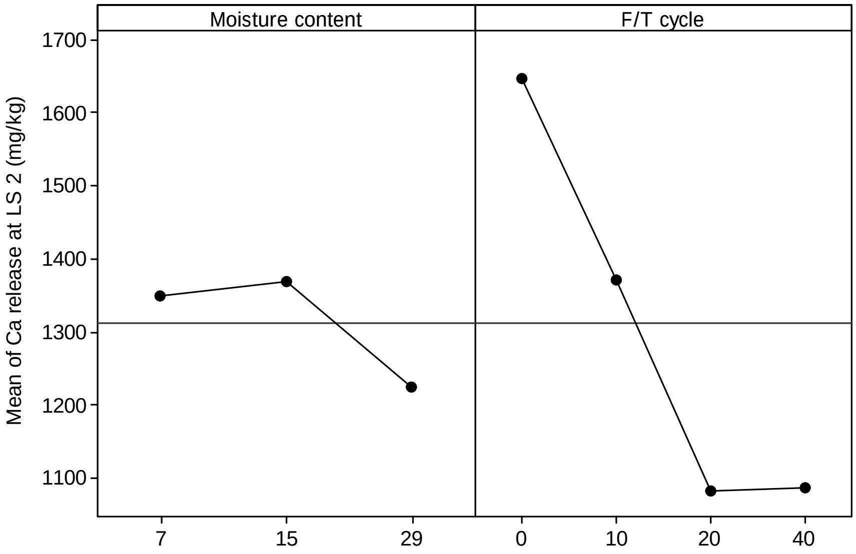


Figure 90. Main effects plots (data means) for calcium release at LS 2 L/kg.

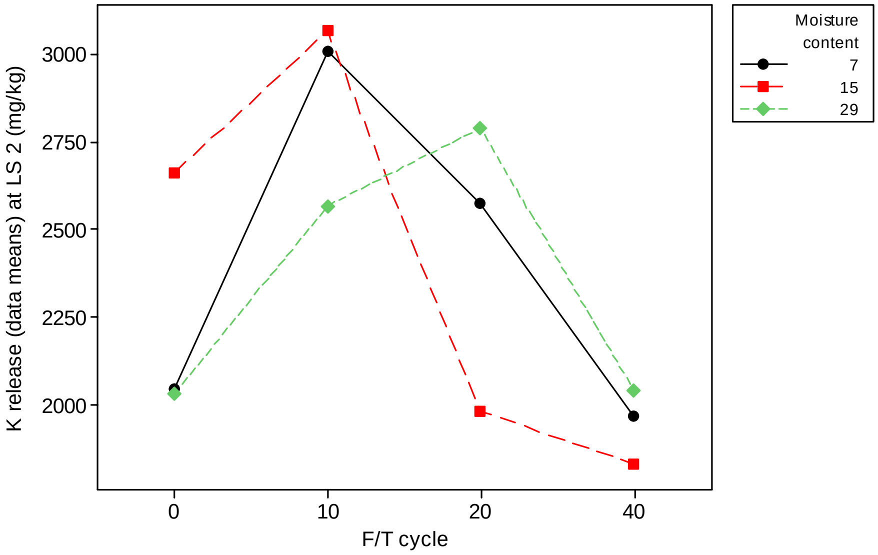


Figure 91. Interaction plots (data means) for potassium release at LS 2 L/kg.

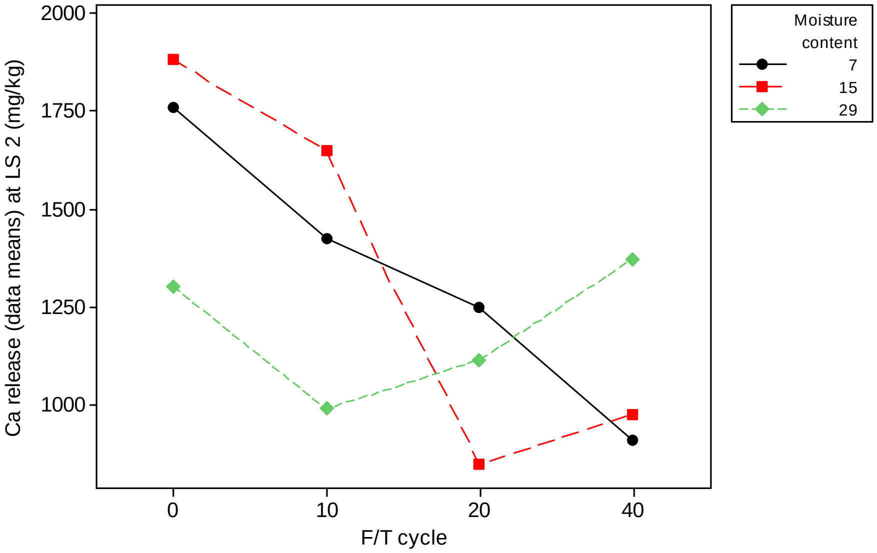


Figure 92. Interaction plots (data means) for calcium release at LS 2 L/kg.

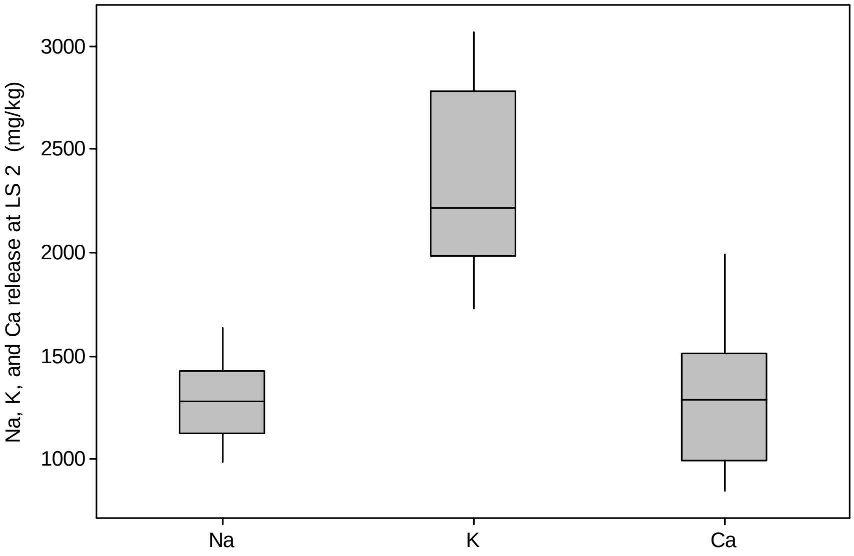


Figure 93. Boxplot of the cumulative release of sodium, potassium, and calcium at LS of 2 L/kg.

ANOVA analysis on cumulative release of primary contaminants

Table 12 shows the calculated p-values of main and interaction effects on the release of arsenic, cadmium, copper, lead, and zinc at an LS of 2 L/kg. The analysis showed that F/T cycles provided a significant difference in the cumulative release of arsenic, copper, and zinc at a confidence level of 95%. Exposure to F/T cycles was not found to be significant for cadmium and lead. The moisture content of the packed material provided a significant difference in the cumulative release of arsenic and zinc at a confidence level of 95%. However, the moisture content was not found to be significant for the release of cadmium, copper, and lead. Interactions between moisture content and number of F/T cycles were found to be significant for the release of arsenic, copper, lead, and zinc, but not for the release of cadmium.

The main effects plots for arsenic, copper, and zinc release at an LS of 2 L/kg are shown in Figure 94, Figure 95, and Figure 96, respectively. The plots showed that arsenic release was significantly greater after exposure to 10 F/T cycles compared to no F/T exposure while it was the same as the no F/T exposure after 20 and 40 F/T cycles. The plots also showed that greater arsenic release was obtained when the material was packed at a moisture content of 15%. For copper, the main effects plots showed an increase in the release as the number of F/T cycles increased from 0 to 20 F/T cycles followed by a significant decreased after exposure to 40 F/T cycles, resulting in a much lower release of copper compared to the no F/T exposure case. For zinc, the main effects plots showed that the release increased after exposure to 10 F/T cycles compared to no F/T exposure and decreased thereafter with increasing number of F/T cycles (20 and 40 F/T cycles), resulting in a lower release of after exposure to 40 F/T cycles compared to no F/T exposure.

For arsenic, copper, lead, and zinc, changes in the release at an LS of 2 L/kg with the number of F/T cycles depended on the moisture content of the packed material at the time of freezing (Figure 97, Figure 98, Figure 99, and Figure 100). The interaction plots indicated that interactions between moisture content and number of F/T cycles were more significant for arsenic when the material was packed at 15% moisture content and for copper and zinc when the material was packed at 7% and 15% moisture content.

The boxplot of arsenic, cadmium, copper, lead, and zinc release at an LS of 2 L/kg (Figure 101) indicated the presence of outliers (values between 1.5 and 3 times away from the middle 50% of the data are outliers) for arsenic, copper, and lead.

Table 12. ANOVA analysis of main and interaction effects on measured cumulative mass release of arsenic, cadmium, copper, lead, and zinc at LS of 2 L/kg.

Source	p-value					Conclusion
	As	Cd	Cu	Pb	Zn	p-value of 0.05
Moisture content	**0.000**	0.360	0.081	0.440	**0.001**	Significant: As, Zn
F/T cycles	**0.000**	0.805	**0.001**	0.068	**0.000**	Significant: As, Cu, Zn
Moisture content*F/T cycles	**0.000**	0.345	**0.009**	**0.029**	**0.000**	Significant: As, Cu, Pb, Zn

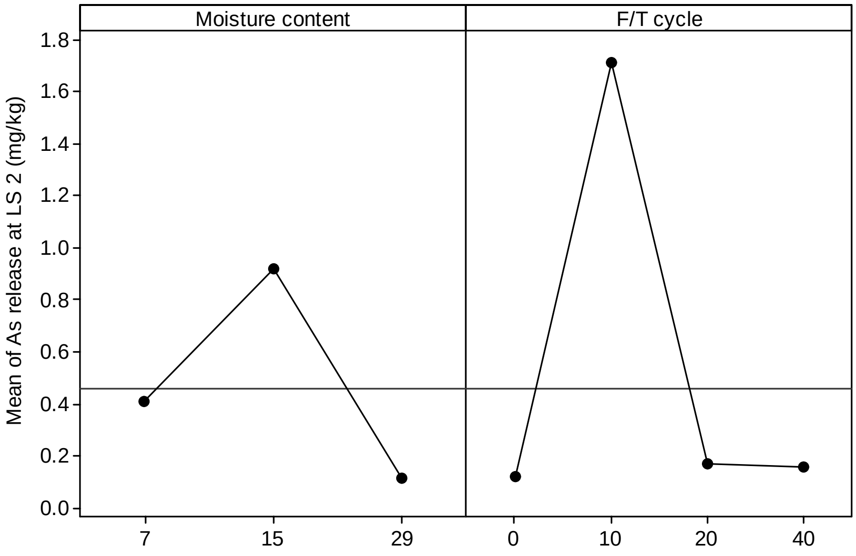


Figure 94. Main effects plots (data means) for arsenic release at LS 2 L/kg.

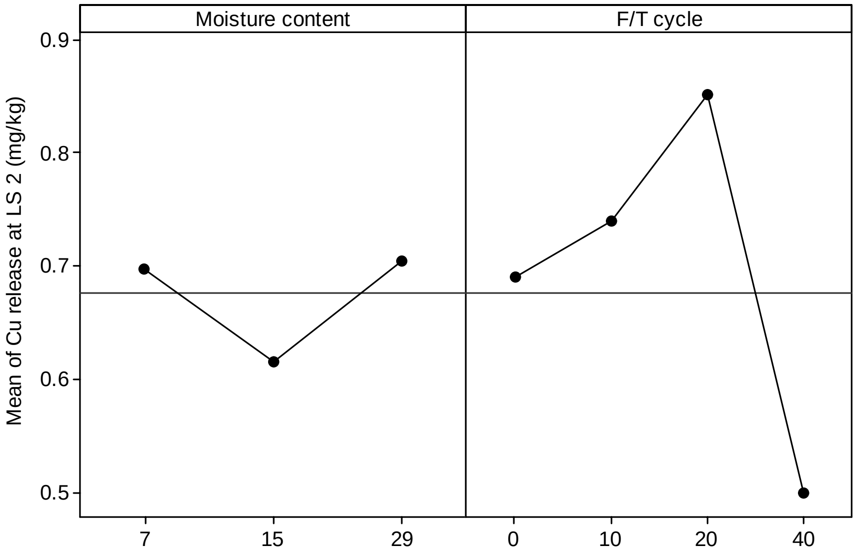


Figure 95. Main effects plots (data means) for copper release at LS 2 L/kg.

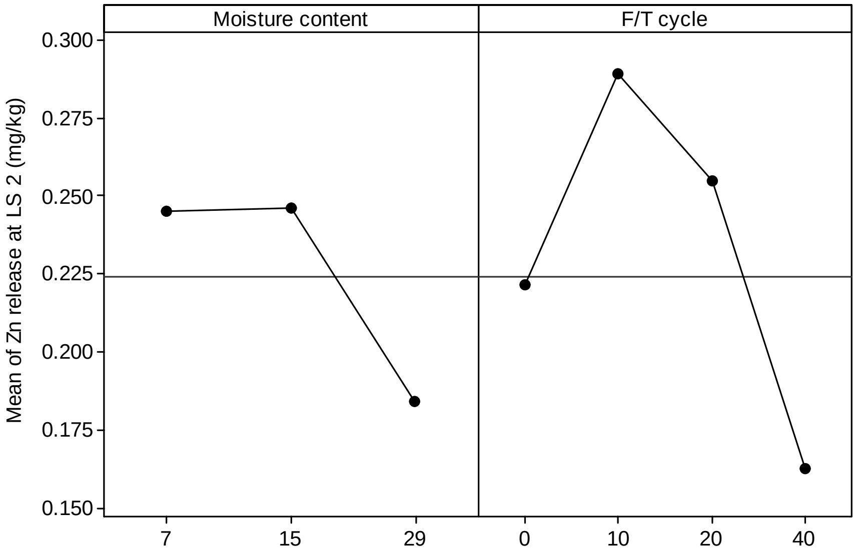


Figure 96. Main effects plots (data means) for zinc release at LS 2 L/kg.

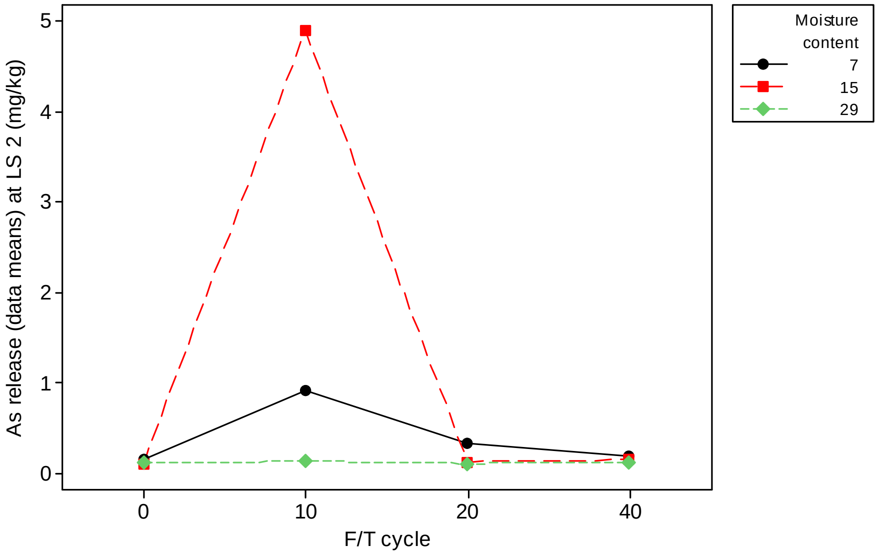


Figure 97. Interaction plots (data means) for arsenic release at LS 2 L/kg.

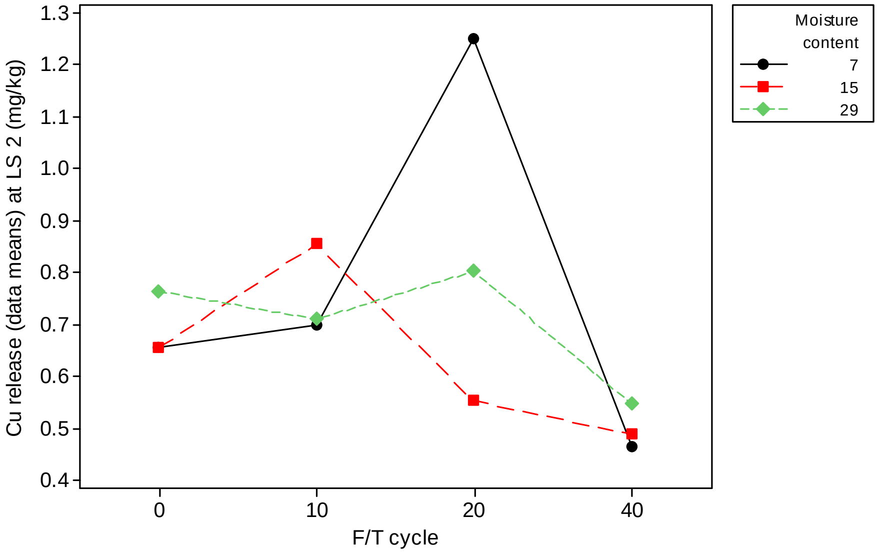


Figure 98. Interaction plots (data means) for copper release at LS 2 L/kg.

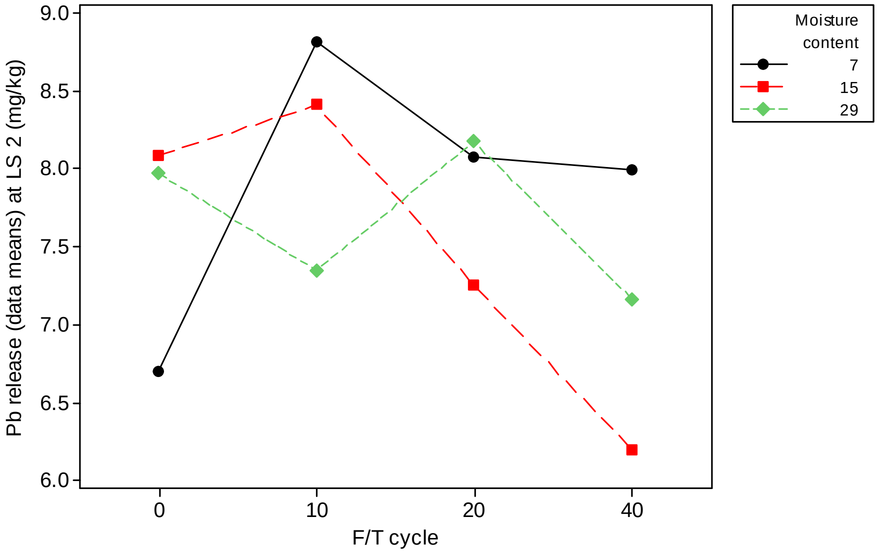


Figure 99. Interaction plots (data means) for lead release at LS 2 L/kg.

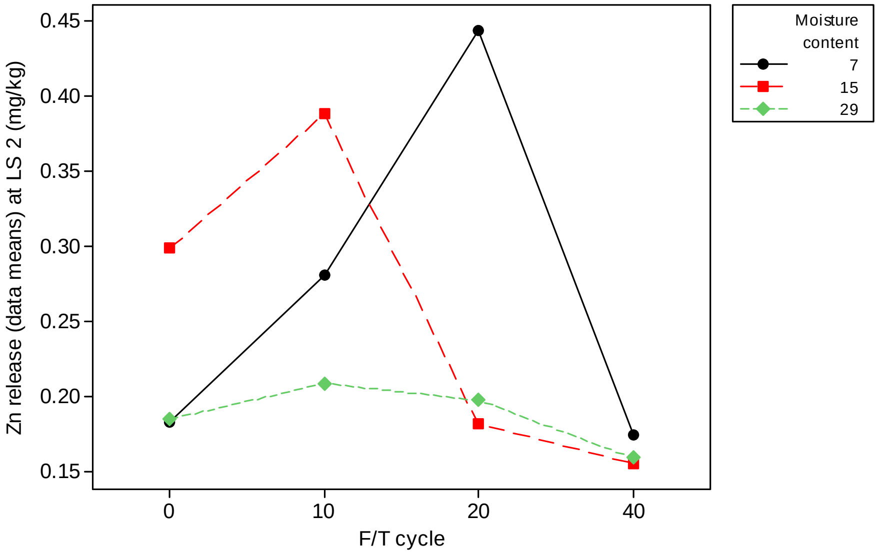


Figure 100. Interaction plots (data means) for zinc release at LS 2 L/kg.

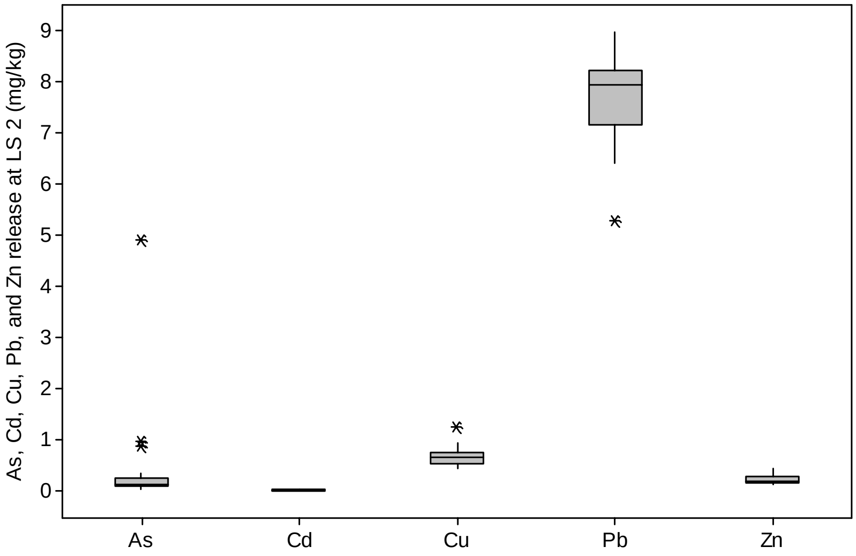


Figure 101. Boxplot of the cumulative release of arsenic, cadmium, copper, lead, and zinc at LS of 2 L/kg.

4.7. CONSTITUENT LEACHING DURING INTERMITTENT WETTING/FLOW-THROUGH COUPLED WITH F/T EXPOSURE

4.7.1. Intermittent wetting (flow-around) coupled with F/T exposure

The following presents results of the effect of tank leaching interspersed with periods of F/T exposure on (i) leachate pH and conductivity, (ii) cumulative release and flux of major material constituents (sodium, potassium, and calcium), and (iii) cumulative release and flux of primary contaminants (arsenic, cadmium, copper, lead, and zinc) for the less than 9.5 mm graded LFC material. The impact of intermittent F/T was illustrated through comparison of constituent cumulative release and flux under intermittent wetting conditions to cumulative release and flux under continuously water-saturated conditions.

Leachate pH and conductivity are presented in Figure 102 as a function of cumulative leaching time (i.e., ignoring non-leaching intervals). No significant effect of intermittent wetting coupled with F/T exposure was observed on leachate pH and conductivity.

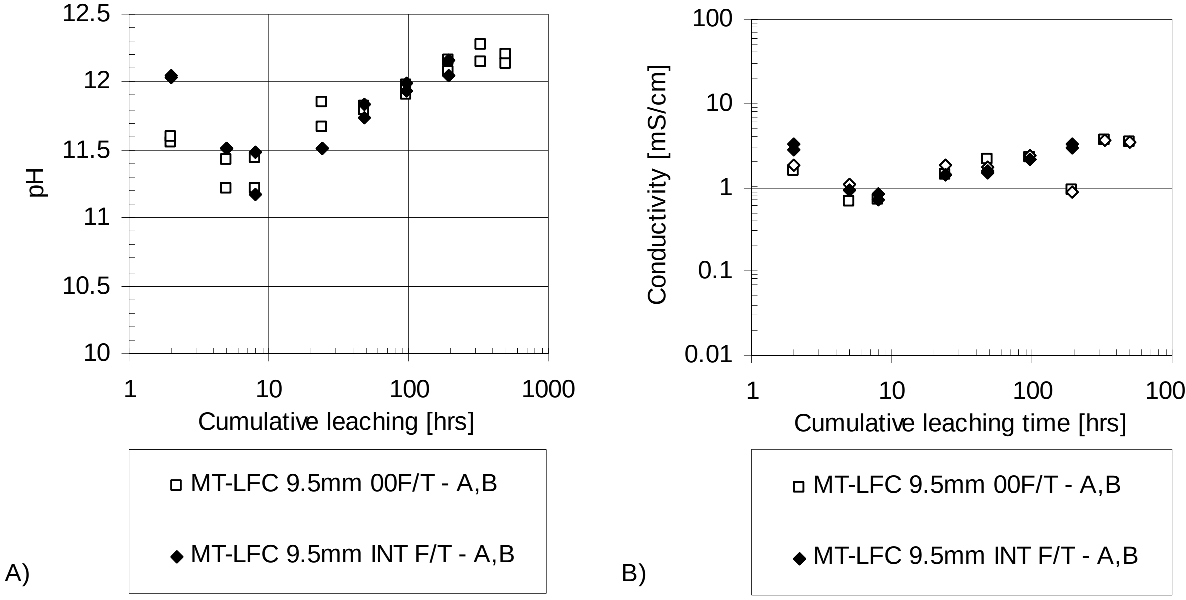


Figure 102. Effect of intermittent wetting (flow-around) coupled with F/T exposure on A) leachate pH and B) leachate conductivity of the less than 9.5 mm graded LFC material.

Although intervals of F/T exposure reduced for most cases the cumulative release of species when compared to the same time interval of continuous leaching without F/T exposure, the influence of intermittent F/T exposure is apparent when equivalent periods of leaching are compared. Therefore, cumulative release of the species of concern is presented as a function of cumulative leaching time (i.e., ignoring non-leaching intervals). However, release fluxes are reported as a function of the overall cumulative time including leaching and F/T exposure times. For the intermittent case, it is assumed that the influx of water during subsequent leaching intervals was relatively rapid and thus insignificant to the overall release process.

In contrast to F/T exposure prior to continuous leaching (see section 4.4), intermittent leaching interspersed with F/T exposure did not have, overall, a significant effect on constituent leaching.

However, the total time of F/T exposure (the longest F/T exposure was 4 F/T cycles between the leaching intervals) was less than that used for F/T exposure prior to continuous leaching (10 and 20 F/T cycles).

The following general observations for the release of the major material constituents were made:

- No significant effect of intermittent wetting coupled with F/T exposure was observed on the release of sodium, potassium, and calcium (Figure 103, Figure 104, and Figure 105, respectively).
- Poor replication was observed on the release flux of calcium during the initial 3 intervals for both leaching conditions (intermittent and continuous).

The following general observations for the release of the primary material contaminants were made:

- A greater release of arsenic (as much as 3 times after 200 hours of leaching) was observed during intermittent leaching coupled with F/T exposure compared to continuous leaching under water saturated conditions (Figure 106). This behavior was in contrast with that observed when the material was subjected to F/T cycles prior to leaching instead of interspersed with leaching and to the visual observation of overall material consolidation. Poor replication in the release of arsenic was obtained, however, for both leaching conditions (intermittent and continuous).
- A lower release of cadmium (as much as 2.5 times after 200 hours of leaching) was observed during intermittent leaching coupled with F/T exposure compared to continuous leaching under water saturated conditions (Figure 107). Poor replication in the release of cadmium was obtained, however, for both leaching conditions (intermittent and continuous).
- Intermittent leaching interspersed with F/T exposure did not have a significant effect on the release of copper, lead, and zinc (Figure 108, Figure 109, and Figure 110, respectively). Poor reproducibility was observed for the release of zinc from the baseline samples (no F/T exposure).

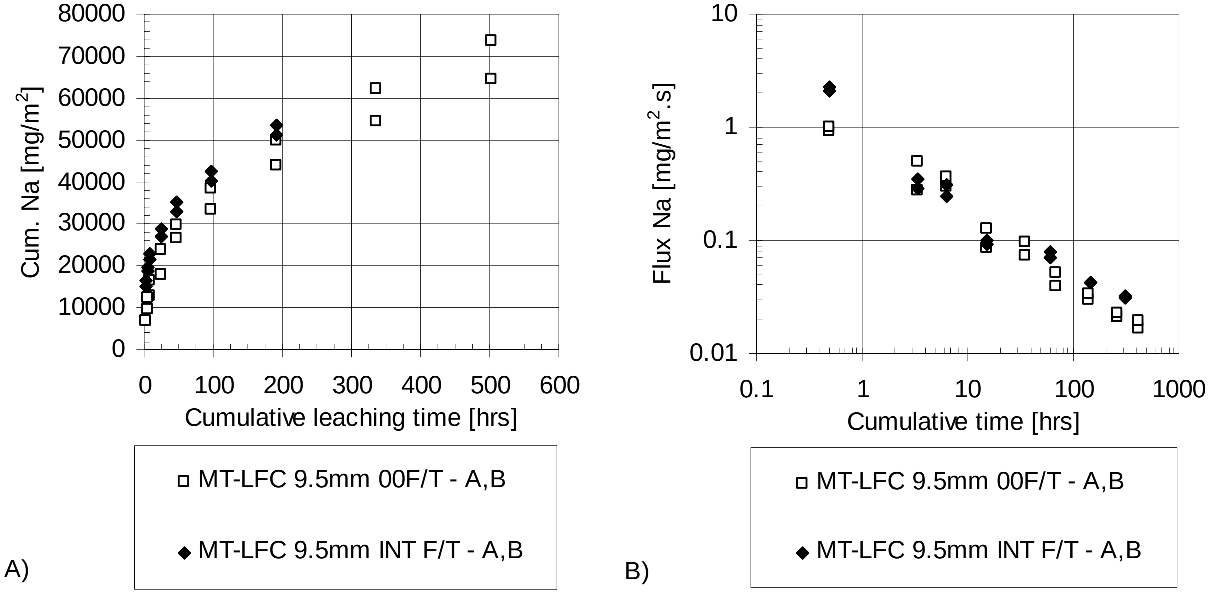


Figure 103. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of sodium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

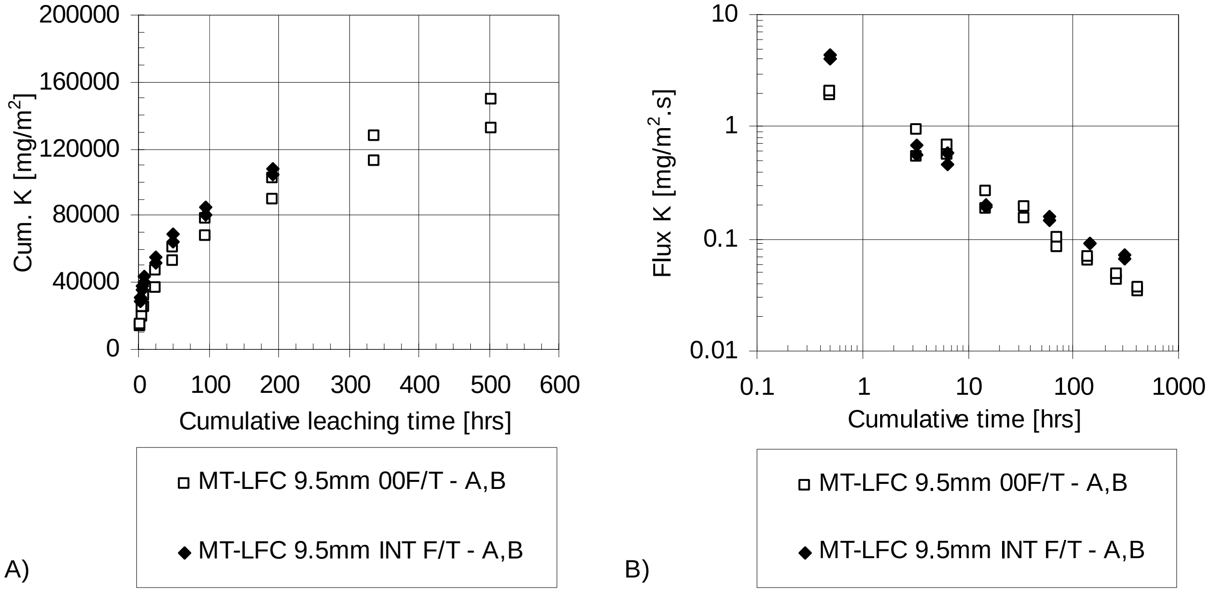


Figure 104. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of potassium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

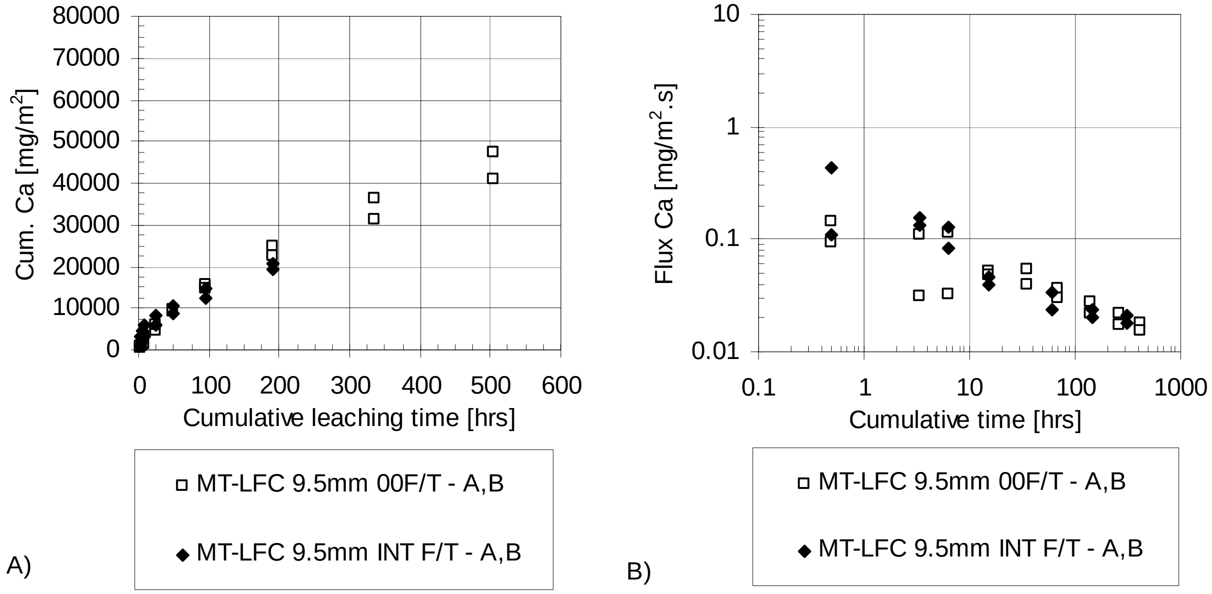


Figure 105. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of calcium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

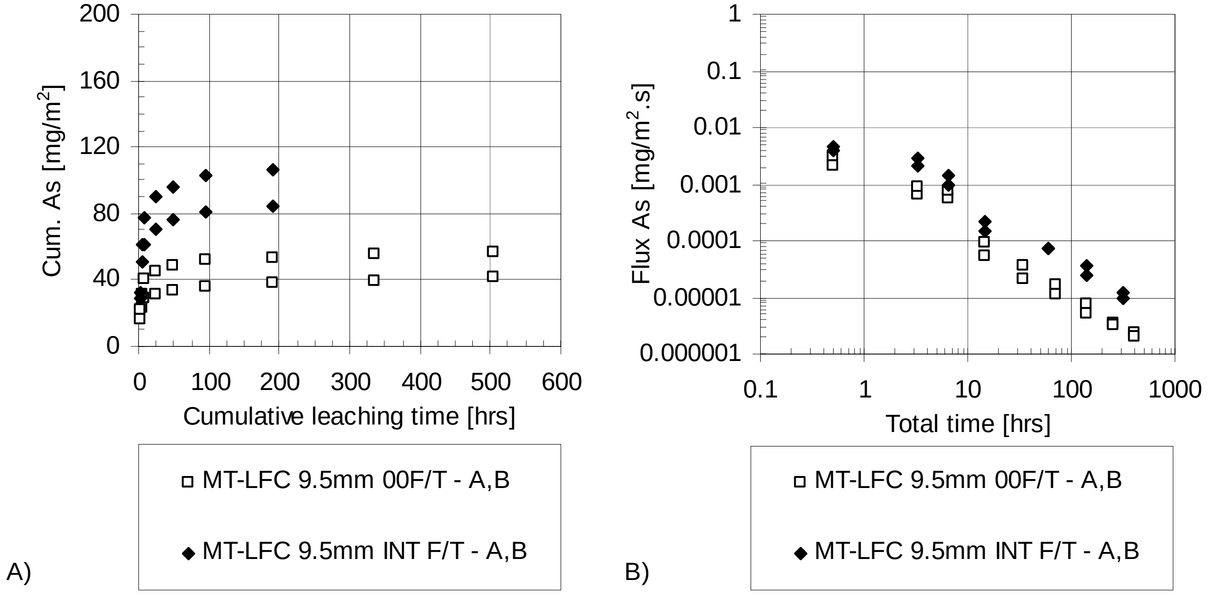


Figure 106. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of arsenic for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

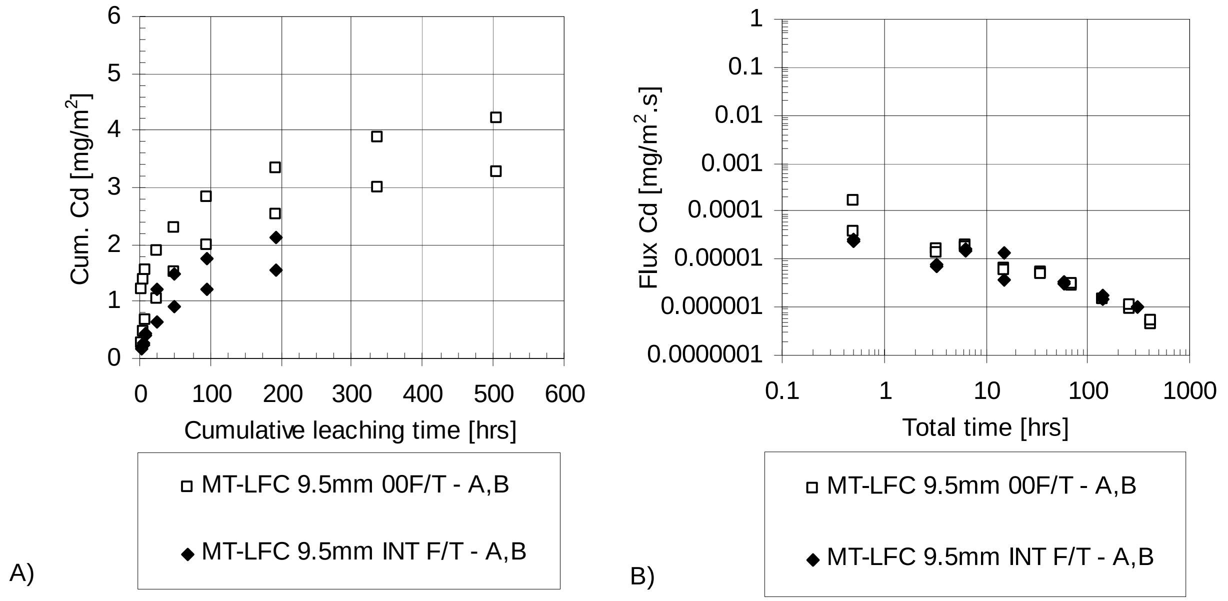


Figure 107. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of cadmium for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

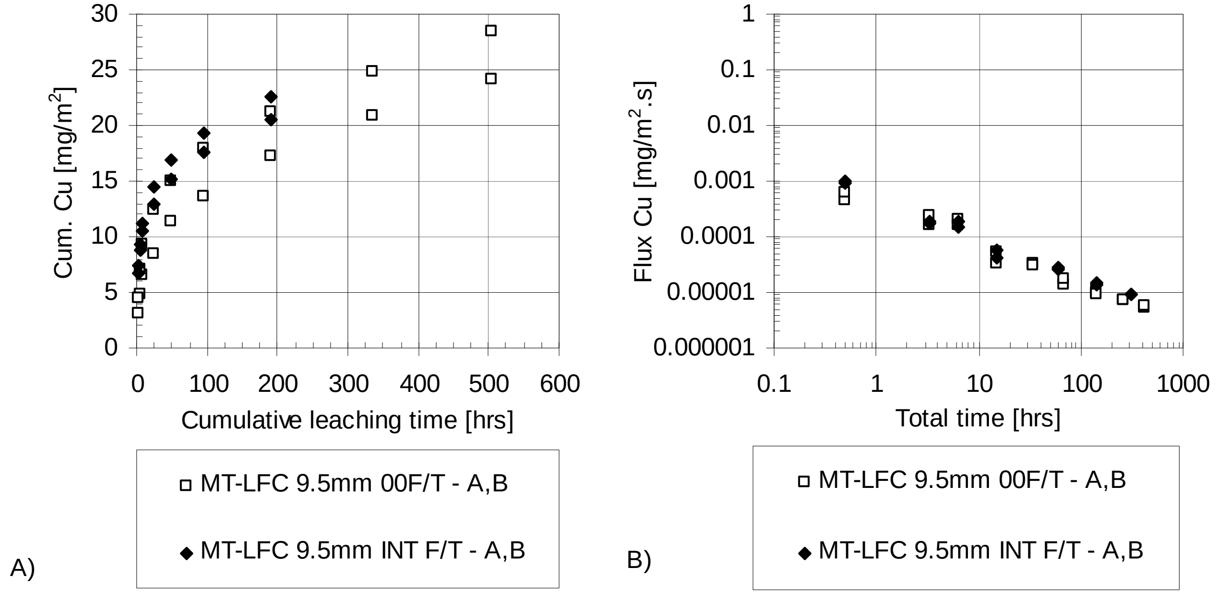


Figure 108. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of copper for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

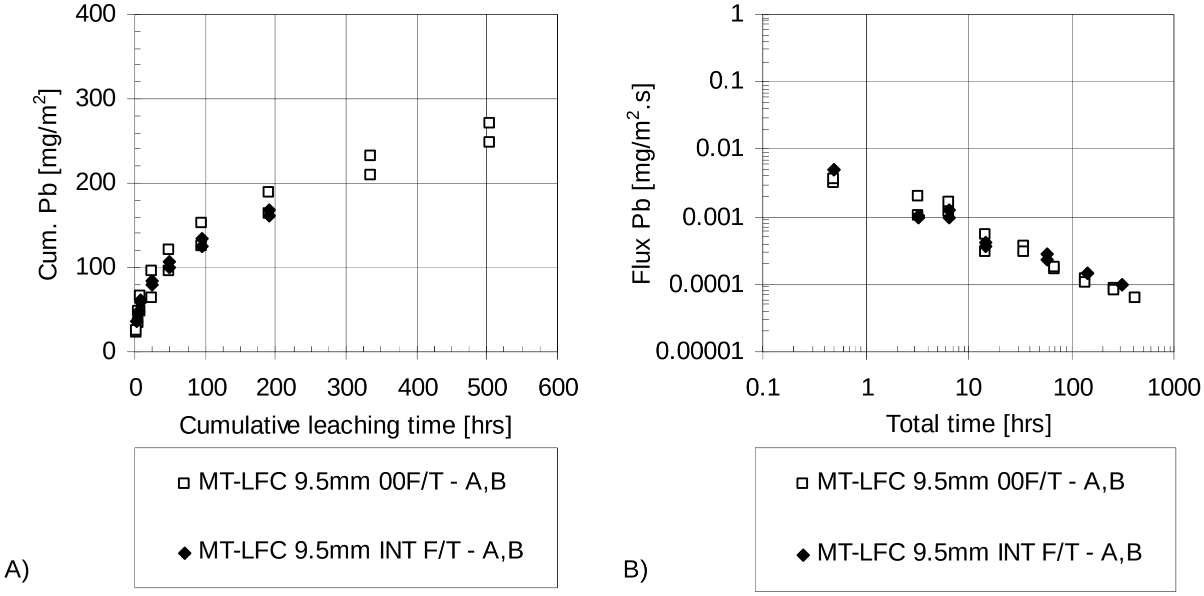


Figure 109. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of lead for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

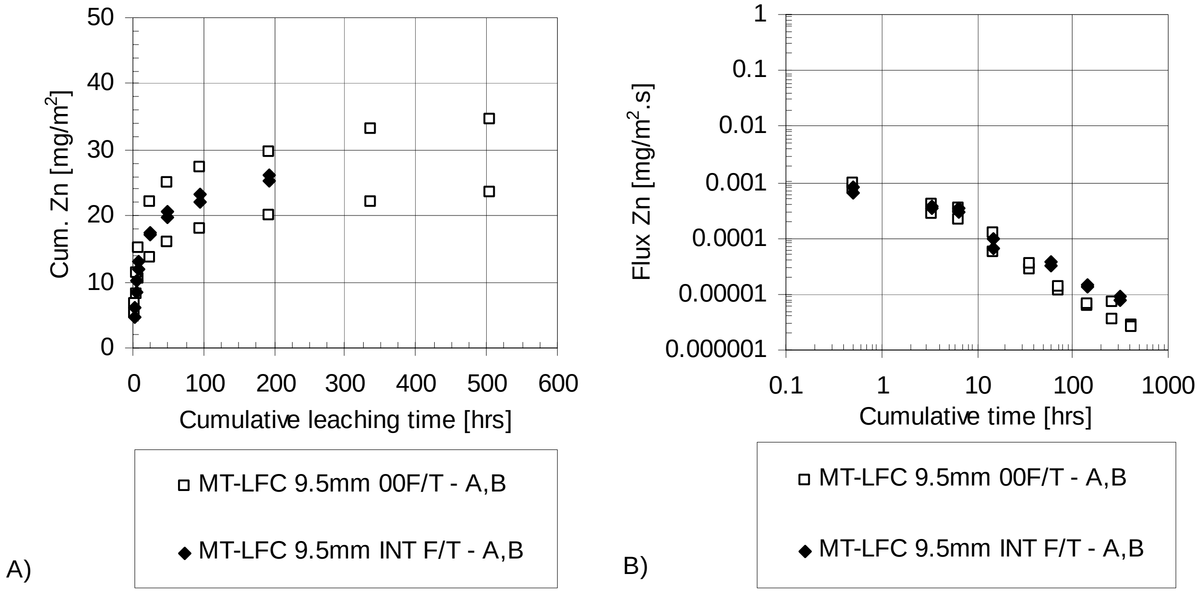


Figure 110. Effect of intermittent wetting (flow-around) coupled with F/T exposure on the release of zinc for the less than 9.5 mm graded LFC material. A) Cumulative release as a function of cumulative leaching time. B) Flux as a function of total time.

4.7.2. Intermittent flow-through coupled with F/T exposure

The following presents results of the effect of flow-through (saturated columns) interspersed with F/T exposure on (i) leachate pH and conductivity, (ii) release of major material constituents (i.e., sodium, potassium, and calcium), and (iii) release of primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) of the LFC material packed at the optimum moisture content (i.e., 29%). The impact of intermittent F/T exposure was illustrated through comparison of constituent cumulative release under intermittent saturated flow-through conditions to cumulative release under continuous saturated flow-through conditions. The cumulative release of the species of concern is presented as a function of LS ratio.

Intermittent flow-though coupled with F/T exposure resulted in lower leachate pH (by as much as 0.5 pH units), as shown in Figure 111A. The difference in leachate pH increased as the LS ratio and the number of alternating F/T exposure increased. No significant effect on the leachate conductivity, however, was observed (Figure 111B).

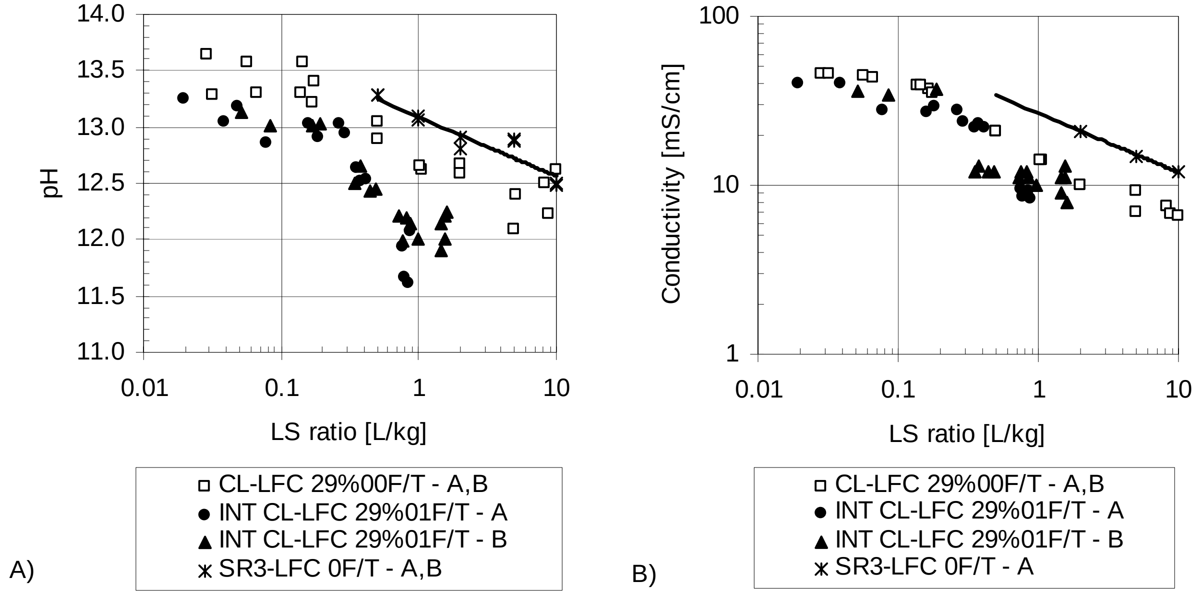


Figure 111. Effect of intermittent flow-through coupled with F/T exposure on A) leachate pH and B) leachate conductivity of the LFC material packed at 29% moisture content (optimum moisture content).

Intermittent flow-through coupled with F/T exposure resulted in a lower cumulative release of sodium and potassium than that obtained under continuous flow conditions (as much as 2.5 and 2 times, respectively at the LS of 1 L/kg), as shown in Figure 112A and Figure 112B. The difference in the release increased as the LS ratio and the number of alternating F/T exposure increased. However, no significant effect of intermittent flow-through coupled with F/T exposure was observed on the release of calcium (Figure 112C).

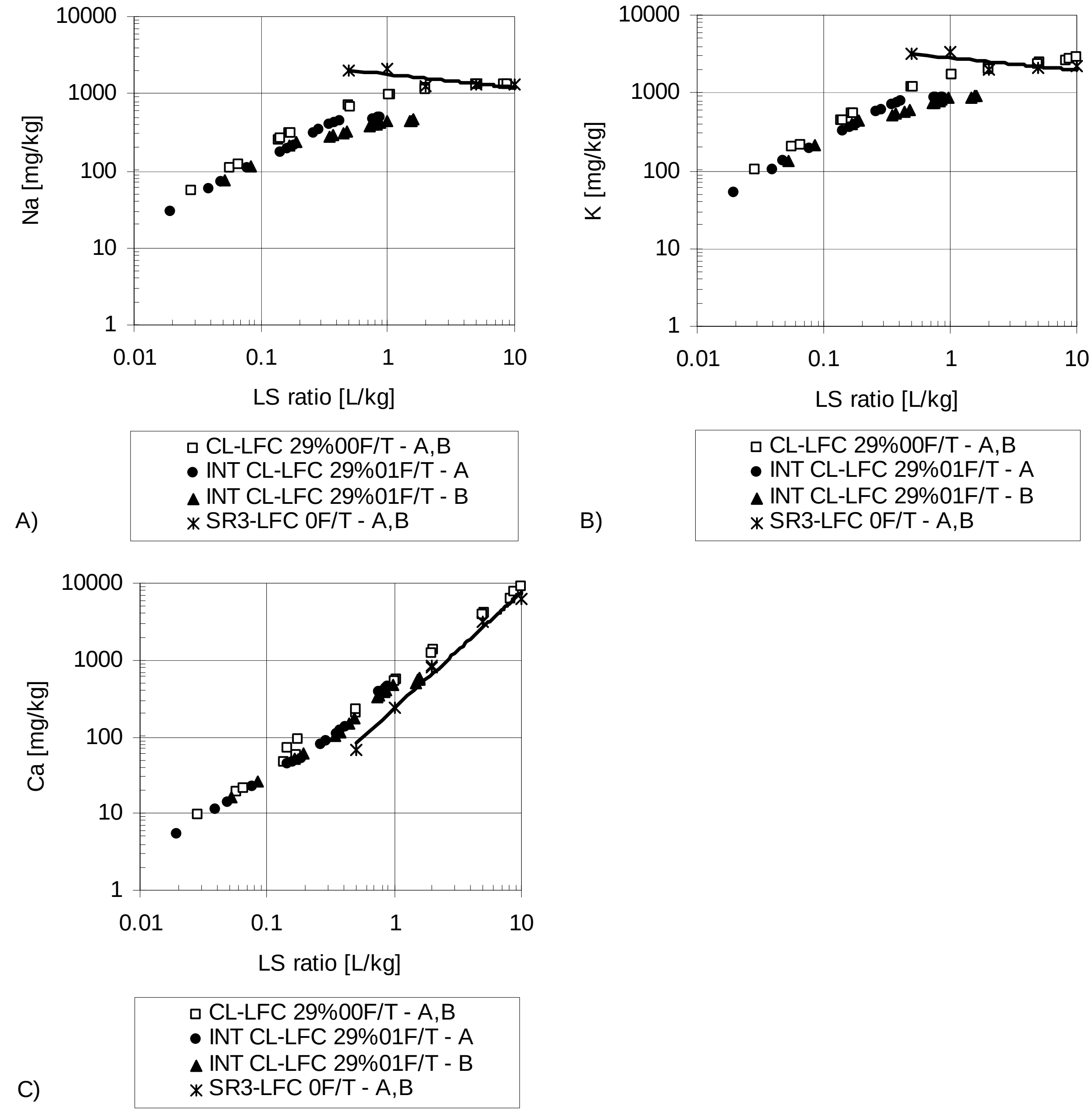
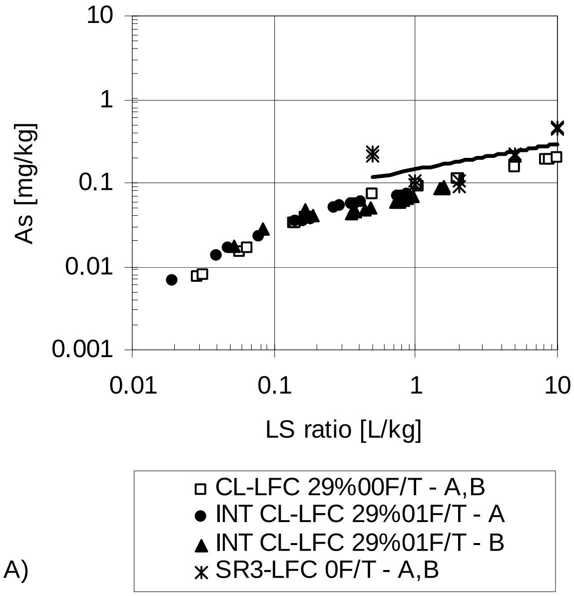


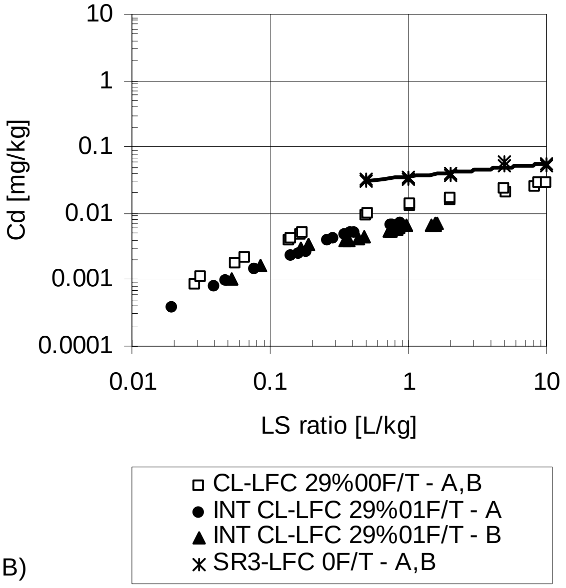
Figure 112. Effect of flow-through coupled with F/T exposure on the cumulative release of major material constituents for the LFC material packed at 29% moisture content (optimum moisture content). A) Cumulative release of sodium. B) Cumulative release of potassium. C) Cumulative release of calcium.

Overall, a lower cumulative release of cadmium (Figure 113B) and copper (Figure 113C) was obtained from the intermittent saturated flow columns coupled with F/T exposure compared to that obtained from the continuous saturated flow columns (by as much as 2.5 and 3 times, respectively, at the LS ratio of 1 L/kg). However, the initial release prior to F/T exposure was already slightly lower for these columns. No significant effect of intermittent flow coupled with

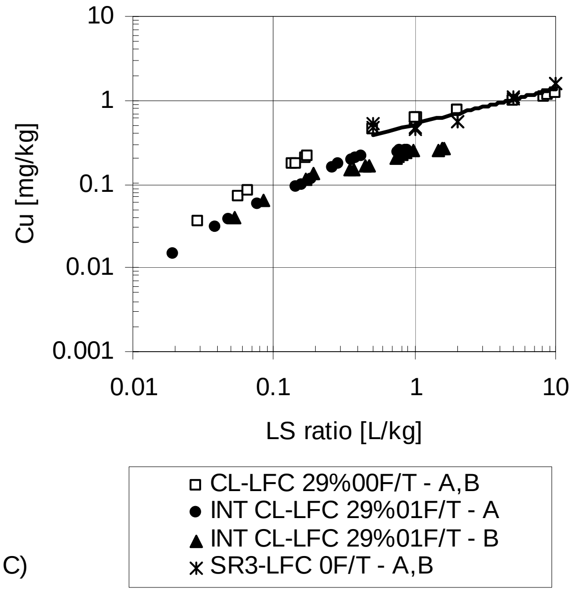
F/T exposure was observed for arsenic, lead, or zinc (Figure 113A, Figure 113D, and Figure 113E).



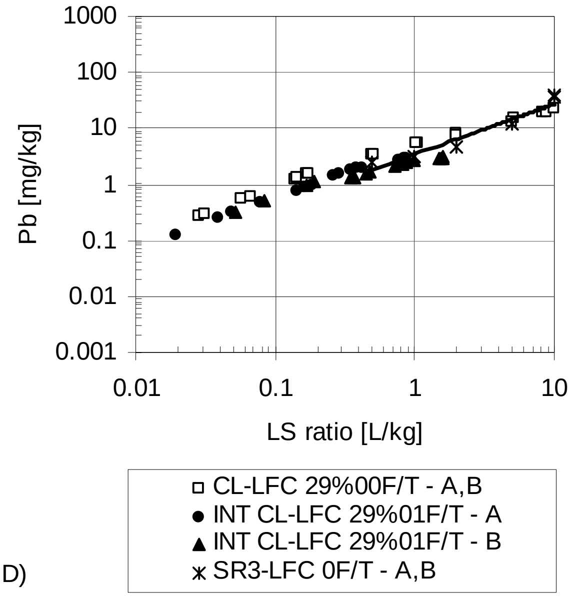
A)



B)



C)



D)

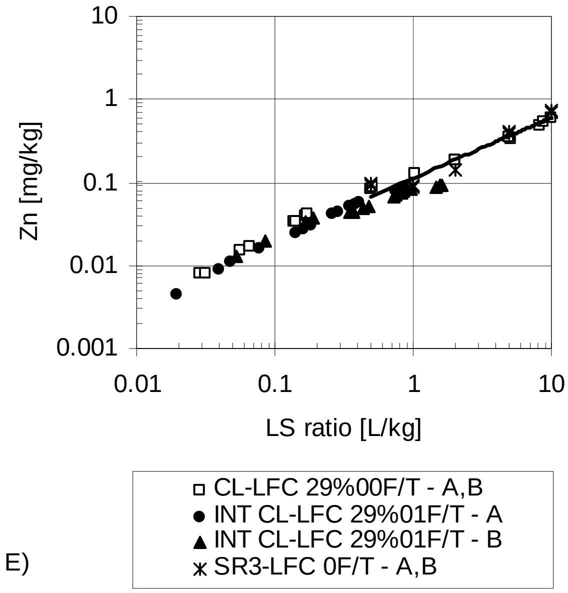


Figure 113. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of primary contaminants for the LFC material packed at 29% moisture content (optimum moisture content). A) Cumulative release of arsenic. B) Cumulative release of cadmium. C) Cumulative release of copper. D) Cumulative release of lead. E) Cumulative release of zinc.

Intermittent saturated flow-through conditions coupled with F/T cycles resulted in similar or slightly lower release of major material constituents and primary contaminants than that obtained for the continuous saturated flow-through cases. In comparison with columns packed at the optimum moisture content subjected to F/T exposure prior to leaching, intermittent flow-through columns coupled with F/T cycles showed, however, for most cases, a greater effect on constituent leaching. However, only 3 periods of exposure to 1 F/T cycle were performed during intermittent saturated flow-though conditions coupled with F/T cycles, which was significantly fewer than that used for F/T exposure prior to continuous leaching (10, 20, and 40 F/T cycles). Additionally, the optimum content was the moisture content for which the least effect of F/T exposure was observed when F/T exposure was performed prior to leaching.

4.8. INITIAL METHOD VALIDATION ON CONSTRUCTION DEMOLITION-DEBRIS

Intermittent flow-through coupled with F/T exposure was used to evaluate the performance of a C&D material. The following presents results of the initial method validation on (i) leachate pH and conductivity, (ii) release of major material constituents (i.e., sodium, potassium, and calcium), and (iii) release of primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) of the C&D material packed at the optimum moisture content. The impact of intermittent F/T exposure was illustrated through comparison of constituent cumulative release from the C&D material under intermittent flow-through conditions to cumulative release from the LFC material under similar conditions and continuous flow-through conditions. The cumulative release of the species of concern is presented as a function of LS ratio.

Overall, similar behaviors of major material constituents and primary contaminants as those obtained from the LFC material were observed for the C&D material under intermittent flow-through conditions.

No significant difference in the release of sodium, potassium, and calcium was observed between the C&D material and the LFC material under intermittent flow-through conditions (Figure 114). At the LS ratio of 1.4 L/kg (corresponding to leaching interspersed with 3 periods of exposure to one F/T cycle), ca. 795 mg/kg, ca. 885 mg/kg (15%), and ca. 615 mg/kg (0.4%) of sodium, potassium, and calcium were released, respectively from the C&D material.

Similarly, no significant difference in the release of cadmium, copper, lead, and zinc was observed between the C&D material and the LFC material under intermittent flow-through conditions (Figure 115). At the LS ratio of 1.4 L/kg (corresponding to leaching interspersed with 3 periods of exposure to one F/T cycle), ca. 0.009 mg/kg, ca. 0.3 mg/kg (0.5%), ca. 3.4 mg/kg, and ca. 0.16 mg/kg (0.2 %), of cadmium, copper, lead, and zinc were released respectively from the C&D material. A greater release of arsenic was observed, however, for the C&D material compared to the LFC material under similar conditions (as much as 60% at the LS ratio of 1.4 L/kg) although the C&D material had a much lower arsenic total content than the LFC material (47 mg/kg and 3225.8 mg/kg, respectively).

These initial results indicated that the LFC material represented a good model system for the C&D material.

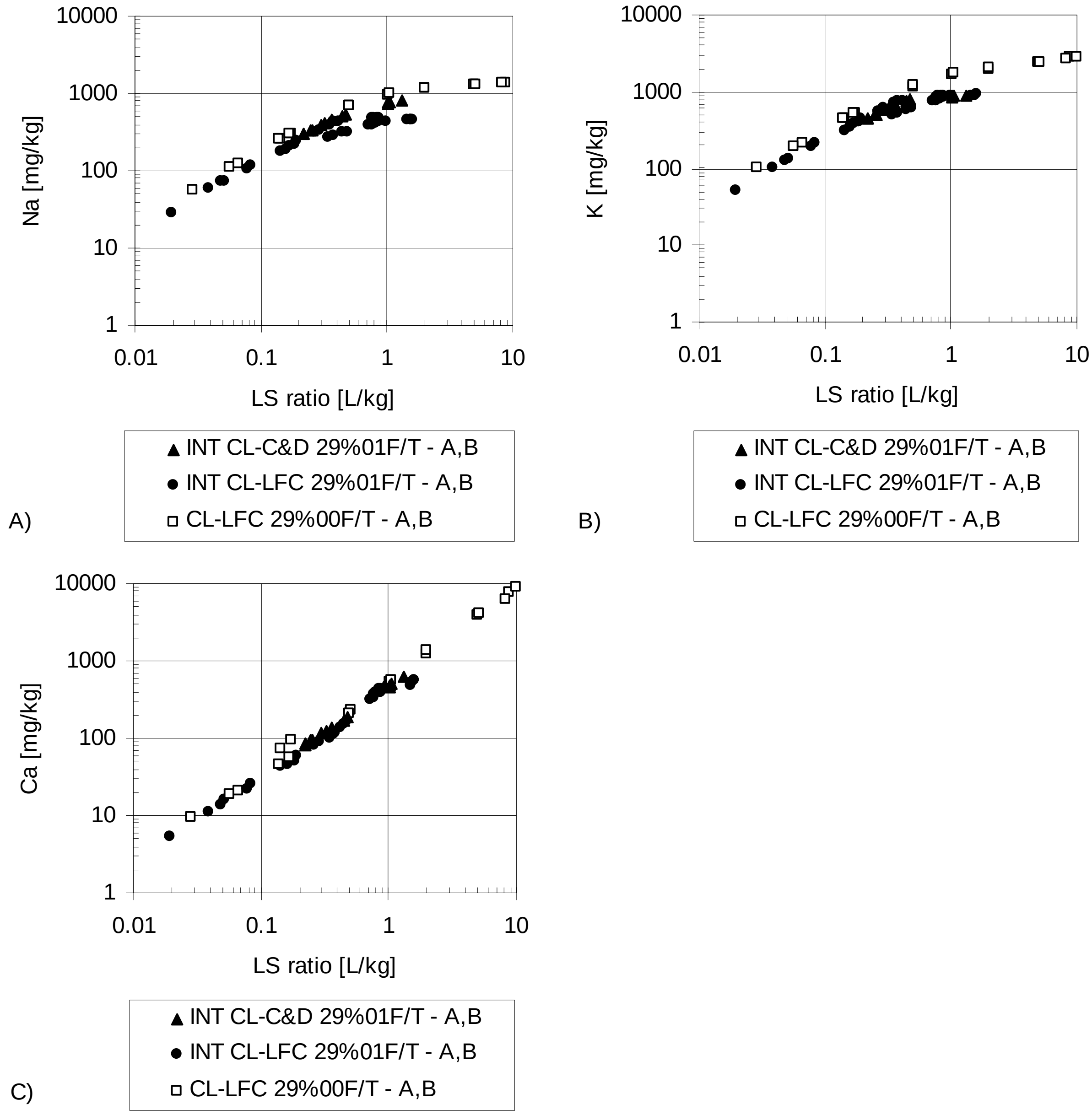
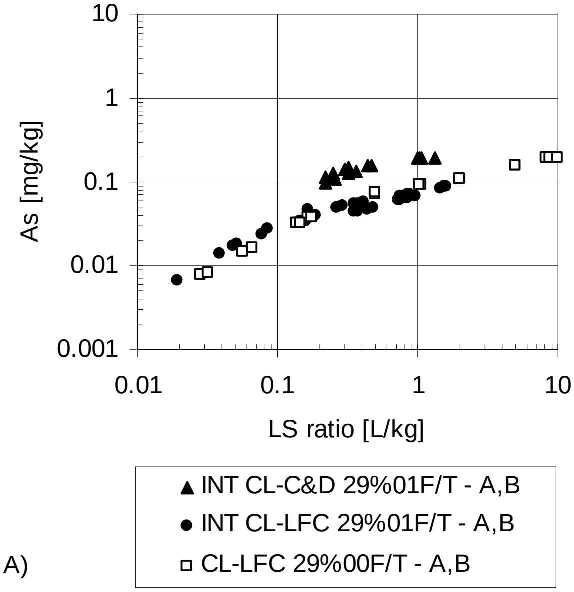
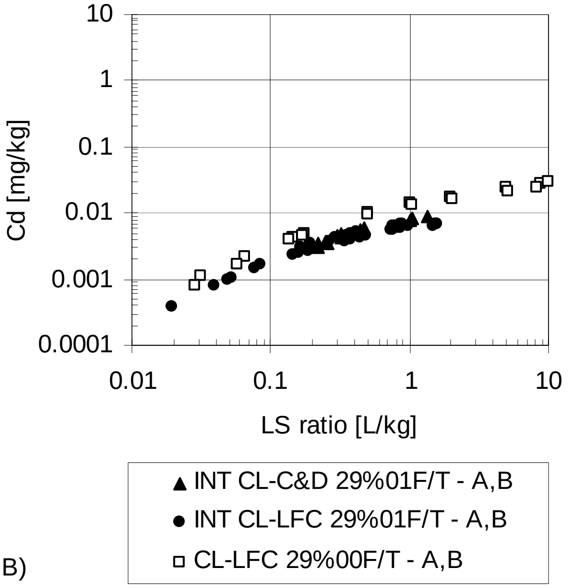


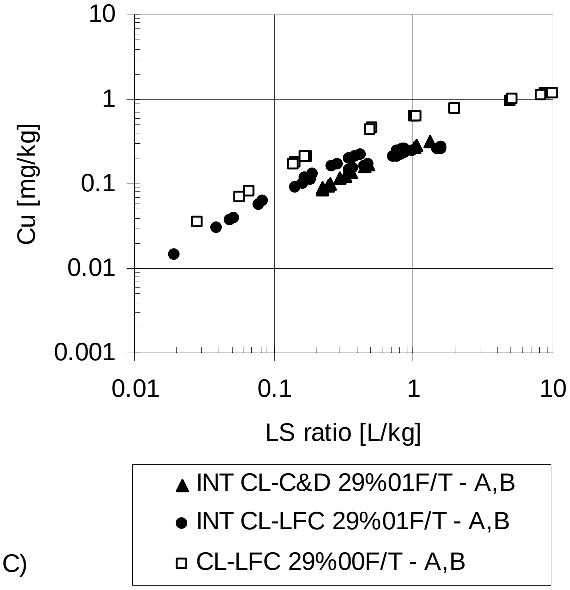
Figure 114. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of major material constituents for the C&D material packed at the optimum moisture content compared to the LFC material. A) Cumulative release of sodium. B) Cumulative release of potassium. C) Cumulative release of calcium.


10
1
0.1
0.01
0.001
As [mg/kg]
0.01
0.1
1
10
LS ratio [L/kg]
▲ INT CL-C&D 29%01F/T - A,B
● INT CL-LFC 29%01F/T - A,B
◻ CL-LFC 29%00F/T - A,B

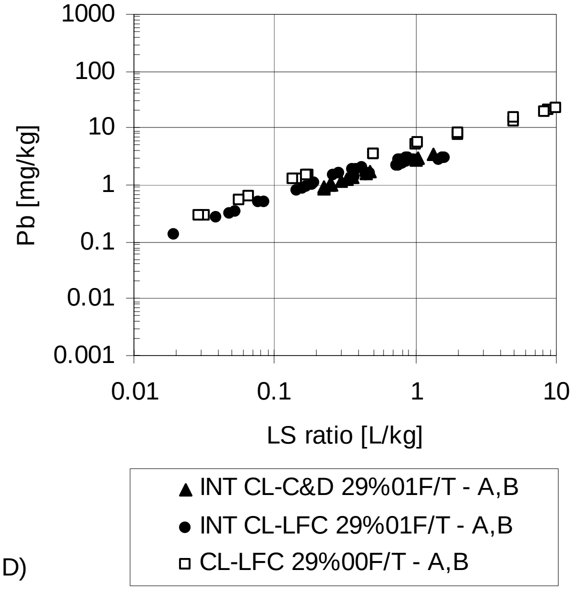
A)


10
1
0.1
0.01
0.001
0.0001
Cd [mg/kg]
0.01
0.1
1
10
LS ratio [L/kg]
▲ INT CL-C&D 29%01F/T - A,B
● INT CL-LFC 29%01F/T - A,B
◻ CL-LFC 29%00F/T - A,B

B)


10
1
0.1
0.01
0.001
Cu [mg/kg]
0.01
0.1
1
10
LS ratio [L/kg]
▲ INT CL-C&D 29%01F/T - A,B
● INT CL-LFC 29%01F/T - A,B
◻ CL-LFC 29%00F/T - A,B

C)


1000
100
10
1
0.1
0.01
0.001
Pb [mg/kg]
0.01
0.1
1
10
LS ratio [L/kg]
▲ INT CL-C&D 29%01F/T - A,B
● INT CL-LFC 29%01F/T - A,B
◻ CL-LFC 29%00F/T - A,B

D)

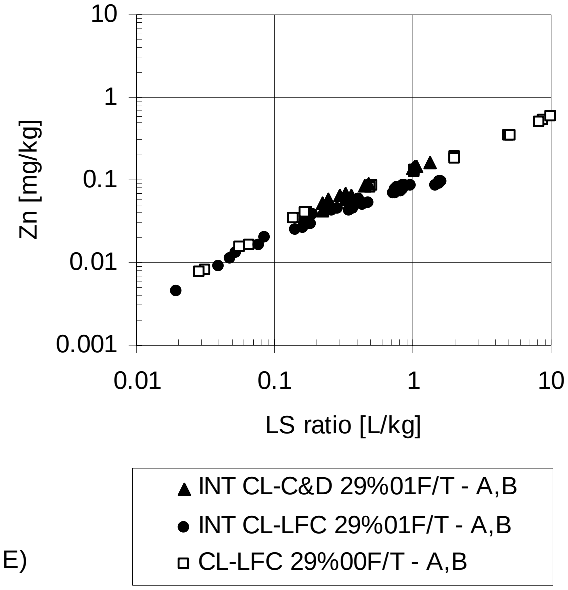


Figure 115. Effect of intermittent flow-through coupled with F/T exposure on the cumulative release of primary contaminants for the C&D material packed at the optimum moisture content compared to the LFC material. A) Cumulative release of arsenic. B) Cumulative release of cadmium. C) Cumulative release of copper. D) Cumulative release of lead. E) Cumulative release of zinc.

5. CONCLUSIONS AND SIGNIFICANCE

The following conclusions from this research are drawn:

Physical and chemical stability of the granular LFC material with respect to F/T exposure

- Exposure to F/T cycles resulted in aggregation of concrete particles and overall consolidation of the packed granular material.
- F/T exposure did not affect the stability of the mineral/chemical components of the LFC material. No significant effect of F/T exposure was observed on leaching at equilibrium of major LFC constituents (i.e., sodium, potassium, and calcium) and primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) over the entire range of pH and LS ratios examined.

Effect of F/T exposure on constituent leaching during flow-around controlled scenario (run-off)

- F/T exposure suppressed the release flux during the initial leaching intervals of all the major material constituents (i.e., sodium, potassium, calcium, chloride, and sulfate) and primary contaminants (i.e., arsenic, cadmium, copper, lead, and zinc) examined, resulting in a significant decrease in the cumulative release as a function of time.
- The decrease in the cumulative release of the major material constituents was greater for the less than 2 mm graded LFC material than the less than 9.5 mm graded LFC material.
- These results are in agreement with the visual observation of particle aggregation and consolidation of the packed granular material.
- For sodium, potassium, chloride, and cadmium, increasing F/T cycles resulted in a greater decrease in the release flux and cumulative release compared to the baseline case (no F/T exposure).
- ANOVA analysis on the cumulative release obtained after 21 days of continuous leaching with periodic renewals showed that F/T exposure provided a significant difference in the release of all major material constituents and primary contaminants examined at a confidence level of 95%. The main effects plots showed for most cases (i) an increase in the release with an increase in material gradation and (ii) a decrease in the release with increasing numbers of F/T cycles. Two exceptions to the general observations were found for calcium and sulfate, which showed (i) a decrease in the release with an increase in material gradation and (ii) a decrease in the release after F/T exposure compared to the no F/T cycles case.

Effect of F/T exposure on flow pattern during percolation flow controlled scenario

- Significant variation of the output flow rate as a function of time was observed with, in some instances, flow reduction by as much as an order of magnitude for the columns that had been exposed to 10 F/T cycles. Overall, the columns exposed to 10 F/T cycles showed an early breakthrough of the flow, independent of the initial moisture content of the packed material, suggesting preferential flow and/or presence of cracks as a result of F/T exposure. This was not observed for longer F/T exposure (i.e., 20 and 40 F/T cycles).
- The average output flow rate for the columns packed at 7% and 15% moisture content indicated an overall reduction of the flow rate after exposure to F/T cycles with increased reduction as the number of F/T cycles increased. This is in agreement with the visual

observation of particle aggregation and overall consolidation of the packed granular material and might have been the result of loose/fine particles blocking the flow path and/or self-cementing of the LFC material during thawing and subsequent permeation.

- Exposure to 10 F/T cycles resulted in a lower bromide recovery compared to the no F/T exposure cases for the columns packed at 7% and 15% moisture content and a greater bromide recovery for the columns packed at 29% moisture content (optimum moisture content).
- In all cases, further exposure to F/T cycles (i.e., exposure to 20 and 40 F/T cycles) did not significantly affect bromide recovery and resulted in the same bromide recovery at 20 days as that obtained for no F/T exposure.

Effect of F/T exposure on constituent leaching during percolation flow controlled (flow-through) scenario

- Exposure to F/T cycles had overall the greatest effect on the leaching of major material constituents and primary contaminants when the LFC material was packed at a moisture content that was ca. 52% (i.e., 15% moisture content) of the value of the optimum moisture content. The greatest variability in the release could be observed between the different levels of F/T exposure and within replicates when the LFC material was packed at a moisture content that was ca. 24% (i.e., 7% moisture content) of the value of the optimum moisture content. The least effect of F/T exposure was observed when the LFC material was packed at the optimum moisture content.
- Overall, as the number of F/T cycles increased, the release of the major material constituents and primary contaminants showed an initial increase generally after exposure to 10 F/T cycles and in some cases after exposure to 20 F/T cycles compared to the no F/T cycles case, followed by a decrease generally after exposure to 20 and 40 F/T cycles. The continued decrease after 40 F/T cycles resulted in a release less than the no F/T exposure cases.
- These results are in agreement with the behavior of the flow rate and visual observation of particle aggregation and overall consolidation of the packed granular material.
- ANOVA analysis on the cumulative release at an LS of 2 L/kg showed that F/T cycles provided a significant difference in the cumulative release of sodium, potassium, calcium, arsenic, copper, and zinc at a confidence level of 95%. Exposure to F/T cycles was not found to be significant for cadmium and lead. The moisture content of the packed material was significant at a confidence level of 95% only for the release of arsenic and zinc. Interactions between moisture content and number of F/T cycles were found to be significant for the release of potassium, calcium, arsenic, copper, lead, and zinc, but not for the release of sodium and cadmium.

  The main effects plots showed that:
    - Sodium, potassium, and zinc release increased after exposure to 10 F/T cycles compared to no F/T exposure and decreased thereafter with increasing number of F/T cycles (20 and 40 F/T cycles), resulting in a lower release after exposure to 40 F/T cycles compared to no F/T exposure.
    - Arsenic release increased after exposure to 10 F/T cycles compared to no F/T exposure while it remained the same as the no F/T exposure after 20 and 40 F/T cycles.

  - Copper release increased as the number of F/T cycles increased from 0 to 20 F/T cycles followed by a significant decreased after exposure to 40 F/T cycles, resulting in a much lower release of copper compared to the no F/T exposure case.
  - Calcium release decreased as the number of F/T cycles increased from 0 to 40 F/T cycles.

Constituent leaching during intermittent wetting/flow-through coupled with F/T exposure

- In contrast to F/T exposure prior to tank leaching under continuously water saturated conditions, intermittent wetting (flow around) coupled with F/T exposure did not have, overall, a significant effect on constituent leaching. However, the numbers of F/T cycles used between the leaching intervals (1, 2, and 4 F/T cycles) were less than that used when F/T exposure was performed prior to leaching (10 and 20 F/T cycles).
- In comparison to F/T exposure prior to column leaching, intermittent flow-through columns coupled with F/T cycles showed, for most cases, a greater effect on constituent release with similar or slightly lower release of major material constituents and primary contaminants compared to the continuous saturated flow-through cases with no F/T exposure.

Initial method validation on construction demolition-debris

- Overall, similar behaviors of major material constituents and primary contaminants as those obtained from the LFC material were observed for the C&D material under intermittent flow-through conditions.
- Initial results indicated that the LFC material represented a good model system for the C&D material.

Summary of conclusions and significance

This research has shown that F/T exposure results in consolidation of granular cement-based materials (self-cementing properties) and therefore can have a significant impact in long-term release of constituents from recycled concrete aggregates, depending upon flow scenario.

For applications where run-off is the primary route for leaching from recycled concrete aggregates, F/T exposure can result in a significant decrease in the cumulative release of constituents as a function of time. A greater decrease was observed when the granular material was more finely grained (i.e., for lower material gradation). This research indicated that where F/T exposure is expected to be an important factor in the potential application, continuous tank leaching is a conservative estimate of the long-term release of constituents from recycled concrete aggregates.

For applications where water percolating through the material is the primary route for leaching from RCA, the moisture content of the packed material at the time of freezing is an important parameter. Greater effects of F/T exposure (increase or decrease in the release) were observed when moisture content at the time of freezing was less than that of the optimum packing density (optimum moisture content). The effect of F/T exposure at the optimum moisture content was minimal and had no significance in the long-term release of constituents. Increases in the release compared to the no F/T exposure cases were observed after exposure to 10 and 20 F/T cycles for most constituents examined except for calcium and in some instances for chloride and sulfate, for which a decrease was observed. Exposure to 40 F/T cycles resulted for most cases in a decrease in the release compared to the no F/T exposure cases. Intermittent saturated flow conditions coupled with F/T exposure resulted in similar or lower release of constituents than under continuously saturated flow conditions. In general, batch testing provided a conservative estimate of column testing results. However, for arsenic and zinc, batch testing may under predict the release where F/T is an important factor and more complex testing may then be necessary. Further investigations are recommended.

This research suggests that, due to the self-cementing properties of RCA, leaching from RCA during run-off or percolation in applications where F/T exposure might be of importance will most likely be minimized with time and increased exposure to F/T cycles. However, an increase in the release might be initially observed during flow-through controlled scenarios due to preferential flow and/or cracks before subsequent decreases, as a result of self-cementing phenomena during further thawing and permeation, are observed.

Further research is needed to better understand the controlling factors of self-cementing processes during freezing and thawing and subsequent permeation.

6. REFERENCES

AASHTO, 1992. NDR T-103. Standard method for soundness of aggregates by freezing and thawing.

Apul, D., Gardner, K., Eighmy, T., Benoit, J., Brannaka, L., 2002. A review of water movement in the highway environment. Implications for recycled materials use. Recycled Materials Resource Center, 104p.

Arm, M., 2001. Self-cementing properties of crushed demolished concrete in unbound layers: results from triaxial tests and field tests. Waste Management 21(3), 235-239.

ASTM, 1978. D 1557. Standard Method for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10 lb. Rammer and 18 in. Drop. American Society for Testing and Materials, Philadelphia, PA.

ASTM, 1980. D 2261-80. Standard Method for Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures. American Society for Testing and Materials, Philadelphia, PA.

Benoit, G.R., 1973. Effect of freeze-thaw cycles on aggregate stability and hydraulic conductivity of three soil aggregate sizes. Proc. Soil Science Society of America 37, 3-5.

Chamberlain, E.J., 1983. Frost heave of saline soils. In: 4th International Conference on Permafrost, July 17-22, Fairbanks, Alaska. Washington DC: National Academy Press.

Chamberlain, E.J., Gow, A.J., 1979. Effect of freezing and thawing on the permeability and structure of soils. Engineering Geology 13(1-4), 73-92.

Cho, Y.-H., Yeo, S.-H., 2004. Application of recycled waste aggregate to lean concrete subbase in highway pavement. Canadian Journal of Civil Engineering 31(6), 1101-1108.

Corr, D.J., Monteiro, P.J.M., Bastacky, J., 2003. Observations of ice lens formation and frost heave in young Portland cement paste. Cement and Concrete Research 33(10), 1531-1537.

Couper, P., 2003. Effects of silt-clay content on the susceptibility of river banks to subaerial erosion. Geomorphology 56(1-2), 95-108.

Ding, M., Geusebroek, M., van der Sloot, H.A., 1998. Interface precipitation affects the resistance to transport in layered jarosite/fly ash. Journal of Geochemical Exploration 62(1-3), 319-323.

Eigenbrod, K.D., 1996. Effects of cyclic freezing and thawing on volume changes and permeabilities of soft fine-grained soils. Canadian Geotechnical Journal 33, 529-537.

Eigenbrod, K.D., 2003. Self-healing in fractured fine-grained soils. Canadian Geotechnical Journal 40(2), 435-449.

Ershov, E.D., 1998. General Geocryology. Cambridge University Press, p. 580.

FHWA, 2004. Transportation applications of recycled concrete aggregate. US Department of Transportation, Federal Highway Administration, 47p.

Ghafoori, N., Mathis, R., 1998. Prediction of freezing and thawing durability of concrete paving blocks. Journal of Materials in Civil Engineering, February 1998.

Hansson, K., J, S., Mizoguchi, M., Lundin, L.-C., Van Genuchten, M.T., 2004. Water Flow and Heat Transport in Frozen Soil: Numerical Solution and Freeze/Thaw Applications. Vadose Zone Journal 3(2), 693-704.

ITM, 2001. 209-01T. Soundness of aggregates by freezing and thawing in a brine solution. Indiana Department of Transportation Materials and Tests Division, Revised July 2001.

Jacobsen, S., Marchand, J., Boisvert, L., 1996a. Effect of cracking and healing on chloride transport in OPC concrete. Cement and Concrete Research 26(6), 869-881.

Jacobsen, S., Sellevold, E.J., 1996b. Self healing of high strength concrete after deterioration by freeze/thaw. Cement and Concrete Research 26(1), 55-62.

Kim, W.-H., Daniel, D.E., 1992. Effects of freezing on hydraulic conductivity of compacted clay. Journal of Geotechnical Engineering 118(7), 1083-1097.

Kosson, D.S., van der Sloot, H.A., Sanchez, F., Garrabrants, A.C., 2002. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. Environmental Engineering Science 19(3), 159-204.

Li, D., Nick, C., 2002. Freeze-thaw cycles and soil amendments. GCM October 2002, 103-117.

Limbachiya, M.C., Marrocchino, E., Koulouris, A., in press. Chemical-mineralogical characterisation of coarse recycled concrete aggregate. Waste Management, Available online 29 March 2006.

Lopez, S., 2006. Evaluation of the impact of environmental conditions on constituent leaching from granular materials during intermittent infiltration. Civil and Environmental Engineering, Vanderbilt University, Nashville. Ph.D dissertation.

Lopez, S., Sanchez, F., Kosson, D.S., 2001. Evaluation of the impact of environmental conditions on constituent leaching from granular materials during intermittent infiltration. In: Beneficial Use of Recycled Materials in Transportation Applications conference. November 12-15, 2001, Washington, D.C.: Air & Waste Management Association's Publications.

Marion, G.M., 1995. Freeze-thaw processes and soil chemistry. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, New Hampshire. Special Report 95-12. March 1995.28.

Othman, M.A., Benson, C.H., 1993. Effect of freeze-thaw on the hydraulic conductivity and morphology of compacted clay. Canadian Geotechnical Journal 30(2), 236-246.

Oztas, T., Fayetorbay, F., 2003. Effect of freezing and thawing processes on soil aggregate stability. CATENA 52(1), 1-8.

Park, T., 2003. Application of construction and building debris as nase and subbase materials in rigid pavement. Journal of Transportation Engineering 129(5), 558-563.

Pawluk, S., 1998. Freeze-thaw effects on granular structure reorganization for soil materials of varying texture and moisture content. Canadian Journal of Soil Science 68, 485-494.

Penttala, V., 1998. Freezing-Induced Strains and Pressures in Wet Porous Materials and Especially in Concrete Mortars. Advanced Cement Based Materials 7(1), 8-19.

Penttala, V., Al-Neshawy, F., 2002. Stress and strain state of concrete during freezing and thawing cycles. Cement and Concrete Research 32(9), 1407-1420.

Poon, C.S., Chan, D., 2006. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Construction and Building Materials 20(8), 578-585.

Poon, C.-S., Qiao, X.C., Chan, D., in press. The cause and influence of self-cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base. Waste Management, Available online 20 February 2006.

Ramm, W., Biscoping, M., 1998. Autogenous healing and reinforcement corrosion of water-penetrated separation cracks in reinforced concrete. Nuclear Engineering and Design 179(2), 191-200.

Reinhardt, H.-W., Jooss, M., 2003. Permeability and self-healing of cracked concrete as a function of temperature and crack width. Cement and Concrete Research 33(7), 981-985.

Shoop, S.A., Bigl, S.R., 1997. Moisture migration during freeze and thaw of unsaturated soils: modeling and large scale experiments. Cold Regions Science and Technology 25(1), 33-45.

Staricka, J.A., Benoit, G.R., 1995. Freeze-drying effect on wet and dry aggregate stability. Soil Science Society of America Journal 59, 218-223.

Talamucci, F., 2003. Freezing processes in porous media: Formation of ice lenses, swelling of the soil. Mathematical and Computer Modelling 37(5-6), 595-602.

Teepe, R., Brumme, R., Beese, F., 2001. Nitrous oxide emissions from soil during freezing and thawing periods. Soil Biology and Biochemistry 33(9), 1269-1275.

US Army Corps of Engineers, 2004. Reuse of concrete materials from building demolition. Department of the Army, US Corps of Engineers, Public Works Technical Bulletin, 201-1-27.

Viklander, P., 1998a. Laboratory study of stone heave in till exposed to freezing and thawing. Cold Regions Science and Technology 27(2), 141-152.

Viklander, P., 1998b. Permeability and volume changes in till due to cyclic freeze-thaw. Canadian Geotechnical Journal 35, 471-477.

Viklander, P., Eigenbrod, D., 2000. Stone movements and permeability changes in till caused by freezing and thawing. Cold Regions Science and Technology 31(2), 151-162.

Williams, P.J., 1989. The frozen earth: fundamentals of geocryology. Cambridge University Press, p. 306.

7. APPENDIX (TABLES OF SUPPORTING DATA)

Appendix A - Chemical stability of the LFC material with respect to F/T exposure

Table A 1. SR002 data for LFC material after exposure to 0 F/T cycles - Major material constituents.

mEq/g	pH		Na (mg/L)		K (mg/L)		Ca (mg/L)	
	A	B	A	B	A	B	A	B
0	12.38	12.45	134	135	217	211	631	646
1.5	12.47	12.21	138	134	221	200	627	2038
2.7	11.77	11.46	129	131	189	185	3417	3326
3.6	11.12	11.25	127	129	181	178	4559	4453
4.1	10.42	10.81	125	134	177	179	5062	5082
4.5	10.03	10.28	124	133	169	180	5372	5542
4.8	9.53	9.85	124	130	165	170	5778	5841
5.2	7.18	7.40	125	129	169	176	6251	6328
5.6	6.71	6.19	124	127	171	182	6497	6763
6.3	4.91	5.49	131	133	191	177	7577	7358
7.3	3.60	3.87	125	136	201	199	8029	8257

Table A 2. SR002 data for LFC material after exposure to 0 F/T cycles - Primary contaminants.

mEq/g	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
0	0.062	0.071	0.005	0.005	0.177	0.178	4.3	4.8	0.078	0.074
1.5	0.073	0.295	0.006	0.004	0.189	0.223	4.7	1.9	0.084	0.057
2.7	0.565	0.600	0.005	0.002	0.123	0.053	0.284	0.030	0.026	0.016
3.6	0.411	0.561	0.002	0.002	0.035	0.037	0.006	0.008	0.019	0.024
4.1	0.993	0.886	0.006	0.003	0.024	0.030	0.002	0.004	0.024	0.025
4.5	0.676	1.160	0.025	0.012	0.022	0.029	0.002	0.002	0.037	0.037
4.8	0.982	NA	0.063	NA	0.035	NA	0.006	NA	0.049	NA
5.2	0.130	0.049	157.0	3.5	0.707	0.089	0.040	0.003	21.1	2.3
5.6	0.083	0.131	225.3	283.5	4.8	29.4	0.205	0.846	121.4	145.7
6.3	0.242	0.225	350.2	303.8	82.9	55.8	261.655	3.3	106.8	132.0
7.3	0.247	0.281	368.7	375.8	97.1	110.9	921.673	982.6	96.0	105.2

NA – Not available.

Table A 3. SR002 data for LFC material after exposure to 10 F/T cycles - Major material constituents.

mEq/g	pH		Na (mg/L)		K (mg/L)		Ca (mg/L)	
	A	B	A	B	A	B	A	B
0	12.5	12.6	128	128	208	211	485	475
3.6	11.4	11.4	127	127	189	187	4579	4552
4.5	10.1	10.0	115	118	163	159	5549	5471
5.2	6.9	7.0	128	123	178	174	6295	6285
6.3	4.8	5.2	120	127	183	189	7297	7381

Table A 4. SR002 data for LFC material after exposure to 10 F/T cycles - Primary contaminants.

mEq/g	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
0	0.086	0.026	0.004	0.003	0.127	0.115	2.1	2.1	0.054	0.049
3.6	0.345	0.398	0.001	0.002	0.050	0.036	0.014	0.008	0.013	0.020
4.5	0.647	0.736	0.002	0.003	0.017	0.019	0.001	0.001	0.025	0.027
5.2	0.148	0.087	156.6	110.4	1.2	0.5	0.065	0.035	62.2	16.4
6.3	0.098	0.089	317.2	301.2	80.1	64.5	311.1	61.8	103.1	117.6

Table A 5. SR003 data for LFC material after exposure to 0 F/T cycles - Major material constituents.

LS (mL/g)	pH		Na (mg/L)		K (mg/L)		Ca (mg/L)	
	A	B	A	B	A	B	A	B
10	12.5	12.5	134	133	218	216	625	613
5	12.9	12.9	262	259	427	419	629	618
2	12.8	12.9	625	620	1022	1013	415	409
1	13.1	13.1	2124	2106	3297	3267	244	240
0.5	13.3	13.3	4043	4078	6264	6326	135	136

Table A 6. SR003 data for LFC material after exposure to 0 F/T cycles - Primary contaminants.

LS (mL/g)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
10	0.047	0.044	0.006	0.005	0.162	0.154	3.9	3.8	0.072	0.069
5	0.044	0.042	0.010	0.012	0.214	0.208	2.4	2.4	0.081	0.079
2	0.046	0.053	0.019	0.019	0.274	0.282	2.4	2.4	0.069	0.070
1	0.093	0.103	0.034	0.032	0.468	0.453	3.1	3.0	0.093	0.089
0.5	0.475	0.412	0.067	0.063	1.022	0.940	5.0	5.0	0.198	0.189

Table A 7. SR003 data for LFC material after exposure to 10F/T cycles - Major material constituents.

LS (mL/g)	pH		Na (mg/L)		K (mg/L)		Ca (mg/L)	
	A	B	A	B	A	B	A	B
10	12.5	12.6	134	133	218	216	625	613
5	12.9	12.8	271	270	447	445	457	454
2	13.0	13.0	653	642	1079	1070	354	345

Table A 8. SR003 data for LFC material after exposure to 10F/T cycles - Primary contaminants.

LS (mL/g)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
10	0.047	0.044	0.006	0.005	0.162	0.154	3.9	3.8	0.072	0.069
5	0.041	0.032	0.006	0.007	0.154	0.174	2.7	3.1	0.051	0.064
2	0.038	NA	0.015	0.015	0.243	0.390	3.4	3.4	NA	NA

NA – Not available.

Appendix B - Flow-around mass transfer tests

Exposure to 0 F/T – Less than 2 mm graded LFC material

Table B 1. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.2	11.2	1.0	1.1
5	11.1	11.2	0.5	0.6
8	11.0	11.2	0.4	0.5
24	11.7	11.8	1.5	1.7
48	11.6	11.8	1.5	1.8
96	11.8	12.0	2.3	2.4
192	12.0	12.1	0.9	0.9
336	12.2	12.1	3.4	3.6
504	12.1	12.1	3.5	3.4

Table B 2. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	29.4	26.8	61.4	53.8	78.6	64.1	9.2	8.5	5.5	5.7
5	19.7	20.5	39.1	39.5	63.8	59.2	5.9	6.5	2.1	2.7
8	14.5	15.6	28.9	29.1	70.4	67.8	4.5	5.0	1.2	1.5
24	48.4	52.0	98.6	104.6	90.1	87.4	14.8	16.0	2.7	3.2
48	46.1	47.7	97.0	94.9	53.1	103.2	8.8	12.9	2.1	2.1
96	60.0	61.0	125.7	120.8	122.0	112.2	14.5	15.2	1.6	2.0
192	81.0	77.8	166.0	156.6	144.4	133.7	19.6	19.0	1.8	2.0
336	81.1	77.2	164.5	153.9	163.9	158.1	18.8	18.5	1.6	1.7
504	67.9	66.6	138.1	134.4	161.7	162.5	16.0	15.4	1.4	1.4

Table B 3. Mass transfer data for the less than 2 mm graded LFC material after exposure to 0 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.078	0.119	0.009	0.012	0.017	0.020	0.071	0.071	0.026	0.031
5	0.047	0.090	0.002	0.002	0.009	0.011	0.043	0.054	0.011	0.017
8	0.025	0.030	0.003	0.002	0.006	0.008	0.039	0.042	0.007	0.007
24	0.021	0.027	0.003	0.003	0.015	0.018	0.135	0.143	0.012	0.044
48	0.007	0.023	0.000	0.007	0.009	0.015	0.083	0.140	0.010	0.021
96	0.014	0.016	0.003	0.003	0.016	0.018	0.174	0.193	0.011	0.014
192	0.016	0.019	0.003	0.005	0.023	0.029	0.278	0.309	0.014	0.025
336	0.015	0.017	0.003	0.003	0.025	0.026	0.295	0.277	0.023	0.053
504	0.015	0.019	0.002	0.003	0.023	0.024	0.264	0.250	0.014	0.018

Exposure to 10 F/T – Less than 2 mm graded LFC material

Table B 4. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.1	11.1	0.4	0.3
5	11.1	11.0	0.3	0.4
8	11.1	11.0	0.3	0.4
24	11.7	11.6	1.0	1.2
48	11.8	11.7	1.4	1.6
96	11.8	11.7	6.4	6.9
192	12.0	12.1	3.4	3.8
336	12.2	12.2	4.0	4.2
504	12.3	12.2	3.7	4.0

Table B 5. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	79.4	9.9	162.0	23.2	86.9	0.4	2.1	1.7	0.501	0.270
5	11.2	9.6	18.1	13.7	9.7	7.6	2.1	2.2	0.250	0.250
8	9.7	9.0	14.0	12.9	7.7	8.5	2.4	2.3	0.250	0.250
24	32.2	31.3	66.0	63.4	8.7	9.0	6.8	6.8	0.364	0.470
48	36.2	39.2	71.6	79.6	15.9	7.8	8.5	8.9	0.459	0.593
96	52.3	55.8	109.6	115.8	35.4	28.3	12.8	12.6	0.697	0.841
192	76.7	79.3	161.3	166.2	45.5	45.5	18.4	18.9	1.011	1.215
336	85.4	88.5	180.9	183.4	80.3	67.5	20.9	20.8	1.327	1.240
504	NA	80.7	NA	165.5	NA	75.4	18.6	19.3	1.187	1.173

Table B 6. Mass transfer data for the less than 2 mm graded LFC material after exposure to 10 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.016	0.017	0.003	0.001	0.019	0.005	0.199	0.021	0.012	0.006
5	0.008	0.007	0.001	0.001	0.004	0.005	0.014	0.030	0.004	0.004
8	0.006	0.005	0.002	0.002	0.006	0.006	0.021	0.034	0.007	0.005
24	0.007	0.005	0.002	0.002	0.008	0.010	0.052	0.088	0.014	0.007
48	0.007	0.005	0.001	0.001	0.009	0.011	0.070	0.106	0.006	0.006
96	0.014	0.007	0.002	0.002	0.014	0.014	0.123	0.153	0.008	0.007
192	0.011	0.008	0.002	0.002	0.021	0.022	0.203	0.237	0.011	0.010
336	0.013	0.010	0.003	0.002	0.026	0.025	0.274	0.272	0.047	0.011
504	NA	0.012	NA	0.002	NA	0.026	NA	0.279	NA	0.011

Exposure to 20 F/T – Less than 2 mm graded LFC material

Table B 7. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.0	10.9	0.3	0.3
5	11.1	11.0	0.4	0.3
8	11.0	11.0	0.3	0.3
24	11.6	11.6	1.2	1.1
48	11.8	11.7	1.6	1.5
96	12.0	11.9	2.3	2.3
192	12.1	12.1	3.6	3.5
336	12.2	12.2	3.8	3.9
504	12.2	12.2	4.0	3.8

Table B 8. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	17.8	7.5	6.6	7.5	9.3	6.3	1.2	0.9	0.3	0.3
5	23.5	14.9	6.1	7.0	9.6	8.4	1.8	1.6	0.3	0.3
8	19.2	13.0	5.1	6.2	6.9	6.2	1.0	1.0	0.3	0.3
24	56.1	40.8	25.5	25.8	55.0	51.8	5.3	5.0	0.3	0.3
48	15.3	5.5	31.4	32.9	67.6	68.0	6.4	6.7	0.3	0.3
96	38.5	21.5	50.5	52.7	111.0	112.4	9.9	10.6	0.5	0.5
192	61.1	54.3	76.1	79.2	166.7	170.6	15.5	16.4	0.9	0.9
336	81.5	72.2	86.7	91.5	186.4	192.3	17.6	18.0	1.0	1.0
504	89.9	74.6	80.3	83.0	169.6	167.7	15.0	15.9	1.1	0.9

Table B 9. Mass transfer data for the less than 2 mm graded LFC material after exposure to 20 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.014	0.012	0.001	0.003	0.009	0.005	0.024	0.015	0.003	0.004
5	0.007	0.005	0.001	0.001	0.006	0.004	0.030	0.020	0.003	0.003
8	0.005	0.003	0.001	0.000	0.003	0.003	0.025	0.019	0.002	0.001
24	0.006	0.054	0.001	0.001	0.007	0.010	0.087	0.071	0.004	0.004
48	0.008	0.006	0.001	0.001	0.010	0.008	0.112	0.102	0.006	0.004
96	0.016	0.007	0.001	0.001	0.013	0.013	0.165	0.163	0.007	0.006
192	0.015	0.009	0.001	0.002	0.023	0.020	0.284	0.274	0.012	0.009
336	0.019	0.011	0.002	0.002	0.030	0.025	0.395	0.328	0.015	0.012
504	0.016	0.011	0.002	0.002	0.027	0.029	0.324	0.303	0.013	0.011

Exposure to 0 F/T – Less than 9.5 mm graded LFC material

Table B 10. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.5	11.6	1.6	1.8
5	11.2	11.4	0.7	1.1
8	11.2	11.4	0.7	0.8
24	11.7	11.8	1.4	1.8
48	11.8	11.8	2.2	1.7
96	11.9	12.0	2.3	2.4
192	12.1	12.2	0.9	0.9
336	12.3	12.1	3.7	3.6
504	12.1	12.2	3.4	3.5

Table B 11. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	5.5	8.3	54.5	57.3	110.2	119.2	12.3	13.3	4.8	5.1
5	2.8	9.5	24.4	42.6	46.8	83.1	5.5	10.0	1.3	2.6
8	2.8	9.8	25.6	31.8	49.9	60.8	6.2	7.9	1.4	1.7
24	24.5	22.3	40.3	59.5	87.9	122.1	9.4	14.9	0.9	1.8
48	38.0	28.1	68.6	50.5	134.6	105.1	17.1	11.8	2.0	1.0
96	51.7	42.2	55.7	71.2	118.2	144.3	13.6	17.6	0.9	1.0
192	77.7	61.4	84.7	92.6	177.0	195.6	20.0	21.6	1.1	0.9
336	92.9	73.5	88.7	96.9	183.3	200.9	21.0	22.7	1.2	1.0
504	89.4	76.5	80.9	94.2	166.0	183.4	18.4	20.0	0.9	0.8

Table B 12. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 0 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.127	0.177	0.002	0.010	0.026	0.036	0.180	0.210	0.043	0.055
5	0.057	0.080	0.001	0.001	0.014	0.022	0.093	0.171	0.023	0.036
8	0.048	0.068	0.002	0.002	0.014	0.018	0.107	0.145	0.019	0.031
24	0.025	0.045	0.003	0.003	0.015	0.025	0.140	0.248	0.025	0.057
48	0.014	0.026	0.004	0.003	0.023	0.021	0.252	0.205	0.019	0.024
96	0.016	0.024	0.004	0.004	0.019	0.024	0.231	0.257	0.016	0.018
192	0.021	0.014	0.004	0.004	0.029	0.027	0.327	0.300	0.017	0.018
336	0.014	0.014	0.004	0.005	0.030	0.030	0.367	0.346	0.015	0.029
504	0.011	0.010	0.002	0.003	0.026	0.029	0.310	0.305	0.014	0.013

Exposure to 10 F/T – Less than 9.5 mm graded LFC material

Table B 13. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.7	11.7	1.1	1.1
5	11.3	11.4	0.6	0.7
8	11.2	11.3	0.6	0.5
24	11.6	11.7	1.1	1.1
48	11.6	11.7	1.4	1.4
96	11.7	11.7	6.3	6.0
192	12.1	12.2	3.4	3.7
336	12.2	12.3	4.1	4.4
504	12.3	12.2	3.7	3.8

Table B 14. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	20.0	20.5	43.5	37.9	94.1	80.8	10.2	9.5	1.583	1.375
5	7.6	5.9	19.4	17.6	38.3	34.0	4.3	4.2	0.631	0.587
8	2.5	4.2	12.1	15.1	23.7	27.5	2.8	3.9	0.298	0.418
24	20.5	14.4	30.0	24.2	68.3	52.0	6.3	5.9	0.448	0.432
48	19.9	18.2	36.7	31.6	82.8	68.9	7.3	6.8	0.433	0.429
96	31.1	26.7	55.6	46.9	124.8	105.4	10.7	9.9	0.549	0.527
192	45.5	43.2	86.2	86.0	188.6	188.8	16.0	17.5	0.668	0.834
336	55.4	64.9	102.5	105.4	216.0	219.0	19.1	20.7	0.740	0.888
504	68.0	59.0	98.8	98.8	195.1	190.8	18.4	17.6	0.738	0.747

Table B 15. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 10 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.020	0.021	0.001	0.001	0.014	0.010	0.143	0.142	0.011	0.010
5	0.013	0.018	0.001	0.001	0.007	0.008	0.068	0.099	0.007	0.009
8	0.010	0.013	0.007	0.009	0.010	0.013	0.061	0.098	0.014	0.013
24	0.006	0.010	0.002	0.005	0.010	0.011	0.125	0.148	0.008	0.012
48	0.007	0.005	0.002	0.001	0.013	0.013	0.136	0.131	0.009	0.009
96	0.005	0.005	0.002	0.002	0.014	0.012	0.153	0.153	0.007	0.008
192	0.007	0.007	0.002	0.002	0.022	0.020	0.254	0.255	0.010	0.010
336	0.005	0.007	0.001	0.002	0.021	0.024	0.248	0.297	0.009	0.011
504	0.008	0.006	0.002	0.001	0.023	0.023	0.260	0.287	0.011	0.010

Exposure to 20 F/T – Less than 9.5 mm graded LFC material

Table B 16. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	11.5	11.5	1.1	0.9
5	11.4	11.4	0.8	0.7
8	11.3	11.4	0.6	0.7
24	11.6	11.6	1.2	1.1
48	11.8	11.7	1.4	1.3
96	12.0	11.9	2.1	2.2
192	12.2	12.1	3.3	3.4
336	12.2	12.2	4.0	3.7
504	12.2	12.2	4.0	3.8

Table B 17. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	25.7	21.8	34.0	27.4	61.1	47.0	8.2	6.7	1.870	1.678
5	28.4	22.5	24.1	17.5	40.8	29.3	5.9	4.5	0.909	0.699
8	30.6	25.8	15.2	17.0	24.4	25.9	4.3	4.6	0.509	0.679
24	58.2	50.1	27.8	25.4	58.3	51.3	6.6	5.8	0.564	0.552
48	64.1	66.5	31.8	29.0	67.9	61.4	8.1	7.1	0.618	0.525
96	10.9	9.0	49.6	49.8	109.9	113.2	12.8	11.6	0.775	0.650
192	29.3	35.8	79.8	74.7	181.5	167.6	17.3	16.7	0.996	1.108
336	53.0	40.0	106.6	96.8	221.5	206.7	23.8	20.8	1.324	1.080
504	53.0	47.9	97.9	94.6	190.7	185.8	20.2	18.4	0.963	0.943

Table B 18. Mass transfer data for the less than 9.5 mm graded LFC material after exposure to 20 F/T cycles – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.027	0.029	0.001	0.001	0.013	0.011	0.111	0.092	0.010	0.008
5	0.017	0.017	0.001	0.001	0.010	0.007	0.099	0.072	0.009	0.007
8	0.016	0.015	0.001	0.001	0.008	0.008	0.083	0.084	0.008	0.006
24	0.020	0.017	0.001	0.002	0.011	0.010	0.116	0.109	0.012	0.011
48	0.013	0.013	0.002	0.002	0.012	0.011	0.127	0.127	0.010	0.010
96	0.022	0.011	0.002	0.002	0.017	0.015	0.180	0.184	0.013	0.010
192	0.018	0.025	0.002	0.002	0.023	0.025	0.276	0.281	0.015	0.020
336	0.016	0.017	0.002	0.002	0.032	0.028	0.379	0.342	0.016	0.021
504	0.015	0.015	0.002	0.002	0.031	0.028	0.332	0.308	0.016	0.014

Appendix C - Flow-through column experiments

Saturated column experiments

LFC material packed at 7% moisture content - Exposure to 0 F/T

Table C 1. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles - pH and conductivity.

Replicate A				Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)		LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.05	13.6	48.0		0.08	13.4	44.0
0.15	13.6	46.0		0.19	13.2	39.0
0.19	13.3	41.0		0.23	13.4	37.0
0.78	13.1	16.0		0.31	12.6	13.0
0.85	12.9	14.0		1.01	12.7	13.0
0.95	12.9	13.0		2.03	12.5	9.1
1.91	12.6	8.9		5.18	12.6	5.6
4.94	12.1	7.3				

Table C 2. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles – Major material constituents.

Replicate A							Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)		LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.05	2340	4180	291	836	773		0.08	2190	3770	188	655	306
0.15	1930	3420	268	718	571		0.19	1680	2890	790	547	199
0.19	1600	2790	307	592	389		0.23	1300	2230	222	461	131
0.78	639	1070	489	277	79		0.31	481	832	679	160	14
0.85	373	648	649	175	29		1.01	302	531	946	143	12
0.95	305	556	667	150	23		2.03	78.4	178	696	72	5
1.91	147	248	2690	62	8		5.18	12.2	65.2	834	NA	NA
4.94	18.6	77.3	731	NA	NA							

NA – Not available.

Table C 3. Column leaching data for the LFC material packed at 7% moisture content after exposure to 0 F/T cycles – Primary contaminants.

Replicate A							Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)		LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.05	0.828	0.070	1.350	8.8	0.410		0.08	0.120	0.021	1.170	9.020	0.264
0.15	0.363	0.019	1.110	6.6	0.211		0.19	0.054	0.015	0.923	7.060	0.195
0.19	0.380	0.022	0.916	5.9	0.191		0.23	0.066	0.013	0.712	5.520	0.144
0.78	0.051	0.011	0.298	3.5	0.098		0.31	0.011	0.003	0.207	3.390	0.058
0.85	0.046	0.007	0.189	2.2	0.085		1.01	0.010	0.003	0.179	2.420	0.056
0.95	0.034	0.005	0.191	2.7	0.073		2.03	0.005	0.001	0.078	1.840	0.045
1.91	0.017	0.003	0.100	2.0	0.059		5.18	0.011	0.001	0.040	1.220	0.042
4.94	0.015	0.002	0.047	1.4	0.039							

LFC material packed at 7% moisture content - Exposure to 10 F/T

Table C 4. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.06	13.3	39.0	0.05	13.3	42.0
0.15	13.4	34.0	0.14	13.4	36.0
0.18	13.3	34.0	0.17	13.3	34.0
0.26	13.2	29.0	0.24	13.2	30.0
0.61	12.9	19.0	0.61	12.9	20.0
1.02	12.6	13.0	1.03	12.6	13.0
2.33	12.2	8.4	2.31	12.6	8.4
4.86	12.0	7.6			

Table C 5. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.06	2270	510	4430	906.7	355.6	0.05	2270	490	4370	925.8	391.6
0.15	2040	526	3940	821.3	275.3	0.14	2210	518	4190	822.9	312.1
0.18	1700	578	3250	736.2	214.3	0.17	1720	552	3310	732.2	232.3
0.26	1500	567	2880	693.7	173.5	0.24	1570	549	2970	690.1	190.7
0.61	920	675	1650	414.5	54.6	0.61	963	697	1740	415.1	61.2
1.02	426	643	886	236.3	20.3	1.03	418	601	873	223.5	20.2
2.33	50	619	161	65.2	NA	2.31	61	604	179	65.8	NA
4.86	6	565	88.5	34.9	NA						

NA – Not available.

Table C 6. Column leaching data for the LFC material packed at 7% moisture content after exposure to 10 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.06	0.72	0.019	0.92	8.63	0.35	0.05	0.82	0.024	1.00	7.87	0.43
0.15	0.88	0.015	0.83	7.77	0.29	0.14	0.86	0.015	0.86	8.00	0.29
0.18	0.79	0.014	0.72	7.06	0.25	0.17	0.81	0.014	0.78	6.92	0.26
0.26	0.86	0.012	0.64	6.41	0.21	0.24	0.99	0.011	0.67	6.43	0.22
0.61	1.19	0.007	0.39	4.33	0.17	0.61	1.30	0.008	0.41	4.40	0.14
1.02	0.05	0.005	0.19	3.14	0.08	1.03	0.04	0.005	0.19	2.95	0.08
2.33	0.03	0.002	0.08	2.26	0.06	2.31	0.03	NA	0.09	2.24	0.05
4.86	0.03	0.002	0.05	1.89	0.05						

NA – Not available.

LFC material packed at 7% moisture content - Exposure to 20 F/T

Table C 7. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.31	13.1	29.0	0.02	13.5	65.0
0.35	13.0	28.0	0.12	13.4	52.0
0.44	13.0	24.0	0.17	13.3	44.0
0.50	12.8	23.0	0.25	13.3	33.0
1.27	12.6	10.0	0.54	12.9	18.0
2.09	12.3	7.8	1.05	12.6	11.0
5.07	11.9	7.3	4.70	11.9	7.4

Table C 8. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.31	1320	402	2600	605.1	164.2	0.02	3040	339	5830	1241.0	676.9
0.35	1180	474	2280	516.7	96.6	0.12	2650	288	5130	1012.6	441.4
0.44	1110	484	1930	470.8	74.7	0.17	2310	393	4500	823.5	294.3
0.50	1130	545	1950	417.0	58.4	0.25	1670	342	3240	701.8	212.3
1.27	296	666	644	175.9	13.6	0.54	869	NA	1560	340.3	47.0
2.09	78.8	722	252	104.7	7.5	1.05	369	NA		115.9	NA
5.07						4.70					

NA – Not available.

Table C 9. Column leaching data for the LFC material packed at 7% moisture content after exposure to 20 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.31	0.72	0.032	1.54	4.96	0.66	0.02	0.68	0.029	1.79	12.50	0.67
0.35	0.14	0.010	1.38	5.76	0.37	0.12	0.16	0.017	1.41	10.80	0.44
0.44	0.13	0.011	0.95	5.18	0.35	0.17	0.13	0.014	1.09	9.69	0.34
0.50	0.10	0.009	0.82	5.49	0.23	0.25	0.06	0.012	0.90	6.81	0.26
1.27	0.04	0.004	0.26	3.02	0.07	0.54	0.03	0.003	0.30	4.14	0.12
2.09	0.01	0.004	0.10	2.47	0.06	1.05	0.01	0.005	0.15	3.12	0.07
5.07						4.70					

NA – Not available.

LFC material packed at 7% moisture content - Exposure to 40 F/T

Table C 10. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.12	13.5	36.0	0.11	13.3	44.0
0.21	13.2	30.0	0.19	13.5	37.0
0.46	13.2	21.0	0.22	13.5	34.0
0.54	13.2	20.0	0.44	13.0	22.0
0.94	12.6	12.0	0.52	13.0	21.0
1.01	12.7	13.0	0.97	12.6	12.0
1.99	12.4	8.7	1.04	12.6	12.0
4.03	12.1	7.8	1.95	12.4	8.8
5.01	12.3	8.5	4.08	12.3	7.2
7.81	11.6	6.6	5.08	12.4	7.6
10.60	12.2	6.7	7.97	11.5	6.2
			10.00	12.0	5.9

Table C 11. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.12	1760	193	3020	595.5	254.9	0.11	1450	140	2490	715.0	357.4
0.21	1610	236	2740	438.8	163.0	0.19	1900	257	3240	580.4	221.1
0.46	1020	335	1710	318.1	51.8	0.22	1520	262	2550	490.5	152.7
0.54	845	341	1420	285.4	41.8	0.44	883	351	1500	331.6	52.8
0.94	339	519	599	146.7	13.5	0.52	795	366	1340	298.1	42.9
1.01	342	499	481	135.8	12.5	0.97	348	569	481	133.7	12.1
1.99	81.8	652	194	73.3	6.3	1.04	290	536	409	125.3	11.2
4.03	12	569	80.5	41.4	3.9	1.95	68.3	620	176	66.1	6.0
5.01	24	953	81.4	33.5	3.4	4.08	17.5	582	89.7	36.0	3.9
7.81	4.85	694	60.8	21.0	2.6	5.08	13.4	658	83.1	26.7	3.2
10.60	1760	1100	133	15.9	2.3	7.97	7.28	484	68.1	NA	NA
						10.00	5.08	595	61.9	1.3	NA

NA – Not available.

Table C 12. Column leaching data for the LFC material packed at 7% moisture content after exposure to 40 F/T cycles – Primary contaminants.

Replicate A							Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)		LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.12	0.34	0.030	0.56	8.57	0.20		0.11	0.54	0.044	0.78	7.34	0.29
0.21	0.27	0.024	0.49	7.75	0.17		0.19	0.30	0.029	0.60	9.34	0.20
0.46	0.12	0.013	0.29	5.24	0.09		0.22	0.23	0.025	0.53	7.81	0.18
0.54	0.11	0.012	0.27	4.56	0.09		0.44	0.10	0.020	0.36	5.22	0.10
0.94	0.04	0.006	0.15	3.16	0.06		0.52	0.09	0.013	0.30	4.80	0.10
1.01	0.04	0.008	0.15	2.83	0.06		0.97	0.04	0.005	0.14	3.13	0.06
1.99	0.03	0.004	0.10	2.40	0.05		1.04	0.03	0.004	0.12	2.87	0.05
4.03	0.03	0.002	0.08	1.79	0.05		1.95	0.02	0.002	0.09	2.21	0.05
5.01	0.03	0.002	0.07	2.67	0.05		4.08	0.02	0.002	0.07	1.81	0.05
7.81	0.02	0.002	0.05	1.57	0.05		5.08	0.03	0.002	0.06	1.80	0.04
10.60	0.02	0.005	0.06	1.76	0.05		7.97	0.03	0.001	0.05	1.24	0.03
							10.00	0.02	0.002	0.03	0.95	0.04

LFC material packed at 15% moisture content - Exposure to 0 F/T

Table C 13. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.11	13.4	36.0	0.15	13.2	33.0
0.14	NA	NA	0.18	NA	NA
0.21	13.2	31.0	0.26	13.1	28.0
0.25	13.2	30.0	0.30	13.2	26.0
0.48	13.0	22.0	0.53	13.0	19.0
1.13	12.6	12.0	1.12	12.6	10.0
1.87	12.2	9.5	2.12	12.2	8.5
3.12	12.6	8.5	3.29	12.2	7.5
4.80	12.3	9.4			

Table C 14. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.11	2110	678	4000	981.9	335.2	0.15	1880	702	3560	864.8	273.0
0.14	1740	692	3300	869.6	242.5	0.18	1490	655	2840	787.1	203.3
0.21	1640	707	3090	813.0	205.1	0.26	1440	678	2720	708.7	165.9
0.25	1350	652	2580	742.7	165.8	0.30	1340	684	2550	638.2	130.7
0.48	1110	782	2110	544.2	80.7	0.53	1010	779	1760	446.4	59.5
1.13	400	1040	811	243.1	NA	1.12	274	1010	585	196.0	NA
1.87	100	1260	287	147.3	NA	2.12	62.5	1150	212	121.3	NA
3.12	17.9	644	110	91.2	6.7	3.29	14	620	109	77.0	6.1
4.80	9.29	784	107	68.9	5.7						

NA – Not available.

Table C 15. Column leaching data for the LFC material packed at 15% moisture content after exposure to 0 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.11	0.24	0.018	0.82	8.72	0.27	0.15	0.26	0.021	0.82	7.86	0.27
0.14	0.16	0.014	0.77	7.28	0.24	0.18	0.15	0.017	0.72	6.26	0.23
0.21	0.17	0.014	0.71	7.01	0.22	0.26	0.11	0.014	0.69	6.04	0.21
0.25	0.07	0.011	0.64	5.72	0.20	0.30	0.06	0.009	0.56	5.68	0.17
0.48	0.06	0.008	0.46	5.27	0.15	0.53	0.05	0.007	0.40	4.43	0.12
1.13	0.02	0.014	0.22	3.20	0.13	1.12	0.01	0.003	0.17	2.72	0.18
1.87	0.02	0.006	0.13	2.81	0.09	2.12	0.02	0.003	0.11	2.46	0.08
3.12	0.02	0.002	0.07	2.25	0.05	3.29	0.02	0.002	0.07	2.16	0.05
4.80	0.02	0.004	0.07	2.66	0.07						

LFC material packed at 15% moisture content - Exposure to 10 F/T

Table C 16. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
NA	NA	NA	0.04	13.4	40.0
NA	NA	NA	0.12	13.4	37.0
NA	NA	NA	0.15	13.3	35.0
NA	NA	NA	0.23	13.3	32.0
NA	NA	NA	0.55	12.9	22.0
NA	NA	NA	1.02	12.6	15.0
NA	NA	NA	2.22	12.3	9.0
NA	NA	NA	5.14	12.3	9.0

NA – Not available. The column leaked.

Table C 17. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
NA	NA	NA	NA	NA	NA	0.04	2170	464	4130	740.2	161.3
NA	NA	NA	NA	NA	NA	0.12	2060	490	3880	691.4	135.0
NA	NA	NA	NA	NA	NA	0.15	1840	514	3470	632.0	107.5
NA	NA	NA	NA	NA	NA	0.23	1700	541	3220	608.6	89.6
NA	NA	NA	NA	NA	NA	0.55	1090	648	1940	386.7	32.3
NA	NA	NA	NA	NA	NA	1.02	523	946	964	222.7	12.2
NA	NA	NA	NA	NA	NA	2.22	67.4	674	196	NA	NA
NA	NA	NA	NA	NA	NA	5.14	7.59	657	91	NA	NA

NA – Not available. The column leaked.

Table C 18. Column leaching data for the LFC material packed at 15% moisture content after exposure to 10 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
NA	NA	NA	NA	NA	NA	0.04	0.29	0.030	1.25	7.67	0.53
NA	NA	NA	NA	NA	NA	0.12	0.35	0.019	1.08	7.05	0.33
NA	NA	NA	NA	NA	NA	0.15	0.68	0.015	0.90	6.34	0.25
NA	NA	NA	NA	NA	NA	0.23	0.32	0.014	0.84	5.90	0.23
NA	NA	NA	NA	NA	NA	0.55	1.03	0.008	0.48	4.16	0.20
NA	NA	NA	NA	NA	NA	1.02	5.19	0.014	0.28	3.28	0.18
NA	NA	NA	NA	NA	NA	2.22	0.02	0.003	0.09	2.51	0.06
NA	NA	NA	NA	NA	NA	5.14	0.01	0.002	0.06	2.27	0.04

NA – Not available. The column leaked.

LFC material packed at 15% moisture content - Exposure to 20 F/T

Table C 19. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.04	13.3	31.0	NA	NA	NA
0.07	13.2	38.0	NA	NA	NA
0.19	13.3	34.0	NA	NA	NA
0.73	12.6	14.0	NA	NA	NA
1.76	12.5	10.0	NA	NA	NA
2.02	12.3	9.5	NA	NA	NA

NA – Not available. The column leaked.

Table C 20. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.04	2020	149	3950	820.6	177.9	NA	NA	NA	NA	NA	NA
0.07	1600	163	2910	744.8	162.4	NA	NA	NA	NA	NA	NA
0.19	1280	194	2350	605.4	101.1	NA	NA	NA	NA	NA	NA
0.73	459	379	690	235.9	14.3	NA	NA	NA	NA	NA	NA
1.76	135	598	323	135.5	7.3	NA	NA	NA	NA	NA	NA
2.02	79.2	616	219	73.6	NA	NA	NA	NA	NA	NA	NA

NA – Not available. The column leaked.

Table C 21. Column leaching data for the LFC material packed at 15% moisture content after exposure to 20 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.04	0.18	0.006	0.95	7.81	0.26	NA	NA	NA	NA	NA	NA
0.07	0.10	0.013	0.71	7.46	0.22	NA	NA	NA	NA	NA	NA
0.19	0.18	0.016	0.64	6.38	0.18	NA	NA	NA	NA	NA	NA
0.73	0.04	0.003	0.19	2.82	0.06	NA	NA	NA	NA	NA	NA
1.76	0.02	0.002	0.11	2.54	0.06	NA	NA	NA	NA	NA	NA
2.02	0.02	0.002	0.10	2.39	0.06	NA	NA	NA	NA	NA	NA

NA – Not available. The column leaked.

LFC material packed at 15% moisture content - Exposure to 40 F/T

Table C 22. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.12	13.2	33.0	0.11	13.4	32.0
0.20	13.1	29.0	0.19	13.4	28.0
0.47	13.2	20.0	0.22	13.1	27.0
0.55	12.9	18.0	0.44	13.0	20.0
1.04	12.6	11.0	0.53	13.1	18.0
2.00	12.5	9.1	1.01	12.7	11.0
2.05	12.4	9.3	1.98	12.4	9.0
4.13	12.6	8.0	2.02	12.5	9.5
5.03	12.6	8.7	4.14	12.3	8.9
8.17	11.9	7.8	4.98	12.5	8.7
10.25	12.1	6.8	5.08	12.5	9.5
			8.01	11.6	7.1
			10.44	12.4	7.7

Table C 23. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.12	NA	904	NA	422.3	79.6	0.11	1620	195	2770	401.4	65.0
0.20	1340	212	2310	350.1	51.8	0.19	1300	204	2230	344.8	45.2
0.47	784	280	1350	242.9	19.5	0.22	1160	283	2000	334.1	36.1
0.55	726	300	1240	227.6	17.3	0.44	NA	NA	NA	243.6	18.5
1.04	356	500	510	122.4	6.7	0.53	717	302	1250	226.9	16.2
2.00	80.6	708	191	74.4	4.0	1.01	327	492	505	125.0	6.5
2.05	73.3	979	176	72.6	3.9	1.98	81.3	684	195	76.8	4.0
4.13	13.2	2880	71.3	46.4	3.0	2.02	76.5	1010	185	75.5	4.0
5.03	9.88	973	66.2	39.1	2.8	4.14	9.88	1050	72.3	46.9	3.1
8.17	NA	NA	59.4	NA	NA	4.98	9.51	971	68.1	38.9	2.9
10.25	4.21	NA	59.1	19.5	2.1	5.08	9.47	983	67.3	38.6	2.9
						8.01	6.09	906	60.1	NA	NA
						10.44	4.22	689	57.5	17.9	2.1

NA – Not available.

Table C 24. Column leaching data for the LFC material packed at 15% moisture content after exposure to 40 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.12	0.29	0.021	0.62	NA	0.18	0.11	0.280	0.020	0.65	7.18	0.17
0.20	0.20	0.014	0.53	1.17	0.14	0.19	0.169	0.016	0.56	5.77	0.14
0.47	0.09	0.008	0.30	3.94	0.08	0.22	0.134	0.014	0.47	5.26	0.12
0.55	0.08	0.007	0.27	3.73	0.07	0.44	NA	NA	NA	NA	NA
1.04	0.04	0.003	0.15	2.71	0.06	0.53	0.071	0.009	0.28	3.85	0.08
2.00	0.03	0.002	0.11	2.44	0.05	1.01	0.036	0.005	0.16	2.74	0.06
2.05	0.02	0.002	0.10	2.42	0.04	1.98	0.022	0.002	0.10	2.49	0.05
4.13	0.03	0.002	0.10	2.14	0.05	2.02	0.024	0.003	0.11	2.53	0.05
5.03	0.03	0.002	0.10	2.17	0.05	4.14	0.022	0.002	0.10	2.33	0.06
8.17	0.03	0.001	0.07	1.76	0.04	4.98	0.020	0.002	0.09	2.21	0.05
10.25	0.02	0.002	0.05	1.30	0.05	5.08	0.020	0.001	0.09	2.25	0.05
						8.01	0.002	0.001	0.07	1.90	0.04
						10.44	0.023	0.003	0.05	1.38	0.06

NA – Not available.

LFC material packed at the optimum moisture content (29% moisture content) - Exposure to 0 F/T

Table C 25. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.03	13.6	46.0	0.03	13.3	46.0
0.06	13.6	44.0	0.07	13.3	43.0
0.14	13.3	39.0	0.14	13.6	39.0
0.17	13.2	37.0	0.17	13.4	35.0
0.50	12.9	21.0	0.50	13.1	21.0
1.05	12.6	14.0	1.03	12.7	14.0
2.01	12.7	10.0	2.00	12.6	10.0
5.07	12.4	9.2	4.97	12.1	6.9
8.18	12.5	7.5	8.76	12.2	6.8
10.29	12.0	7.0	9.85	12.6	6.5

Table C 26. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.03	1950	332	3490	74.0	103.5	0.03	NA	NA	NA	76.8	101.1
0.06	1860	333	3350	66.0	91.3	0.07	1820	313	3160	68.3	86.1
0.14	1680	351	2950	460.6	72.0	0.14	1670	1000	2920	452.3	69.0
0.17	1540	355	2670	422.4	56.6	0.17	1450	342	2530	405.6	52.5
0.50	793	554	1370	247.6	15.7	0.50	817	468	1390	250.1	15.3
1.05	286	755	506	124.7	5.5	1.03	284	685	504	122.3	5.3
2.01	88.7	896	190	70.2	3.2	2.00	81.5	786	182	67.0	3.1
5.07	10.2	845	65.7	31.6	2.1	4.97	NA	1000	72.4	32.7	2.0
8.18	4.62	671	55.2	18.0	1.7	8.76	NA	1100	NA	19.6	1.6
10.29	11.2	1150	130	13.7	1.5	9.85	NA	1110	NA	33.1	NA

NA – Not available.

Table C 27. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 0 F/T cycles – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.03	0.267	0.029	1.23	9.77	0.27	0.03	0.253	0.034	NA	9.27	0.25
0.06	0.253	0.034	1.29	9.27	0.25	0.07	0.229	0.028	1.25	8.83	0.24
0.14	0.188	0.022	1.18	8.33	0.20	0.14	0.196	0.025	1.20	8.35	0.22
0.17	0.152	0.020	0.96	7.62	0.18	0.17	0.156	0.021	0.94	7.16	0.18
0.50	0.048	0.009	NA	4.57	0.09	0.50	0.059	0.010	0.49	4.33	0.10
1.05	0.025	0.004	NA	3.10	0.07	1.03	0.019	0.004	0.19	2.79	0.06
2.01	0.014	0.002	NA	2.45	0.05	2.00	0.014	0.003	0.09	2.08	0.05
5.07	0.018	0.002	NA	1.84	0.05	4.97	0.016	0.002	0.05	1.82	0.05
8.18	0.003	0.001	0.03	1.13	0.04	8.76	0.004	0.000	0.05	1.66	0.05
10.29	0.016	0.003	0.04	1.51	0.06	9.85	0.004	0.001	0.04	1.64	0.06

NA – Not available.

LFC material packed at the optimum moisture content (29% moisture content) - Exposure to 10 F/T

Table C 28. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles - pH and conductivity.

Replicate A				Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)		LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.04	13.3	39.0		0.06	13.4	36.0
0.12	13.2	35.0		0.13	13.2	34.0
0.16	13.2	33.0		0.17	13.3	33.0
0.24	13.3	31.0		0.25	13.3	30.0
0.51	13.0	21.0		0.49	13.0	20.0
1.03	12.6	13.0		0.79	12.7	17.0
1.96	12.4	8.6		4.88	12.0	9.0
4.90	12.1	9.0				

Table C 29. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles – Major material constituents.

Replicate A							Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)		LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.04	1890	312	3660	775.2	183.5		0.06	1870	321	3630	857.3	206.1
0.12	1780	333	3480	723.1	153.6		0.13	1740	326	3380	770.3	162.1
0.16	1700	355	3280	663.5	125.8		0.17	1610	337	3120	708.6	127.4
0.24	1430	345	2780	637.3	104.4		0.25	1490	353	2890	659.8	108.0
0.51	983	422	1720	399.1	38.9		0.49	942	395	1640	420.9	41.9
1.03	456	595	831	223.1	14.7		0.79	658	503	1170	304.6	21.1
1.96	78.1	570	215	70.9	NA		4.88	7.43	616	92.8	39.0	NA
4.90	9.03	658	93.6	NA	NA							

NA – Not available.

Table C 30. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 10 F/T cycles – Primary contaminants.

Replicate A							Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)		LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.04	0.221	0.015	1.04	7.38	0.27		0.06	0.261	0.016	1.04	7.50	0.27
0.12	0.238	0.018	0.98	7.22	0.25		0.13	0.250	0.013	0.99	6.91	0.23
0.16	0.188	0.013	0.85	6.83	0.21		0.17	0.209	0.012	0.90	6.45	0.20
0.24	0.163	0.012	0.80	5.86	0.19		0.25	0.187	0.013	0.76	6.00	0.19
0.51	0.074	0.006	0.44	4.15	0.11		0.49	0.089	0.006	0.44	3.90	0.11
1.03	0.031	0.005	0.23	3.03	0.08		0.79	0.054	0.006	0.31	3.48	0.09
1.96	0.024	0.003	0.09	2.26	0.05		4.88	0.025	0.002	0.06	2.10	0.05
4.90	0.016	0.002	0.07	2.34	0.06							

NA – Not available.

LFC material packed at the optimum moisture content (29% moisture content) - Exposure to 20 F/T

Table C 31. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles - pH and conductivity.

Replicate A				Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)		LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.08	13.3	38.0		0.03	13.28	45
0.12	13.2	33.0		0.06	13.41	43
0.21	13.2	29.0		0.12	13.30	40
0.31	13.1	25.0		0.16	13.23	36
1.04	12.8	13.0		0.39	13.02	19
1.72	12.4	11.0		1.05	12.70	15
2.06	12.3	9.6		1.75	12.58	11
				2.17	12.42	9.2
				4.99	11.85	8.2

Table C 32. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles – Major material constituents.

Replicate A							Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)		LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.08	1970	3820	319	700.4	9.0		0.03	2110	4070	242	777.0	152.3
0.12	1720	3310	329	643.8	13.0		0.06	1920	3710	221	736.4	138.9
0.21	1540	2950	338	588.8	21.1		0.12	1780	3410	206	693.8	118.2
0.31	1290	2490	364	508.3	26.9		0.16	1720	3340	226	653.4	95.4
1.04	506	921	556	213.5	50.2		0.39	1100	1930	329	403.7	33.6
1.72	131	358	730	121.8	55.9		1.05	515	959	505	209.2	11.0
2.06	104	302	831	118.1	57.9		1.75	181	458	690	127.1	5.7
							2.17	85.9	273	702	102.5	4.7
							4.99	7.2	106	697	49.7	NA

NA – Not available.

Table C 33. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 20 F/T cycles – Primary contaminants.

Replicate A							Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)		LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.08	0.250	0.017	0.996	7.77	0.270		0.03	0.163	0.014	1.200	7.69	0.273
0.12	0.203	0.012	0.918	6.95	0.217		0.06	0.089	0.014	0.992	7.10	0.255
0.21	0.178	0.012	0.845	6.98	0.203		0.12	0.117	0.009	0.975	6.98	0.219
0.31	0.120	0.009	0.852	5.37	0.136		0.16	0.094	0.009	0.866	6.52	0.185
1.04	0.023	0.004	0.301	2.99	0.067		0.39	0.029	0.006	0.399	5.08	0.078
1.72	0.018	0.003	0.204	2.73	0.058		1.05	0.035	0.004	0.212	3.04	0.066
2.06	0.016	0.004	0.104	2.94	0.065		1.75	0.023	0.004	0.131	2.66	0.066
							2.17	0.022	0.004	0.103	2.51	0.066
							4.99	0.023	0.002	0.069	NA	0.057

NA – Not available.

LFC material packed at the optimum moisture content (29% moisture content) - Exposure to 40 F/T

Table C 34. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles - pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.04	13.5	44.0	0.04	13.3	42.0
0.08	13.5	41.0	0.12	13.5	37.0
0.15	13.3	35.0	0.16	13.2	35.0
0.19	NA	NA	0.27	13.2	30.0
0.49	13.0	21.0	0.46	13.1	22.0
0.56	13.1	19.0	0.57	12.9	19.0
1.07	12.7	11.0	1.04	12.7	11.0
2.01	12.4	9.0	1.98	12.3	8.4
4.08	12.5	7.0	2.02	12.4	8.3
4.94	12.0	8.8	4.07	12.4	8.2
5.04	12.4	9.0	4.95	12.4	8.6
8.16	11.8	7.2	5.04	12.2	8.7
10.30	12.3	7.0	8.08	11.6	7.6
			10.19	12.1	7.3

Table C 35. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.04	1820	347	3130	518.8	72.8	0.04	1700	381	2920	507.8	79.2
0.08	1660	360	2850	482.5	68.1	0.12	1670	391	2840	465.0	66.6
0.15	1680	434	2870	443.5	56.5	0.16	1490	394	2540	413.8	51.6
0.19	1460	400	2510	397.9	44.3	0.27	1280	411	2200	362.3	39.2
0.49	885	470	1540	264.4	17.4	0.46	928	442	1580	278.8	19.7
0.56	741	491	1280	239.0	14.3	0.57	741	474	1290	231.4	14.0
1.07	283	777	518	116.1	5.1	1.04	308	750	560	118.6	5.3
2.01	92	1060	218	68.3	3.3	1.98	73	869	181	70.8	3.3
4.08	13	994	79	43.7	2.5	2.02	76	1170	180	70.8	3.4
4.94	8	930	66	36.0	2.3	4.07	10	894	71	44.5	2.6
5.04	9	942	70	37.0	2.3	4.95	8	917	69	38.7	2.5
8.16	6	873	64	NA	NA	5.04	7	957	68	37.8	2.5
10.30	3	413	40	19.7	1.8	8.08	6	728	58	NA	NA
						10.19	4	697	NA	19.7	2.0

NA – Not available.

Table C 36. Column leaching data for the LFC material packed at the optimum moisture content (29% moisture content) after exposure to 40 F/T cycles – Primary contaminants.

Replicate A							Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)		LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.04	0.207	0.030	1.15	8.02	0.26		0.04	0.302	0.028	0.97	7.68	0.22
0.08	0.257	0.029	1.01	7.25	0.21		0.12	0.283	0.025	0.93	7.45	0.20
0.15	0.194	0.026	0.67	7.46	0.18		0.16	0.199	0.022	0.62	6.42	0.17
0.19	0.154	0.022	0.59	6.49	0.16		0.27	0.147	0.019	0.49	5.74	0.14
0.49	0.066	0.011	0.33	4.2	0.09		0.46	0.082	0.011	0.32	4.31	0.09
0.56	0.056	0.010	0.30	3.69	0.08		0.57	0.062	0.009	0.30	3.70	0.08
1.07	0.021	0.003	0.13	2.35	0.04		1.04	0.028	0.004	0.15	2.80	0.05
2.01	0.018	0.002	0.10	2.54	0.04		1.98	0.020	0.004	0.10	2.16	0.05
4.08	0.021	0.001	0.09	2.25	0.05		2.02	0.021	0.002	0.10	2.30	0.05
4.94	0.021	0.002	0.08	1.93	0.05		4.07	0.011	0.002	0.08	2.03	0.04
5.04	0.018	0.001	0.07	2.08	0.04		4.95	0.016	0.002	0.08	2.02	0.05
8.16	0.018	0.001	0.06	1.77	0.04		5.04	0.017	0.002	0.08	1.95	0.04
10.30	0.023	0.002	0.04	0.713	0.05		8.08	0.018	0.001	0.06	1.45	0.04
							10.19	0.020	0.002	0.05	1.41	0.06

Appendix D - Intermittent wetting/flow-through coupled with F/T exposure

<u>Intermittent flow-around mass transfer test coupled with F/T aging</u>

Table D 1. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – pH and conductivity.

Cum time (hr)	pH		Conductivity (mS/cm)	
	A	B	A	B
2	12.05	12.03	3.30	2.80
5	11.52	11.51	0.91	0.94
8	11.49	11.17	0.72	0.83
24	11.51	11.51	1.40	1.40
48	F/T exp.	F/T exp.	F/T exp.	F/T exp.
72	11.74	11.84	1.50	1.60
120	F/T exp.	F/T exp.	F/T exp.	F/T exp.
168	11.99	11.94	2.10	2.10
264	F/T exp.	F/T exp.	F/T exp.	F/T exp.
360	12.16	12.05	3.30	3.00

Table D 2. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – Major material constituents.

Cum time (hr)	Na (mg/L)		K (mg/L)		Ca (mg/L)		Cl (mg/L)		SO_4^{2-} (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	6.3	24.9	122.1	132.9	230.7	253.4	39.1	45.0	29.3	34.4
5	11.8	13.4	30.3	25.3	59.2	49.7	9.0	7.5	4.9	4.5
8	7.2	11.4	21.5	27.4	39.9	50.9	6.7	8.4	2.5	3.8
24	21.8	18.5	43.7	45.9	89.7	93.3	11.8	13.0	2.9	3.3
48	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
72	23.2	16.6	48.4	54.5	102.9	112.5	12.0	13.7	1.9	2.3
120	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
168	28.4	32.9	59.9	60.1	129.3	126.3	14.4	15.1	1.4	2.3
264	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
360	58.2	50.1	90.3	86.9	198.8	188.7	20.8	20.3	1.3	1.2

Table D 3. Mass transfer data for intermittent flow-around coupled with F/T exposure of the less than 9.5 mm graded LFC material – Primary contaminants.

Cum time (hr)	As (mg/L)		Cd (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)	
	A	B	A	B	A	B	A	B	A	B
2	0.230	0.258	0.002	0.001	0.055	0.060	0.298	0.298	0.050	0.037
5	0.184	0.241	0.001	0.001	0.016	0.015	0.091	0.084	0.032	0.030
8	0.085	0.128	0.001	0.001	0.013	0.016	0.087	0.110	0.025	0.029
24	0.071	0.102	0.002	0.006	0.020	0.026	0.173	0.189	0.031	0.046
48	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
72	0.051	0.051	0.002	0.002	0.018	0.019	0.163	0.194	0.023	0.026
120	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
168	0.033	0.050	0.002	0.002	0.019	0.020	0.208	0.206	0.019	0.021
264	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.	F/T exp.
360	0.026	0.033	0.003	0.003	0.025	0.027	0.281	0.285	0.026	0.022

Intermittent flow-though columns coupled with F/T aging

Table D 4. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – pH and conductivity.

Replicate A			Replicate B		
LS ratio (L/kg)	pH	Conductivity (mS/cm)	LS ratio (L/kg)	pH	Conductivity (mS/cm)
0.019	13.3	40.0	0.052	13.13	36
0.039	13.1	40.0	0.084	13.003	34
0.048	13.2	NA	0.167	13.006	NA
0.078	12.9	28.0	0.190	13.033	37
0.144	NA	NA	0.264	NA	NA
F/T exp.			F/T exp.		
0.160	13.0	27.0	0.348	12.498	12
0.185	12.9	29.0	0.373	12.659	13
0.265	13.0	28.0	0.442	12.429	12
0.290	12.9	24.0	0.482	12.451	12
F/T exp.			F/T exp.		
0.353	12.6	22.0	0.729	12.216	11
0.378	12.5	23.0	0.759	11.986	12
0.415	12.5	22.0	0.823	12.186	12
F/T exp.			0.860	12.14	11
0.757	11.9	9.5	F/T exp.		
0.784	11.7	8.6	0.974	12.001	9.9
0.854	11.6	9.2	1.442	12.144	11
0.878	12.1	8.3	1.473	11.902	9
			F/T exp.		
			1.550	12.205	13
			1.570	12.009	11
			1.598	12.242	7.8

NA – Not available.

Table D 5. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – Major material constituents.

Replicate A						Replicate B					
LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)	LS ratio (L/kg)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Cl (mg/L)	SO_4^{2-} (mg/L)
0.019	1490	2700	278	584.6	383.3	0.052	1400	2560	309	538.8	335.7
0.039	1500	2700	293	582.5	344.2	0.084	1210	2230	315	480.2	226.5
0.048	1420	2590	275	425.9	162.1	0.167	1100	2040	310	443.0	189.1
0.078	995	1830	321	448.8	141.0	0.190	1450	2640	299	534.5	277.2
0.144	NA		NA	NA	NA	0.264	NA	NA	NA	NA	NA
F/T exp.						F/T exp.					
0.160	1110	2010	106	435.3	114.7	0.348	400	826	493	147.9	20.7
0.185	1090	1960	336	403.1	96.0	0.373	375	783	525	139.7	18.2
0.265	1290	2300	387	366.0	79.4	0.442	355	742	539	132.4	16.7
0.290	893	1620	339	311.9	52.3	0.482	359	750	580	123.0	14.6
F/T exp.						F/T exp.					
0.353	923	1450	328	304.5	46.1	0.729	242	527	601	104.5	10.6
0.378	907	1330	354	95.1	9.5	0.759	217	486	638	97.0	9.8
0.415	176	410	601	NA	NA	0.823	194	440	624	90.7	8.9
F/T exp.						0.860	903	1330	380	248.0	37.2
0.757	83	255	700	85.8	7.1	F/T exp.					
0.784	77	213	509	84.4	6.9	0.974	161	383	649	95.6	9.1
0.854	72	206	497	79.0	6.4	1.442	NA	NA	NA	NA	NA
0.878	62	187	471	67.1	5.5	1.473	146	355	656	91.5	8.5
						F/T exp.					
						1.550	67	211	696	63.2	6.7
						1.570	362	690	527	8.3	NA
						1.598	219	437	436	8.1	NA

NA – Not available.

Table D 6. Column leaching data for intermittent flow-through coupled with F/T exposure of the LFC material packed at the optimum moisture content (29% moisture content) – Primary contaminants.

Replicate A						Replicate B					
LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	LS ratio (L/kg)	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
0.019	0.338	0.019	0.746	6.57	0.231	0.052	0.342	0.0197	0.764	6.25	0.248
0.039	0.394	0.021	0.825	6.75	0.216	0.084	0.253	0.0173	0.662	5.55	0.171
0.048	0.243	0.019	0.775	6.32	0.208	0.167	0.222	0.0162	0.598	5.10	0.154
0.078	0.178	0.013	0.516	4.61	0.132	0.190	0.334	0.0198	0.781	6.51	0.209
0.144	NA	NA	NA	NA	NA	0.264	NA	NA	NA	NA	NA
F/T exp.						F/T exp.					
0.160	0.008	0.005	0.492	4.53	0.117	0.348	0.040	0.0045	0.172	2.36	0.067
0.185	0.163	0.015	0.577	5.06	0.149	0.373	0.046	0.0046	0.169	2.34	0.067
0.265	0.138	0.013	0.555	6.17	0.141	0.442	0.048	0.0044	0.165	2.37	0.064
0.290	0.120	0.011	0.468	4.27	0.118	0.482	0.043	0.0046	0.158	2.50	0.064
F/T exp.						F/T exp.					
0.353	0.039	0.009	0.409	3.82	0.106	0.729	0.039	0.0041	0.161	2.24	0.065
0.378	0.068	0.010	0.412	3.76	0.114	0.759	0.037	0.0037	0.154	2.25	0.063
0.415	0.033	0.003	0.137	2.06	0.063	0.823	0.036	0.0035	0.144	2.19	0.062
F/T exp.						0.860	0.063	0.0095	0.449	3.77	0.107
0.757	0.029	0.004	0.082	2.05	0.058	F/T exp.					
0.784	0.032	0.004	0.088	2.14	0.061	0.974	0.032	0.0037	0.128	2.16	0.060
0.854	0.032	0.003	0.081	2.16	0.059	1.442	NA	NA	NA	NA	NA
0.878	0.029	0.003	0.077	1.98	0.054	1.473	0.034	0.0031	0.132	2.12	0.063
						F/T exp.					
						1.550	0.029	0.0033	0.105	1.95	0.066
						1.570	0.049	0.0038	0.193	2.05	0.090
						1.598	0.046	0.0038	0.143	2.12	0.074

NA – Not available.