

# **Service Life Prediction Based on Sorptivity for Highway Concrete Exposed to Sulfate Attack and Freeze-Thaw Conditions**

by

**Dale P. Bentz, Mark A. Ehlen, Chiara F. Ferraris  
and John A. Winpigler**

**Building and Fire Research Laboratory  
National Institute of Standards and Technology  
Gaithersburg, MD 20899 USA**

**Reprinted from Federal Highway Administration Report No. FHWA-RD-01-162, U.S.  
Department of Transportation, 62 pages, March 2002.**

**NOTE: This paper is a contribution of the National Institute of Standards and  
Technology and is not subject to copyright.**



**National Institute of Standards and Technology**  
Technology Administration, U.S. Department of Commerce

# Service Life Prediction Based on Sorptivity for Highway Concrete Exposed to Sulfate Attack and Freeze-Thaw Conditions

PUBLICATION NO. FHWA RD-01-162

MARCH 2002



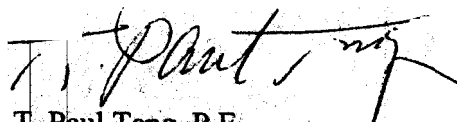
US Department of Transportation  
**Federal Highway Administration**

Research, Development, and Technology  
Turner-Fairbank Highway Research Center  
6300 Georgetown Pike  
McLean, VA 22101-2296

## FOREWORD

This report documents the investigation of permeability as an indicator of the general durability of hydraulic cement concrete. Since many deterioration mechanisms for concrete depend on ingress of moisture and other materials into the concrete, it was theorized that permeability might be a good indicator of durability potential. During the investigation, it was determined that sorptivity is a more relevant characteristic of the concrete, and a test method was developed to measure sorptivity in several ways, in order to simulate field exposure. Once the concrete sorptivity was selected as influencing durability, models were developed to predict the service life of concrete when exposed to external sulfate attack or a freeze-thaw environment. These models were packaged in a trial version software package called CONCLIFE.

This report will be of interest to those involved in concrete durability, as well as those involved in the design, construction, and analysis of concrete pavements. Sufficient copies are being distributed to provide five copies to each FHWA Resource Center, two copies to each FHWA Division, and two copies to each State highway agency. Direct distribution is being made to the FHWA Division Offices. Additional copies may be purchased from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161.



T. Paul Teng, P.E.  
Director, Office of Infrastructure  
Research and Development

## NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturer's names appear in this report only because they are considered essential to the object of the document.

1. Report No. <b>FHWA-RD-01-162</b>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <b>Service Life Prediction Based on Sorptivity for Highway Concrete Exposed to Sulfate Attack and Freeze-Thaw Conditions</b>		5. Report Date <b>March 2002</b>	
		6. Performing Organization Code	
7. Author(s) <b>Dale P. Bentz, Mark A. Ehlen, Chiara F. Ferraris, and John A. Winpigler</b>		8. Performing Organization Report No.	
9. Performing Organization Name and Address <b>National Institute of Standards and Technology 100 Bureau Drive Gaithersburg, MD 20899</b>		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. <b>DTFH61-98-Y-50058</b>	
12. Sponsoring Agency Name and Address <b>Federal Highway Administration Office of Infrastructure Research and Development 6300 Georgetown Pike McLean, VA 22101-2296</b>		13. Type of Report and Period Covered <b>Final Report 1998-2001</b>	
		14. Sponsoring Agency Code <b>HRDI-12</b>	
15. Supplementary Notes: <b>FHWA Contracting Officer's Technical Representative (COTR): Dr. Stephen W. Forster Special thanks to these highway agencies for their assistance: Maryland, Missouri, Rhode Island, and Virginia.</b>			
16. Abstract This report documents a study that investigated permeability as an indicator of the general durability of hydraulic cement concrete. Since many concrete deterioration mechanisms depend on the ingress of moisture and other materials into the concrete, it was theorized that permeability might be a good indicator of durability potential. During the project, it was determined that sorptivity is the most relevant transport characteristic of the concrete. A test method for sorptivity was therefore developed, which has two different setups, in order to better reproduce the exposure condition being simulated. User-friendly software, CONCLIFE, was then developed for estimating the service life of concrete pavements and bridge decks exposed to sulfate attack and freeze-thaw deterioration. CONCLIFE uses three concrete models and user-specified data on concrete properties and external environmental conditions to estimate the time at which the concrete surface spalls beyond a user-specified limit. Ingress of sulfate ions and water are the primary means of degradation considered by the software. CONCLIFE uses the results of the laboratory test described above, currently in the ASTM standardization process, for measuring concrete sorptivity. The software produces graphs of concrete sorptivity, annual precipitation, and estimated rates of concrete spalling based on the input. Details of the experimental program conducted in support of the software development and the underlying technical bases for the computer models employed in CONCLIFE are also included.			
17. Key Word <b>Concrete bridge decks, concrete pavements, concrete durability, concrete permeability, environmental conditions, freeze-thaw deterioration, service life, sorptivity, sulfate attack.</b>		18. Distribution Statement <b>No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.</b>	
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of Pages <b>62</b>	22. Price



# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find	Symbol
--------	---------------	-------------	---------	--------	---------------	-------------	---------	--------

<b>LENGTH</b>								
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches
ft	feet	0.305	meters	m	m	meters	3.28	feet
yd	yards	0.914	meters	m	m	meters	1.09	yards
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles
<b>AREA</b>								
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>	mm <sup>2</sup>	square millimeters	0.0016	square inches
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	10.764	square feet
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	1.195	square yards
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>	km <sup>2</sup>	square kilometers	0.386	square miles
<b>VOLUME</b>								
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces
gal	gallons	3.785	liters	L	L	liters	0.264	gallons
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	35.71	cubic feet
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	1.307	cubic yards
<b>MASS</b>								
oz	ounces	28.35	grams	g	g	grams	0.035	ounces
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "T")	Mg (or "T")	megagrams (or "metric ton")	1.103	short tons (2000 lb)
<b>TEMPERATURE (exact)</b>								
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature
<b>ILLUMINATION</b>								
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles
fl	foot-Lamberts	3.426	candelas/m <sup>2</sup>	cd/m <sup>2</sup>	cd/m <sup>2</sup>	candelas/m <sup>2</sup>	0.2919	foot-Lamberts
<b>FORCE and PRESSURE or STRESS</b>								
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force
lbf/in <sup>2</sup>	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch

NOTE: Volumes greater than 1000 l shall be shown in m<sup>3</sup>.

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

## TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
<b>CHAPTER 1. INTRODUCTION .....</b>	<b>1</b>
PROJECT OVERVIEW .....	1
DISCLAIMER .....	4
<b>CHAPTER 2. SORPTIVITY TESTING.....</b>	<b>5</b>
MATERIALS.....	5
METHODOLOGY DEVELOPMENT.....	10
Conditioning of the Specimens.....	10
Sorptivity Test.....	12
Results.....	16
Standardization Efforts.....	17
<b>CHAPTER 3. COMPUTER MODELS.....</b>	<b>19</b>
CONCRETE SURFACE TEMPERATURE AND TIME OF WETNESS (HEAT-TRANSFER) MODEL .....	19
SULFATE ATTACK SERVICE LIFE MODEL .....	23
FREEZE-THAW DETERIORATION SERVICE LIFE MODEL .....	24
<b>CHAPTER 4. SUMMARY .....</b>	<b>27</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>31</b>
<b>APPENDIX A. Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Mortars or Concretes.....</b>	<b>33</b>
NECESSARY EQUIPMENT .....	33
TEST SPECIMENS .....	33
SAMPLE CONDITIONING .....	34
PROCEDURE.....	34
Preparation of Specimens for Measurements after Conditioning.....	34
Sorpton Measurement Procedures .....	35
Procedure A: Absorption by capillary suction (bottom surface exposure) .....	35
Procedure B: Absorption by ponding.....	35
Calculations.....	36
Report.....	37
APPENDIX A-1. EXAMPLE RATE OF ABSORPTION TEST .....	38
<b>APPENDIX B. CONCLIFE USER'S MANUAL .....</b>	<b>41</b>
INSTALLATION .....	41
MAIN CONCLIFE SCREENS.....	41
Analysis Set Section.....	42
Sulfate Attack Tab Panel.....	43
Input Parameters.....	43
Time of Wetness.....	44
Sorptivity Function.....	44
Service Life .....	44
Freeze-Thaw Tab Panel.....	45

## TABLE OF CONTENTS (continued)

<b><u>Section</u></b>	<b><u>Page</u></b>
<u>Input Parameters</u> .....	46
<u>Time of Wetness</u> .....	46
<u>Sorptivity Function</u> .....	46
<u>Service Life</u> .....	46
SUPPLEMENTARY CONCLIFE SCREENS .....	47
<b>Edit Own Weather Data Window</b> .....	47
<b>Compute Sorptivity Function Window</b> .....	48
<b>Graphs and Maps</b> .....	49
<u>U.S. Map for Weather Locations</u> .....	49
<u>Sorptivity Function Graph</u> .....	50
<u>Weather Data Graph</u> .....	51
<u>Spalling Graph</u> .....	52
EXAMPLE ANALYSES.....	53
REFERENCES .....	57

# LIST OF FIGURES

## Figure

Figure 1. Relationships between the environment and concrete microstructure and properties in determining service life. ....	1
Figure 2. RH achieved after the various pre-conditionings. ....	11
Figure 3. RH of the air inside the conditioning jars vs. time. ....	12
Figure 4. Comparison of sorption measured by bottom water exposure (capillary) and by ponding. (A) The water content per surface area vs. linear time as measured; (B) the water content per surface area vs. square root of time for the first 7 h only. ....	13
Figure 5. Schematic of the bottom water exposure (capillary) sorption test.....	14
Figure 6. Schematic of the ponding sorption test.....	14
Figure 7. Pictures of observed leaks with the incorrect tape. (A) the water is leaking between the two layers of tape; (B) the water has leaked in between the tape and the specimen sides and is wetting the bottom (non tested surface).....	15
Figure 8. Calculation of the sorption coefficient.....	16
Figure 9. Basic configurations of one-dimensional heat-transfer models for concrete pavements and bridge decks. ....	20
Figure 10. Temperature predictions for a concrete pavement in Providence, RI in the spring.....	22
Figure 11. Plots of wetting events in (top) Kansas City, MO, and (bottom) Providence, RI, both for concrete pavements. ....	23
Figure 12. Schematic of Procedure A. ....	35
Figure 13. Schematic of Procedure B.....	36
Figure 14. CONCLIFE main window showing sulfate attack tab panel.....	42
Figure 15. Freeze-thaw tab panel. ....	45
Figure 16. Generate own data window.....	47
Figure 17. Screen for computing sorptivity function from measured data. ....	48
Figure 18. Map of weather data cities. ....	49
Figure 19. Graph of typical sorptivity function.....	50
Figure 20. Time-of-wetness data for a concrete pavement in Providence, RI. ....	51
Figure 21. Graph of estimated spalling over time for a pavement in Providence, RI, exposed to sulfate attack. ....	52
Figure 22. CONCLIFE sulfate attack tab panel for concrete pavement from Missouri Rt. 65 driving lane.....	54
Figure 23. CONCLIFE freeze-thaw tab panel for concrete pavement from Missouri Rt. 65 driving lane. ....	55



## LIST OF TABLES

<b><u>Table</u></b>	<b><u>Page</u></b>
Table 1. Geographical locations included in the initial release of the CONCLIFE software. ....	3
Table 2. Mix design and concrete properties for the specimens from the Virginia DOT. ....	6
Table 3. Mix design and concrete properties for the specimens from the Maryland DOT. ....	7
Table 4. Mix design and concrete properties for the specimens from the Missouri DOT. ....	8
Table 5. Mix design and concrete properties for the specimens from the Rhode Island DOT. ....	9
Table 6. Modulus of elasticity for the concretes. ....	9
Table 7. Sorptivity properties for the concretes. ....	17
Table 8. Generic material properties for the heat-transfer/time-of-wetness model. ....	20
Table 9. Predicted service lives for the concretes. ....	54

# CHAPTER 1. INTRODUCTION

## PROJECT OVERVIEW

The durability of concrete continues to be a topic of worldwide concern. Despite improvements in materials and methods, many concrete structures still fail prematurely, leading to costly and time-consuming repairs. As shown in figure 1, concrete degradation is a complex topic requiring a fundamental understanding of the exposure environment, the concrete's mechanical and transport properties, and chemical interactions between the concrete and its environment. For most degradation mechanisms, the interaction between the top surface layer of the concrete and its immediate environment is critical to performance.<sup>(1,2)</sup> With this in mind, in 1998, the Federal Highway Administration (FHWA) funded a 3-year research project to be conducted in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) to quantitatively examine the relationships between the transport properties of the concrete surface layer and its durability during field exposure. The initial objective of the project was three-fold: (1) to determine if relationships between service life, considering major degradation processes, and transport properties can be established; (2) if such relationships can be established, to determine if current tests for measuring transport properties can be used to establish the relationships; and (3) if current tests can meet the need, to develop guidelines for selecting, using, and interpreting the results of recommended tests. Because of ongoing FHWA-funded research efforts concerning the influence of concrete diffusivity on service life at other institutions, the NIST research was limited to transport mechanisms other than diffusion and degradation mechanisms other than rebar corrosion.

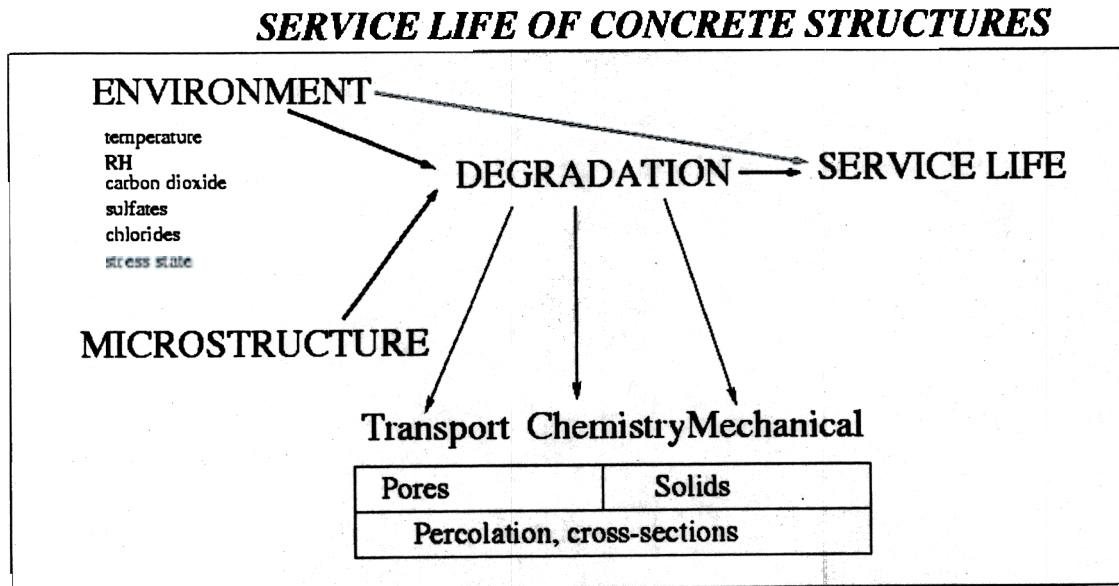


Figure 1. Relationships between the environment and concrete microstructure and properties in determining service life.

Although permeability was originally considered as the primary transport property of relevance for highway concretes, following an extensive review of the existing literature,<sup>(3)</sup> it was determined that (after diffusion) the most likely mode for transport of water and deleterious ions into a field concrete is via sorption by the partially saturated concrete. Concrete sorptivity is defined as the rate (per unit area) at which water is imbibed by a partially saturated concrete. Because the sorption properties of concrete depend critically on its saturation state, in-situ evaluation of concrete sorptivity was rejected due to the highly variable saturation state of field concrete, the difficulties of pre-conditioning concrete to a known saturation state in the field, and the added variability of field temperature and relative humidity conditions. Upon selecting a laboratory-based evaluation of concrete cores obtained from the field, the first step was to develop a pre-conditioning methodology that produces concrete cores with a consistent, uniform, and known internal relative humidity (RH) that is typical of field conditions. Using concrete cores provided by the Maryland, Missouri, Rhode Island, and Virginia State Departments of Transportation (DOT), appropriate laboratory pre-conditioning procedures were developed to produce concrete specimens with a uniform internal RH near 50 percent, within a reasonable period of time. Because no standard test method, neither the American Society for Testing and Materials (ASTM) nor the American Association of State Highway and Transportation Officials (AASHTO), currently exists for evaluating concrete sorptivity in the laboratory, a previously submitted draft ASTM standard for sorptivity testing was revised and championed back into the ASTM committee C09 standardization process (see Appendix A for a generic version of this testing procedure). The revised standard is currently under balloting for the second time and will ultimately be published as an ASTM C09 standard. The standard considers sorption both in the case where the bottom surface of the concrete is in contact with the solution and in the case where water is “ponded” on the concrete surface.

Once sorption was identified as the primary transport mechanism, computer models comprising the CONCLIFE software were developed to relate sorption to degradative spalling for the cases of sulfate attack and freeze-thaw deterioration. In the former case, sorption is responsible for the ingress of deleterious sulfate ions that react with components of the concrete’s cementitious matrix to form expansive products (such as ettringite) that ultimately lead to cracking of the concrete. In the latter case, sorption is responsible for the slow saturation of the concrete’s air void system, compromising the freeze-thaw protection that it normally provides. Sorption will also be relevant to alkali-silica and alkali-carbonate reactions, as moisture is necessary for both of these reactions to proceed at any appreciable rate. For these reactions, the alkali content of the cement and any supplementary cementitious materials (and the environment) and the mineralogical and physical properties of the aggregate will be equally critical in determining the rates of degradation. At the present time, no suitable models exist to quantitatively predict the degradation of concrete due to these reactions under field conditions. **Thus, the degradation modes currently considered by CONCLIFE are limited to sulfate attack and freeze-thaw deterioration.**

A necessary precursor to implementing both of these degradation models was the development of a computer model to predict the surface temperature and time-of-wetness of a field concrete as a function of system geometry, concrete and soil (subbase) thermal properties, and geographical location.<sup>(4)</sup> To quantitatively characterize the local climate, typical meteorological year weather data files supplied by the National Renewable Energy Laboratory<sup>(5)</sup> (NREL;

<http://www.nrel.gov>) were employed. The NREL database contains detailed typical yearly weather data (at 1-hour intervals) for 239 different geographical locations throughout the United States. Thirteen of these locations (see table 1) were selected for inclusion in the initial release of the CONCLIFE software. For these cities, ambient temperatures, dewpoint temperatures, relative humidities, wind speeds, solar irradiance, cloud cover data, and precipitation events were extracted from the data files and used as input into the heat-transfer model. The heat-transfer model considered conduction within the concrete (and any subbase in the case of concrete pavements), convection at exposed concrete surfaces, incoming solar radiation, and radiation emitted from the top concrete surface to the surroundings. A one-dimensional finite difference solution was then employed to estimate the concrete surface temperature as a function of time over the course of 1 year. Whenever the concrete surface temperature fell below freezing, freezing events were logged in a separate time-of-freezing file (developed for each geographical location and construction type). Furthermore, by comparing this surface temperature to the current dewpoint temperature, condensation events were predicted and included along with precipitation events in a time-of-wetness file for each geographical location and default construction type (pavement or bridge deck). Based on the predicted time-of-wetness history of the concrete and its laboratory-measured sorptivity, models were then developed for predicting degradative spalling due to either sulfate attack or freeze-thaw deterioration.<sup>(6)</sup>

Table Geographical locations included in the initial release of the CONCLIFE software.

U.S. City	NREL city code
Kansas City, MO	03947
Tampa, FL	12842
Providence, RI	14765
Lubbock, TX	23042
Tucson, AZ	23160
Cheyenne, WY	24018
Pierre, SD	24025
Seattle, WA	24233
Fresno, CA	93193
Baltimore, MD	93721
Bridgeport, CT	94702
Alpena, MI	94849
Waterloo, IA	94910

The sulfate attack model is based on Atkinson and Hearne's work,<sup>(7)</sup> but whereas they considered diffusion to be the dominant mechanism of sulfate ion transport, CONCLIFE uses sorption as the primary transport mechanism. In this case, in addition to the concrete material properties (sorptivity, elastic modulus, fracture energy, etc.) and the exposure environment, the CONCLIFE user must also specify the concentration of sulfate ions present in the external solution (rainwater or condensation) for the selected geographical location. Based on these inputs, the ingress of sulfate ions during each wetting event is calculated and used to determine the occurrence of spalling due to expansive ettringite formation. The service life is reached when a user-specified spalling depth is exceeded.



The third computer model in CONCLIFE estimates the service life of concrete pavements or bridge decks when the primary mechanism of degradation is freeze-thaw deterioration. Based on the research of Fagerlund,<sup>(8)</sup> this model considers that failure (concrete cracking) under freeze-thaw conditions is due to the slow saturation of the concrete's air void system, which compromises the protection normally provided by the "empty" air voids. The slow saturation rate is characterized by the sorption rate after the "nick-point" time in the measured sorptivity-vs.-time curve.<sup>(6)</sup> For this prediction, the user provides estimates of concrete porosity, air void content, and the critical saturation (zero to one) necessary to compromise the air void system, along with the concrete sorptivity, time-of-wetness, and time-of-freezing data. For each wetting event whose duration exceeds the nick-point time, the cumulative saturation of the air voids at various depths within the concrete is updated. When the local saturation of the air voids exceeds the user-supplied critical value, spalling at that depth occurs with the next freezing event as recorded in the appropriate time-of-freezing file. Once again, the service life is reached when a user-specified spalling depth is exceeded.

This report summarizes the technical research conducted in support of the development of the CONCLIFE software package. Chapter 2 provides details on the development of the sorptivity test method. Chapter 3 provides details on the underlying technical bases for the computer models employed in CONCLIFE. Following a summary chapter, appendices provide a generic version of the standard sorptivity test currently being considered by ASTM and a user's manual for the CONCLIFE software, including example analyses.

## **DISCLAIMER**

The CONCLIFE software was developed at the National Institute of Standards and Technology by employees of the Federal Government in the course of their official duties. Pursuant to title 17 Section 105 of the United States Code, this software is not subject to copyright protection and is in the public domain. CONCLIFE is an experimental system. NIST and FHWA assume no responsibility whatsoever for its use by other parties, and make no guarantees, expressed or implied, about its quality, reliability, or any other characteristic. We would appreciate acknowledgment if the software were used.

The U.S. Department of Commerce makes no warranty, expressed or implied, to users of CONCLIFE, and accepts no responsibility for its use. Users of CONCLIFE assume sole responsibility under Federal law for determining the appropriateness of its use in any particular application, for any conclusions drawn from the results of its use, and for any actions taken or not taken as a result of analyses performed using these tools.

CONCLIFE is intended for use only by those competent in the field of concrete technology and is intended to supplement the informed judgment of the qualified user. Lack of accurate predictions by the CONCLIFE models could lead to erroneous conclusions with regard to materials selection and design. An informed user should evaluate all results.

## CHAPTER 2. SORPTIVITY TESTING

To develop a test to measure the rate of ingress of water into a concrete specimen, there are two approaches: (1) in-situ testing, i.e., the concrete is tested in place in the field; (2) laboratory testing, i.e., concrete cores are taken and brought to a laboratory for testing. Both approaches have their advantages and disadvantages. In the in-situ approach, the concrete cannot be easily conditioned and it is thus not possible to know the water content (saturation) of the concrete, which has a large effect on measured transport properties.<sup>(3)</sup> This makes it very difficult to use these measured values in quantitative service life models where the transport coefficient is inherently a function of concrete saturation. In addition, the variable temperature and RH present under field conditions compound the testing variability problem. In the laboratory approach, the concrete might not be exactly the “same” as the in-situ concrete, i.e., curing, hydration degree, etc., if, for example, substantial time elapses between obtaining the cores and testing them. Nevertheless, the goal of the test is to determine the properties of the in-situ concrete.

Here, laboratory testing of consistently pre-conditioned field cores was selected because of its higher reliability. The data will give a good quantitative estimate of the material transport properties that can then be used to model the performance of the in-situ concrete as a function of the exposure environment using the developed CONCLIFE software.

### MATERIALS

To develop the sorptivity test, cores from either the actual construction or from in-situ specially cast specimens or cast cylinders were used. The specimens were provided to NIST by the following State DOTs: Virginia, Maryland, Missouri, and Rhode Island. The sets received from Virginia and Maryland were used to develop the conditioning methodology. Those received from Missouri and Rhode Island were used for finalizing the sorptivity test methodology using the ponding option.

Tables 2 to 5 give the mix designs of the various specimens received. The specimens received from Maryland and from Virginia were cast cylinders from the same concrete as the main structure at the construction site.

The specimens received from the Rhode Island DOT were cores from small blocks (610 mm x 610 mm x 914 mm deep or 2 ft x 2 ft by 3 ft). The blocks were prepared by pumping the concrete into the molds. The blocks were then field cured and the cores were obtained after 28 days by drilling into the top surface of the concrete blocks. The cores were 368 mm (14.5 in) in length and 100 mm (4 in) in diameter. The specimens received from the Missouri DOT were cores from actual pavement slabs, not from separately cast specimens. These were taken from Route 65 in Benton County and from Route 13 in Henry County. The cores were from both the driving lanes (DL) and the passing lanes (PL) and were all from the northbound direction of the road.

Table 2. Mix design and concrete properties for the specimens from the Virginia DOT.  
(All the data were provided by the DOT and were not remeasured at NIST.)

	<b>MIX #1</b> <b>(FHWA-72 A/C)</b>	<b>Mix #2</b> <b>(FHWA-72 D/F)</b>
Date	7/7/99	6/30/99
<b>Mixture Proportions</b>		
Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	234 (395)	251 (423)
Slag kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	100 (169)	
Fly ash kg/m <sup>3</sup> (lb/yd <sup>3</sup> )		84 (141)
Pozzolan (mass %)	30	25
Coarse aggregates (No. 57) kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1092 (1840)	1092 (1840)
Fine aggregates kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	722 (1217)	729 (1229)
Water kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	148 (250)	148 (250)
W/cm	0.44	0.44
Admixtures	AEA	AEA
<b>Concrete Properties</b>		
Slump mm (in)	63.5 (2.5)	38.1 (1.5)
Air content (%)	5.0	4.2
Concrete temperature °C (°F)	30.5 (87)	28 (82)
Compressive strength MPa (psi) at 28 d on cylinders 152 mm x 508 mm (6 in x 20 in)	36.5 (5300)	33.9 (4920)
Flexural strength MPa (psi) at 28 d on prisms 152 mm x 152 mm x 508 mm (6 in x 6 in x 20 in)	5.4 (785)	
Rapid Chloride Permeability at 28 d (ASTM C1202)	1584	700
<b>Curing</b>	Moist cured at 23°C for 7 d followed by moist curing at 38°C for 21 d and testing at 28 d Kept in plastic molds with the same curing as 1)	
<b>Shipped and further curing</b>	Shipped in plastic bags or in their original molds; received by NIST on 8/17/99. At NIST, the specimens were stored in limewater until testing, if received in bags; in their molds in a moist cabinet until testing, if received in molds	

Table 3. Mix design and concrete properties for the specimens from the Maryland DOT.  
(All the data were provided by the DOT and were not remeasured at NIST.)

	<b>MIX #1 (FHWA-68)</b>
Date	3/2/99
<b>Mixture Proportions</b>	
Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	262 (442)
Newcem kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	141 (238)
Pozzolan (mass %)	35
Coarse aggregates (No. 57) kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1080 (1820)
Fine aggregates kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	688 (1160)
Water kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	158 (267)
W/cm	0.39
Admixtures	AEA and HRWRA
<b>Concrete Properties</b>	
Slump mm (in)	50-127 (2-5)
Air content (%)	6.5
Concrete temperature °C (°F)	Not measured
Designed compressive strength MPa (psi) at 28 d	31 (4500)
Rapid Chloride Permeability at 28 d (ASTM C1202)	Not measured
<b>Curing</b>	Moist cured at 23°C until pick up date
<b>Shipped and further curing</b>	Picked up on 7/21/99; transported in plastic bags with wet burlap. At NIST, the specimens were stored in limewater until testing.



Table 4. Mix design and concrete properties for the specimens from the Missouri DOT.  
(All the data were provided by the DOT and were not remeasured at NIST.)

	<b>Route 65 (FHWA-152/154)</b>	<b>Route 13 (FHWA-153)</b>
Date cast	06/29/00	06/29/00
Date Core taken	07/26/00	07/25/00
<b>Mixture Proportions</b>		
Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	290 (488)	251 (423)
Fly ash kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	51 (86)	
Pozzolan (mass %)	15	0
Coarse aggregates (limestone) kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1069 (1801)	992 (1672)
Fine aggregates kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	586 (988)	729 (1038)
Water kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	123 (207)	88 (148)
W/cm	0.36	0.35
Admixtures	AEA (0.5 L/m <sup>3</sup> )	AEA (0.58 L/m <sup>3</sup> )
<b>Concrete Properties</b>		
Slump mm (in)	30.5 (1.2)	(44.5) 1.75
Air content (%)	5.0	4.2
Concrete temperature °C (°F)	27 (80)	28 (82)
<b>Curing</b>	<b>In situ</b>	
<b>Shipped and further curing</b>	Shipped in plastic bags; received by NIST on 8/2/00. At NIST, the specimens were stored in limewater until testing.	

Table 5. Mix design and concrete properties for the specimens from the Rhode Island DOT.  
(All the data were provided by the DOT and were not remeasured at NIST).

	<b>MIX #1 (FHWA-150)</b>
Date cast	6/14/00
<b>Mixture Proportions</b>	
Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	417 (703)
Coarse aggregates (3/4" and pea stones) kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1054 (1776)
Fine aggregates kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	681 (1148)
Water kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	163 (275)
W/cm	0.39
Admixtures	DCI
<b>Concrete Properties: none available</b>	
<b>Curing</b>	Unknown
<b>Shipped and further curing</b>	Received on 7/31/00. At NIST, the specimens were stored in limewater until testing.

For the specimens from Missouri and Rhode Island, the elastic moduli were measured based on the resonance frequency method as described in ASTM C 215.<sup>(9)</sup> The mode used was longitudinal, i.e., the accelerometer was on the same axis as the driver. The values obtained, along with their measured standard deviations, are given in table 6. It is interesting to note that the driving lane has systematically higher values than the passing lane. We have no explanation for this phenomenon. More information on the casting pattern, the date and time of casting, the curing, or any other differences in the treatment or the materials used needs to be available in order to attempt to explain the difference.

Table 6. Modulus of elasticity for the concretes.

<b>Rhode Island</b>	<b>Missouri Rt. 65</b>		<b>Missouri Rt. 13</b>	
	Driving Lane	Passing Lane	Driving Lane	Passing Lane
44 ± 1 GPa	46 ± 0.3 GPa	42 ± 0.2 GPa	48 ± 0.3 GPa	43 ± 0.2 GPa

## METHODOLOGY DEVELOPMENT

### Conditioning of the Specimens

To develop a laboratory test to measure sorptivity, two main hurdles needed to be overcome: (1) the conditioning of the specimen, and (2) the test itself.

As the sorptivity depends critically on the water saturation of the concrete, the conditioning of the specimen is of paramount importance. The following are requirements for a good conditioning procedure for the specimens:

- Equilibrium with the same RH should be achieved with any concrete (to replicate the field RH conditions).
- The RH in equilibrium with the specimen should be around 50 percent, because it is a likely limit on the lowest RH commonly encountered in the field.
- The duration of the conditioning should be as short as possible.
- The methodology should not require sophisticated instrumentation. This will allow the implementation of the test by most laboratories.

The more severe conditioning consisting of drying the specimen to constant mass in an oven was rejected a priori. On the average, a concrete specimen 100 mm in diameter and 50 mm in length will need 2 to 3 months to be completely oven dried. This duration is not acceptable. The following methodology was adopted to determine the optimum conditioning:

- Vacuum saturate the specimen as described in ASTM C1202.<sup>(10)</sup>
- Place the specimens in an environmental chamber at 80 percent RH and 50°C. The duration of this treatment should be the shortest possible to obtain the same equilibrium internal RH with all concretes. Note that an RH of 80 percent is used in this step because, once the temperature of the specimen is lowered from 50°C to 20°C in the next step, the specimen RH will be reduced significantly (hopefully approaching the desired value of 50 percent). Place the specimen in a closed container at 20°C until the specimen has the same RH throughout its thickness. The RH of the air in the container will be monitored to determine this equilibrium.

Therefore, the first point to determine was the duration of the treatment in the environmental chamber to obtain a consistent RH for all specimens. The procedure to determine the duration was to expose concrete specimens obtained from the Maryland and Virginia DOTs to various durations of exposure and measure the RH after a subsequent 2-week storage in the closed containers. The goal was to obtain a similar RH for all specimens. The durations selected were:

- T1: No time in the environmental chamber. The specimens were placed directly in closed containers after being vacuum saturated
- T2: 24 h
- T3: 48 h
- T4: 3 d

- T5: 7 d
- T6: The specimens were kept in the environmental chamber until they achieved constant mass. The duration was on the order of 3 to 4 months depending on the specimen.
- T7: The specimen was kept in the environmental chamber until it achieved constant mass but the temperature of the chamber was changed to 20°C. The duration was about 6 months.

Figure 2 shows the results obtained. Each result represented on the bar chart is the average of two specimens. The bars show the influence of the mixture design on the final RH achieved, while the line plot shows the average for all specimens in any mixture design for a given conditioning. The goal is to obtain the conditioning that results in the smallest variation between the specimens while also producing a relative humidity of about 50 percent. It is clear that the conditioning from T3 and higher are acceptable, with the unexplained exception of T4. Therefore, we suggest that the specimens should be kept in the environmental chamber for at least 48 h prior to placement in the container to equilibrate the RH. Of course the smallest variation between specimens is obtained when a constant mass is achieved (conditions T6 and T7), but the duration of these conditionings is not acceptable for a standard test.

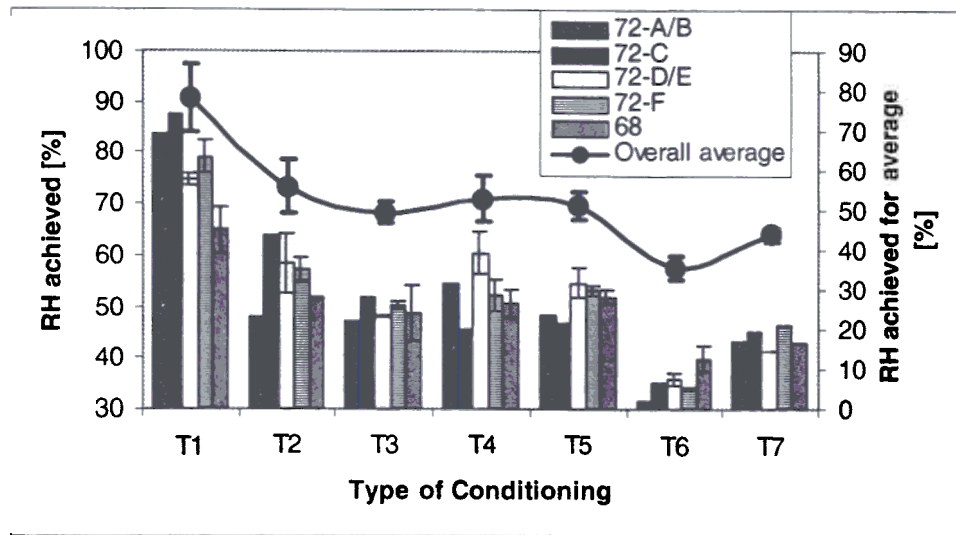


Figure 2. RH achieved after the various pre-conditionings.

(The main difference is the duration spent in the environmental chamber at 50°C and 80 percent RH. T1: no time; T2: 24 h; T3: 48 h; T4: 3 d; T5: 7 d; T6: until constant mass; T7: until constant mass but at 20°C and 80 percent RH. The right scale is not identical to the left scale for better visualization of the average curve.)

The second step that needs to be addressed is the duration of the conditioning of the specimen in a closed container to obtain a uniform RH throughout the specimen. To determine the shortest duration needed, specimens were placed in special containers. These containers were wide-mouth plastic jars with a metal lid. The mouth of the jars was wide enough to accommodate the placement of the specimen inside the jar. Two valves were attached to the lid. These valves open only when a male connection is attached to them. A dew point hygrometer was used to measure the RH inside the jars. It was connected regularly to each jar through the one-way valves in the lids of the jars. The RH was monitored once a day for at least 2 weeks. Figure 3



shows the evolution of the RH vs. time. It can be deduced that after about 10 days the RH does not change significantly. Therefore, the duration adopted was 15 days to guarantee a uniform RH throughout the specimen.

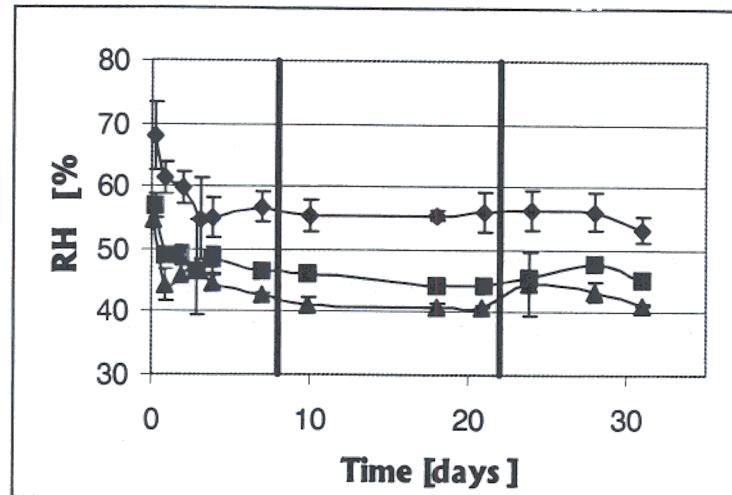


Figure 3. RH of the air inside the conditioning jars vs. time.

### Sorptivity Test

Water ingress into a non-saturated concrete structure is due to sorption, driven by capillary forces.<sup>(3)</sup> If the water is on top of the concrete surface, gravity also will play a role in the water penetration. Figure 4 shows the different results obtained with the two methods: bottom water exposure (against gravity) or ponding (with gravity). It is clear that the specimens have a higher water intake by ponding than by capillary transport during bottom water exposure alone. Therefore, it is necessary to use the method more appropriate for the application of the concrete structure to be evaluated. The determined sorptivity coefficients are  $3.8 \times 10^{-3} \text{ mm}/\sqrt{\text{min}}$  for the bottom water exposure sorption and  $4.6 \times 10^{-3} \text{ mm}/\sqrt{\text{min}}$  for the ponding sorption for the data presented in figure 4.

To measure the sorption coefficient of concrete, a new test was developed. The method is similar to that recently published as a Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les Constructions (RILEM) recommendation,<sup>(11)</sup> and has been submitted to ASTM for standardization. The principle of the method is that a concrete specimen has one surface in contact with water while all others are sealed, to allow a direct and accurate assessment of its sorptivity.

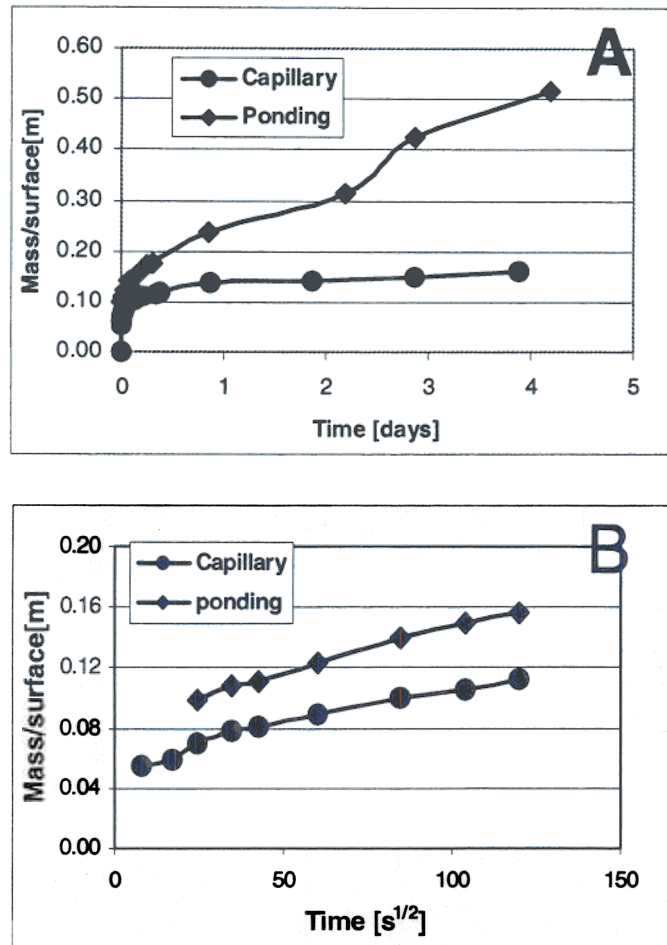


Figure 4. Comparison of sorption measured by bottom water exposure (capillary) and by ponding. (A) The water content per surface area vs. linear time as measured; (B) the water content per surface area vs. square root of time for the first 7 h only.

The proposed standard test allows either the top surface (simulation of water on a pavement or bridge deck) or the bottom surface (substrate in contact with water) to be in contact with water. The first case is referred to as ponding sorption and the second as bottom water exposure or capillary sorption.

The concrete specimens evaluated in the test were 50-mm- (2-in-) thick disks sliced from the received specimens. The sides were covered with duct tape prior to the pre-conditioning, in order to treat all specimens equally prior to the initial vacuum saturation procedure used in this study. By contrast, in the detailed test procedure provided in Appendix A, the specimens are sealed (taped) **after** the pre-conditioning and just prior to actual testing. This should somewhat reduce the time necessary to reach moisture equilibrium within the specimen during pre-conditioning. Taping was chosen over the application of an epoxy coating because it is faster, reversible, and doesn't cause any penetration of the pore structure of the concrete specimens.

In both cases, the surface not tested was covered with a plastic wrap secured with a rubber band or an equivalent system. In the case of capillary sorption (figure 5), the specimens were then ready for testing. For ponding sorption, some duct tape was used to form a pool (dike) as shown in figure 6. A two-component epoxy caulk was used to seal the space between the tape and the concrete.

The mass of the specimen was then regularly measured after the tested surface was patted dry. Of course, in the case of ponding, the water inside the dike needed to be poured out before patting the surface dry.

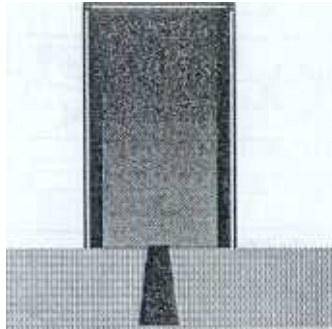


Figure 5. Schematic of the bottom water exposure (capillary) sorption test.

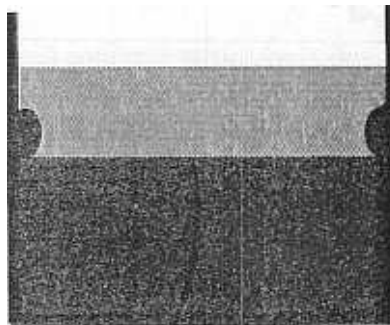


Figure 6. Schematic of the ponding sorption test.

It should be mentioned that the tape used in these tests needs to be evaluated in order to avoid leaks. These leaks will be deleterious to obtaining correct results, especially in the ponding configuration. Figure 7 shows the possible cases of leakage that can alter the validity of the results; the water leaks between the two sides of the tape or between the tape and the specimen and wets the non-testing surface. In both cases, the results will show a higher sorption coefficient than the correct value.

To select the correct tape and caulk, one can use any concrete cylinder as a “dummy” specimen. The steps to follow are:

- Dry the specimen somewhat by placing it in an oven at 50°C overnight.
- Prepare the specimen for the ponding tests as described above and use the tape to be tested.

- Pour water in the dike and leave the specimen overnight.

In general, if the tape is inadequate, the leaks will appear in less than 24 h. It would have been more scientific to develop clear criteria for determining the “stickiness” of the tape, but it was beyond the scope of this project. Some valuable information on selecting an appropriate tape can be found in a guide to tapes for use in backpacking.<sup>(12)</sup>

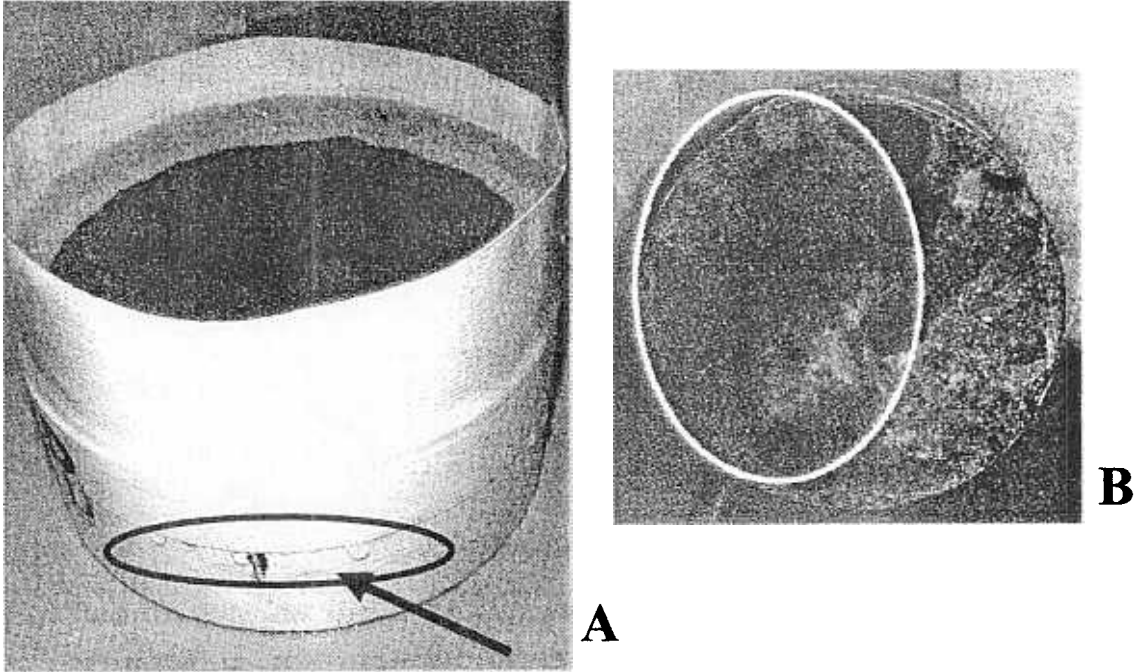


Figure 7. Pictures of observed leaks with the incorrect tape. (A) the water is leaking between the two layers of tape; (B) the water has leaked in between the tape and the specimen sides and is wetting the bottom (non tested surface).

To determine the sorption coefficient, the mass gain divided by the surface area of the top surface is plotted vs. the exposure time. The sorption coefficients are defined as shown in the following equation:

$$\frac{W}{\rho A} = S\sqrt{t} + I_0 \quad (1)$$

where

$W$  = mass gain (kg)

$A$  = surface area tested (m<sup>2</sup>)

$T$  = time elapsed (min)

$S$  = early age sorption coefficient (mm/min<sup>1/2</sup>) if 1 min <  $t$  < 7 h  
 later age sorption coefficient (mm/min<sup>1/2</sup>) if  $t$  > 1 d

$I_0$  = initial sorption (mm) occurring immediately upon contact with water

$\rho$  = density of water (kg/m<sup>3</sup>)

Figure 8 shows these two slopes or sorption coefficients. Two slopes have been observed for the results obtained from a wide variety of concretes and mortars.<sup>(13)</sup> The later-age sorption coefficient is usually attributed to other phenomena besides the capillary forces alone, such as filling of the larger pores and air voids. The nick-point time is defined as the time where the lines with the two slopes cross as shown in figure 8. Because the two lines have different slopes, they will also have different intercepts or initial sorptivity ( $I_0$ ) values.

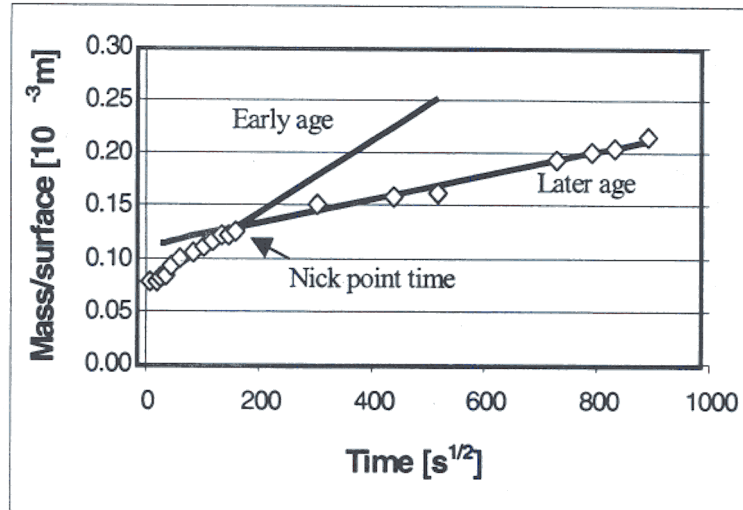


Figure 8. Calculation of the sorption coefficient.

## Results

Many tests were conducted to develop the test using many of the specimens described above. Here, we will present only the data obtained in ponding sorption for the concretes from Rhode Island and from Missouri, as these tests were performed after the testing methodology was well established.

Typical measured sorptivity values for the three concretes (following the 7-d environmental chamber-conditioning regime) are provided in table 7. The concrete from Rhode Island is seen to exhibit a rapid initial sorption relative to the two concretes from Missouri (as seen in the values of  $I_0$ ). After this initial absorption, the values of  $S$  (early age) for the 3 concretes are seen to be very similar (a coefficient of variation between the 3 samples of only 13 percent). The values of  $S$  (later age) exhibit a much higher variability between the 3 concretes (coefficient of variation of 60 percent), with the concrete from Rhode Island once again exhibiting the largest value.

Table 7. Sorptivity properties for the concretes.  
(S is the sorptivity and  $I_0$  is the initial sorption.)<sup>(6)</sup>

Sorption Property	Rhode Island	Missouri Rt. 65 Driving Lane	Missouri Rt. 13 Driving Lane
$I_0$ (early age) (mm)	5.46	0.075	0.017
S (early age) ( $10^{-3}$ mm/ $\sqrt{\text{min}}$ )	2.79	3.25	3.64
Nick point time (h)	7	7	6
$I_0$ (later age) (mm)	5.34	0.065	0.034
S (later age) ( $10^{-3}$ mm/ $\sqrt{\text{min}}$ )	8.98	3.95	3.02

### Standardization Efforts

Based on previous drafts prepared by Prof. Douglas Hooton of the University of Toronto, the sorption coefficient test was updated and presented to ASTM Committee C09.66. The first C09.66 subcommittee ballot has been completed and the comments from the subcommittee members have been introduced into a revised draft. This revised draft (a generic version of which is provided in Appendix A) was sent for discussion to the members, prior to the June 2001 meeting. A precision and bias statement is currently being developed and will be presented at the December 2001 ASTM C09 meeting for subcommittee C09.66 balloting.



**THIS PAGE LEFT INTENTIONALLY BLANK**

## CHAPTER 3. COMPUTER MODELS

### CONCRETE SURFACE TEMPERATURE AND TIME OF WETNESS (HEAT-TRANSFER) MODEL

To perform a sorptivity-based estimate of concrete service life, it is necessary to know when and for how long the concrete pavement or bridge deck is wet, in addition to knowing the sorption properties of the concrete as a function of its saturation or RH. Thus, a precursor to developing the specific service life models was to develop a heat-transfer model for a concrete pavement or bridge deck. Knowing the concrete surface temperature will allow the prediction of condensation (when the surface temperature drops below the dewpoint temperature) and the adjustment of the measured concrete sorptivity for temperature. The basic one-dimensional model for heat transfer within a concrete pavement or bridge deck has been presented previously.<sup>(4)</sup> Figure 9 below shows the basic concrete pavement and bridge deck configurations considered by the model, along with the relevant modes of heat transfer within the concrete and to/from its exposed surfaces.<sup>(4,6)</sup> In the final version of the CONCLIFE software, the user has the option of changing the dimensions or the fixed temperature at the bottom soil surface to better model a specific system of interest. The computer model considers heat transfer by conduction, convection, and radiation. For radiation to the sky, the sky temperature is estimated based on a series of equations first presented by Walton<sup>(14)</sup> and detailed below. Default material properties for the concrete and soil layers<sup>(15)</sup> are provided in table 8. In the final version of CONCLIFE, the user also has the option of altering these values if more specific information is available, essentially creating their own concrete surface temperature, time-of-wetness and time-of-freezing data files. Environmental data for the heat-transfer model are taken from the Typical Meteorological Year (TMY2) weather data files provided by the NREL.<sup>(5)</sup> These files provide typical weather data including ambient RH, ambient temperature, cloud cover, dewpoint temperature, incident global horizontal solar radiation, precipitation events, and wind speed on an hourly basis.

Both systems shown in figure 9 are modeled with a one-dimensional finite difference grid with a default spatial resolution of 20 mm. Four modes of heat transfer are considered at the top concrete surface: conduction into the concrete, convection, solar absorption, and grey-body irradiation to the surroundings. For conduction, the heat flow contribution (in  $W/m^2$ ) is given by:

$$Q_{cond} = k_{conc} * \frac{(T_0 - T_1)}{\Delta x} \quad (2)$$

where  $k_{conc}$  is the thermal conductivity of the concrete in  $W/(m \cdot ^\circ C)$ ,  $T_0$  and  $T_1$  are the surface temperature and temperature at the first internal node, respectively, and  $\Delta x$  is the node spacing (0.02 m). For the convection term at the top surface, the heat flow is given by:

$$Q_{conv} = h_{conv} * (T_0 - T_{ambient}) \quad (3)$$

where  $T_{ambient}$  is the ambient temperature and  $h_{conv}$  is the convection coefficient in  $W/(m^2 \cdot ^\circ C)$ .

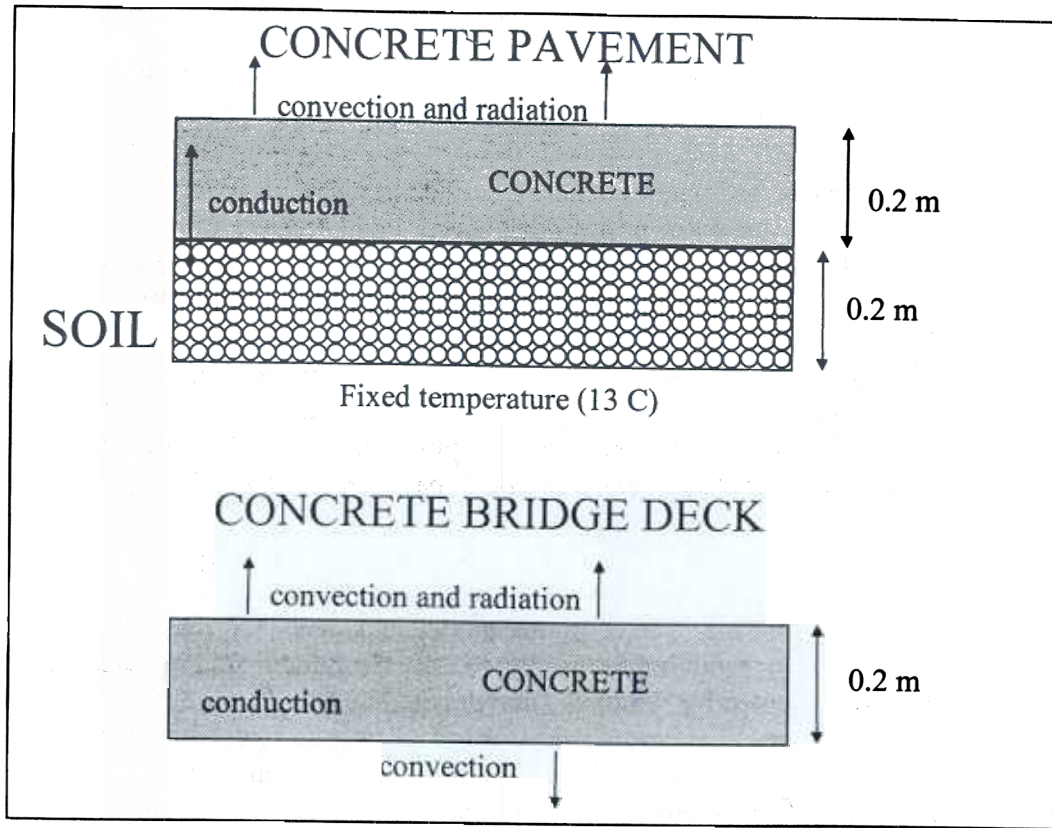


Figure 9. Basic configurations of one-dimensional heat-transfer models for concrete pavements and bridge decks.

Table 8. Generic material properties for the heat-transfer/time-of-wetness model.

Material	Heat Capacity (J/(kg-°C))	Thermal Conductivity (W/(m-°C))	Density (kg/m <sup>3</sup> )	Emissivity	Solar Absorptivity
Concrete	1000	1.5	2350	0.9	0.65
Soil	800	0.3	1600	---	---

While several empirical relationships to estimate convection coefficients exist, for this study the convection coefficient was calculated based on the wind speed available in the weather data files and the following equations used in the commercially available FEMMASSE system:<sup>(16)</sup>

$$\begin{aligned}
 h_{conv} &= 5.6 + 4.0v_{wind} \quad \text{for } v_{wind} \leq 5 \text{ m/s} \\
 h_{conv} &= 7.2 * v_{wind}^{0.78} \quad \text{for } v_{wind} > 5 \text{ m/s}
 \end{aligned}
 \tag{4}$$

where  $v_{wind}$  is the measured wind speed in m/s. For radiation absorbed from the incoming sunlight, the heat flow contribution is given by:

$$Q_{sun} = \gamma_{abs} * Q_{inc} \tag{5}$$

where  $Q_{inc}$  is the incident solar radiation from the TMY2 data file ( $W/m^2$ ) and  $\gamma_{abs}$  is the solar absorptivity of the concrete (default value of 0.65). For the top surface, finally, the irradiation heat loss to the sky is given by:

$$Q_{sky} = \sigma \epsilon * (T_{0K}^4 - T_{sky}^4) \quad (6)$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $5.669 * 10^{-8} W/(m^2 \cdot ^\circ C)$ ),  $\epsilon$  is the emissivity of the concrete (assumed to be 0.9),  $T_{0K}$  is the concrete surface temperature in K, and  $T_{sky}$  is the calculated sky temperature, also in K. The sky temperature was estimated based on an algorithm presented by Walton<sup>(14)</sup> using the following series of equations:

$$T_{sky} = \epsilon_s^{1/4} * T_{ambient} \quad (T \text{ in } K) \quad (7)$$

where the sky emissivity,  $\epsilon_s$ , is given by:

$$\epsilon_s = 0.787 + 0.764 * \ln\left(\frac{T_{dew}}{273}\right) * F_{cloud} \quad (8)$$

where  $T_{dew}$  is the dewpoint temperature in K taken from the TMY2 data file, and with the cloud cover factor,  $F_{cloud}$ , as:

$$F_{cloud} = 1.0 + 0.024N - 0.0035N^2 + 0.00028N^3 \quad (9)$$

where  $N$  is the “tenths cloud cover,” taking values between 0.0 and 1.0, and also available in the TMY2 data files.

The time step in the finite difference scheme is established based on the discretized element thickness (0.02 m) and the thermal properties of the materials to ensure numerical convergence of the solution.<sup>(17)</sup> The ambient environmental conditions at any specific time are calculated by linear interpolation of the hourly values available from the TMY2 weather files.

Based on these equations, the environmental inputs, and the concrete material properties, the computer model predicts the concrete surface temperature (see figure 10 for an example) and logs wetting and freezing events for the concrete surface. During the middle of a sunny day, the concrete surface temperature will rise above the ambient temperature due to the incoming solar radiation. Occasionally, on a clear night, the concrete surface temperature will fall below the ambient value, due to radiation emitted to the night sky. Wetting may be due to a precipitation event or condensation that occurs when the concrete surface temperature drops below the current dewpoint temperature. Each wetting event is characterized by a starting time, a concrete surface temperature, an external RH prior to wetting, and a duration. Each freezing event is characterized by a starting time, a minimum temperature achieved during freezing, and a duration. Figure 11 shows plots of the wetting events for concrete pavements in Kansas City, MO and Providence, RI. Clearly, the Rhode Island environment is wetter (776 total h wet during the year, vs. 448 for Kansas City). These wetting and freezing event files are then used in the concrete service life models described next.

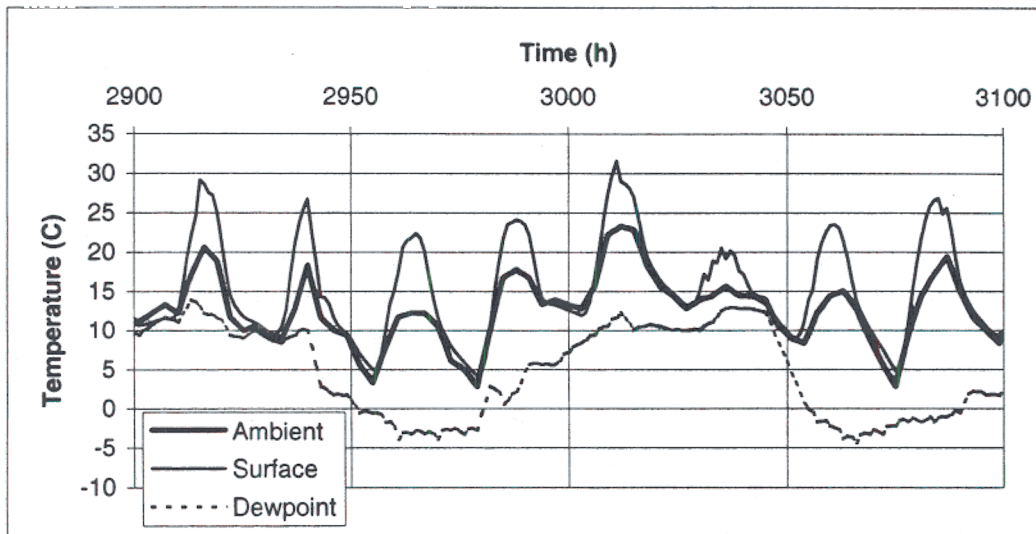


Figure 10. Temperature predictions for a concrete pavement in Providence, RI in the spring. (Time indicates cumulative hours from beginning of year.)

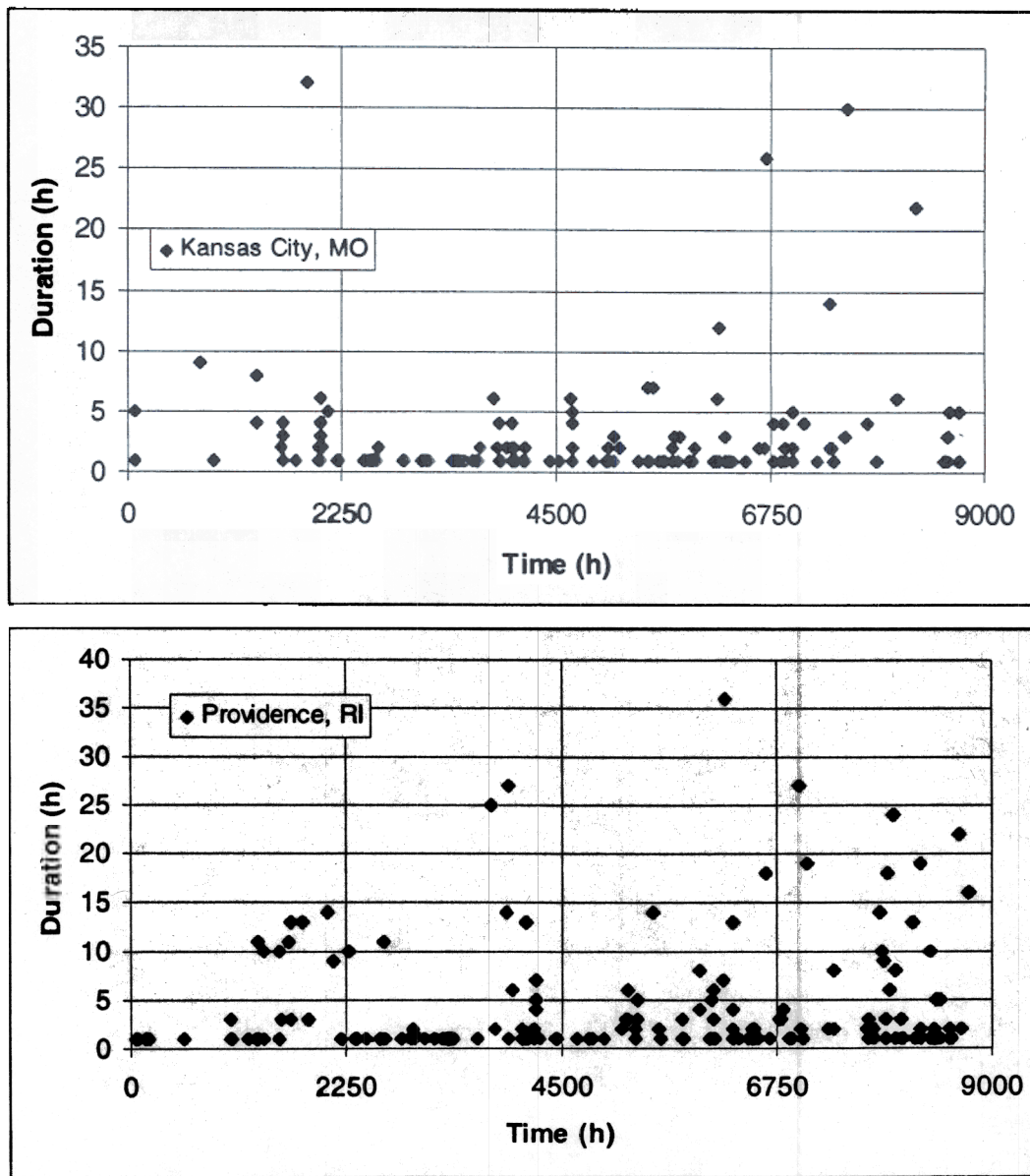


Figure 11. Plots of wetting events in (top) Kansas City, MO, and (bottom) Providence, RI, both for concrete pavements.

## SULFATE ATTACK SERVICE LIFE MODEL

The service life model for sulfate attack is based on the model developed by Atkinson and Hearne.<sup>(7)</sup> While their development considered the main mode of sulfate ion transport into the concrete to be by diffusion, here we will develop a similar model for sulfate ions transported via sorption from the external environment. The basic equation developed by Atkinson and Hearne is:<sup>(7)</sup>

$$X_{spill} = \frac{2\alpha\gamma_f(1-\nu)}{E(\beta C_E)^2} \quad (10)$$



where

$C_E$  = concentration of reacted sulfate as ettringite (mol/m<sup>3</sup>)

$E$  = Young's modulus of the concrete (GPa)

$X_{spall}$  = concrete spalling depth (m)

$\alpha$  = roughness factor for fracture path (default value of one)

$\beta$  = linear strain caused by reaction of sulfate ions to form one mole of ettringite (m<sup>3</sup>/mol, default value of  $1.8 \times 10^{-6}$ )

$\gamma_f$  = fracture surface energy of the concrete (N/m or J/m<sup>2</sup>)

$\nu$  = Poisson's ratio of concrete (e.g., 0.3)

The basic assumption of this model is that deleterious expansion and cracking is due to the formation of expansive ettringite within the concrete. When the strain produced by the growing ettringite crystals exceeds the fracture energy of the concrete, failure occurs, as a layer  $X_{spall}$  thick spalls from the concrete surface. For a sorptivity-based model, the buildup of ettringite is considered to be due to external sulfate ions penetrating into the concrete along with the sorbed external solution.<sup>(3)</sup> To use this model, the user must specify the concentration of sulfate ions in the external solution (e.g., rainwater or groundwater) and the sorption properties of the concrete. Specifically, for each wetting event, the CONCLIFE program calculates a penetration depth based on the duration of the event, the concrete sorptivity, and the environmental conditions (RH and concrete surface temperature). The measured sorption coefficients are adjusted for the RH just prior to the wetting event, using linear interpolation and assuming a sorptivity value of zero at 100 percent RH (saturated) conditions. They are further adjusted for the concrete surface temperature based on the physical properties (viscosity and surface tension) of water as a function of temperature.<sup>(6)</sup> Assuming that sorptivity scales as  $(\sigma/\eta)^{1/2}$ ,<sup>(6)</sup> where  $\sigma$  is surface tension (expressed in units of kg/(m-s)  $\times 10^{-4}$ )<sup>(18)</sup> and  $\eta$  is viscosity (in units of dynes/cm),<sup>(17)</sup> one finds:

$$\sqrt{\frac{\sigma}{\eta}} = 2.054 + 0.0334 * T - 0.000085 * T^2 \quad (11)$$

where  $T$  is expressed in °C.

Based on these adjusted sorption coefficients, the concrete internal "sulfate (ettringite) concentrations" down to the penetration depth are updated and equation 10 is used to evaluate whether or not new spalling will occur. If so, the spalling depth is updated. This process is repeated until the spalling depth exceeds the user-specified failure criteria, indicating the estimated service life for the concrete. This model comprises one of the two main user screens of the CONCLIFE program as detailed in the user's manual in Appendix B.

## **FREEZE-THAW DETERIORATION SERVICE LIFE MODEL**

The service life model for freeze-thaw deterioration is based on the critical air void saturation concept of Fagerlund.<sup>(8)</sup> The basic assumption is that the air voids in field concrete are slowly filled by liquid water during environmental exposure. This "filling" rate is assumed to be equivalent to the later age sorption coefficient (after the nick-point time) discussed above. When a critical fraction of these air voids have become saturated (water-filled), the next freeze-thaw cycle will cause damage to the concrete. For the purposes of the model developed in

CONCLIFE, failure is characterized by the time necessary to achieve the critical saturation. The subsequent cracking developed due to cyclic freezing and thawing is not considered. Critical parameters are the porosity and air void content of the concrete and its sorption characteristics. To implement this model in the CONCLIFE program, each wetting event is examined in turn. If the duration of the wetting event exceeds the nick-point time, the penetration depth is computed based on the sorption coefficients and the concrete porosity. The sorption occurring after the nick-point time is used to update the saturation of the air voids within this penetration depth. If the saturation at some depth is greater than the user-specified critical saturation, spalling occurs. Once again, when the cumulative spalling exceeds the user-specified failure criteria, an estimate of the concrete service life is achieved. This model comprises the second main user screen within the CONCLIFE program as detailed in the user's manual in Appendix B.

**THIS PAGE LEFT INTENTIONALLY BLANK**

## CHAPTER 4. SUMMARY

The technical basis for the CONCLIFE software has been presented. Upon an extensive literature review, the sorptivity of concrete was determined to be more important than its permeability with respect to degradation in a typical highway field exposure. Thus, a methodology and procedures for evaluating the sorptivity of field concrete cores were developed. The complete procedures for this sorptivity test can be found in Appendix A of this report. For this test, laboratory evaluation of cores from field concrete was selected over in-situ measurement, due to the variable environmental conditions present in the field and the resultant variable moisture content (saturation) of the concretes. By subjecting all field concrete cores to the same laboratory pre-conditioning regimen, useful comparisons can be made between the subsequently measured sorption coefficients.

The developed test is simple to execute, requiring a minimum set of laboratory equipment (laboratory balance, device to measure relative humidity, etc.). Basically, it consists of measuring the mass gain over time of a partially saturated concrete core with one surface exposed to water (and all other surfaces sealed).

The sorption of sulfate ions and water by partially saturated concrete have been related to degradation due to sulfate attack and freeze-thaw damage, respectively. Knowing the measured sorption properties of the concrete and its exposure conditions (surface temperature, time-of-wetness, etc.), the ingress of sulfate ions and the slow saturation of the air void system can be quantitatively predicted. A necessary first step in implementing this analysis was the development of a simple one-dimensional heat-transfer computer model to predict the surface temperature and time-of-wetness of the concrete as a function of geographical location. The developed heat-transfer model considers heat transfer due to conduction within the concrete (and subbase) layer, convection at exposed concrete surfaces, incoming solar radiation, and radiation emitted by the top surface of the concrete. Because of their different geometries and materials (subbase), separate heat-transfer models were developed for the cases of concrete pavements and bridge decks. Because it lacks an insulating subbase, a concrete bridge deck will generally experience lower temperatures than a concrete pavement, leading to an increase both in the number of condensation events (when the concrete surface temperature falls below the dewpoint temperature) and in the number of freezing events (when the concrete surface temperature falls below 0°C).

For the heat-transfer models, environmental data were obtained from the typical meteorological year weather data files supplied by the NREL.<sup>(5)</sup> Using these data files along with the laboratory-measured properties of the field concretes, spalling damage due to either sulfate attack or freeze-thaw deterioration can be quantitatively predicted. Ultimately, the service life of the concrete is defined as the time needed to achieve a user-specified level of spalling from the top surface of the concrete. In the case of sulfate attack, spalling is due to the expansive ettringite that is formed when the ingressing sulfate ions react with the cementitious matrix.<sup>(7)</sup> In the case of freeze-thaw deterioration, spalling is due to the expansion of water during freezing, for the case where there is no longer an adequate air void system<sup>(8)</sup> to "relieve" these swelling pressures.

The three developed computer models have been integrated into a user-friendly software package, called CONCLIFE. The complete user's manual for the CONCLIFE software is provided in Appendix B of this report. The software presents the user with a set of screens that can be used to produce quantitative predictions of concrete spalling under either sulfate attack or freeze-thaw conditions. CONCLIFE can also be used to determine the sorptivity coefficients of a concrete by analysis of measured laboratory data and to establish user-specific concrete surface temperature, time-of-wetness, and time-of-freezing files for concrete pavements and bridge decks with different geometries or different thermal properties than those of the default systems (defaults as detailed in figure 9 and table 8). The software produces graphs of concrete sorptivity, annual precipitation for different geographical locations, and estimated rates of concrete spalling.

CONCLIFE has the following limitations: 1) it considers transport of sulfate ions and water only due to sorption (neglecting diffusion for example); 2) it considers the concrete sorptivity coefficients to be constant with time (whereas they could well decrease due to hydration/carbonation or increase due to leaching or other degradation); and 3) it assumes that the internal RH of the surface layer of the concrete is equivalent to the external environment RH just prior to any wetting event (precipitation or condensation). These limitations may be addressed in future versions of the software.

Example analyses provided in Appendix B indicate that the measured sorptivities do have a major influence on the calculated concrete service lives for both sulfate attack and freeze-thaw deterioration. In addition to the sulfate attack and freeze-thaw deterioration considered explicitly in this study, sorptivity will also have a strong influence on degradation due to the ingress of chloride ions (rebar corrosion) and due to alkali-silica and alkali-carbonate reactions between aggregates and the concrete pore solution. It should be further noted that the service life predictions provided by CONCLIFE have not yet been validated on real concrete structures.

As described in this report, both experimental and computational research have played major roles in the development of the current CONCLIFE software package. This combined experimental/computer modeling approach is viewed as the most fruitful avenue for advancing the science of service life prediction of concrete structures.

In the future, it is expected that improvements in the degradation models and the characterization of the local concrete microclimate will increase the accuracy of these service life estimates. As the fundamental mechanisms of concrete degradation are further elucidated, revisions to and extensions of the degradation models will become possible. More accurate and complete data on the “local” concrete environmental conditions can also be incorporated into future versions of CONCLIFE. Thus, CONCLIFE is viewed only as a starting point for the complex topic of service life prediction for concrete pavements and bridge decks. It addresses only specific modes of failure (sulfate attack and freeze-thaw deterioration due to sorption) based on the current state of the art and understanding of these degradation modes. But the general methodology of combining concrete physical properties and local environmental data to predict concrete performance must surely be utilized in all future service life models if the state of the art and our understanding are to be significantly advanced.

In summary, the initial objectives provided in the Project Overview section of this report have been met. Relationships between service life, considering sulfate attack and freeze-thaw deterioration, and **sorptivity** have been established. No current U.S. standard tests (either ASTM or AASHTO) for evaluating concrete sorptivity exist, so a standard laboratory-based procedure for the evaluation of field concrete cores was developed. The CONCLIFE software was developed to provide a means for determining sorptivity coefficients based on the laboratory measurements and to further utilize these coefficients in providing quantitative predictions of service life.



**THIS PAGE LEFT INTENTIONALLY BLANK**

## **ACKNOWLEDGMENTS**

The authors would like to thank the Maryland, Missouri, Rhode Island, and Virginia State Departments of Transportation for providing concrete core samples for this study. They would also like to thank Mark Felag of the Rhode Island Department of Transportation for useful discussions, Dr. George Walton of BFRL for useful discussions concerning the concrete heat-transfer model, and Prof. Douglas Hooton of the University of Toronto for providing an advanced draft of the proposed sorptivity test standard, which greatly expedited the process of preparing a test for balloting by ASTM C09.

**THIS PAGE LEFT INTENTIONALLY BLANK**

## **APPENDIX A. Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Mortars or Concretes<sup>1</sup>**

### **NECESSARY EQUIPMENT**

The following equipment is needed to conduct the test:

- Pan - A watertight polyethylene or other corrosion-resistant pan large enough to accommodate the test specimen with the surface to be tested exposed to water.
- Support Device - Rods, pins, or other devices, made of materials resistant to corrosion by water or alkaline solutions, which allow free access of water to the test surface of the test specimen during the test. Alternately, the sample can be supported on several layers of blotting paper or filter papers with a total thickness of at least 1 mm.
- Top-Pan Balance - With sufficient capacity for the test specimens and accurate to at least 0.1 g. The balance should comply with ASTM C1005.
- Timing Device - Stopwatch or other suitable timing device accurate to 1 s.
- Tissue Paper or Cloths - For wiping excess water from specimen surfaces.
- Environmental Chamber - The chamber should have a fan and should be able to maintain a temperature of  $50 \pm 2^{\circ}\text{C}$  and a relative humidity at  $80 \pm 3\%$ . Alternatively, an oven able to maintain a temperature of  $50 \pm 2^{\circ}\text{C}$  and a dessicator can be used. The relative humidity (RH) is controlled in the dessicator with a salt solution of potassium bromide. The dessicator needs to be large enough to contain the specimens to be tested.
- Polyethylene Storage Container - With sealable lid, which is large enough to contain a test specimen. The container should not have a volume larger than five times the specimen volume. An option for the container could be to have lock valves in the lid that could be connected to a system to measure the RH inside the container.
- Potassium Bromide, reagent grade - Only required if the oven/dessicator is used.

### **TEST SPECIMENS**

- Use, as the standard test specimen, a 100-mm $\pm$  6-mm-diameter core or cylinder, with a length of  $50 \pm 3$  mm. The cross section of the specimen should be constant ( $\pm 5$  mm<sup>2</sup>). Measure the actual diameter of the specimen for use in calculations by averaging at least four diameters. For tests to evaluate curing effectiveness, take cores from the central portion of slabs at least 30 mm from any edge.
- Test a minimum of two specimens.
- Since water absorption is affected by curing, conduct replicate tests on specimens having test surfaces at the same depth with respect to the exposed surface.

---

<sup>1</sup> This method was proposed to ASTM Subcommittee C09.66 on Resistance to Fluid Penetration. It is currently in the balloting process.

## SAMPLE CONDITIONING

Proper sample conditioning is essential. This is the method that was devised to obtain a uniform RH in the specimen. Ideally the RH obtained is about 50-60%.

- Place test specimens in the environmental chamber at a temperature of  $50 \pm 2^\circ\text{C}$  and RH of  $80 \pm 3\%$  for 3 days. Alternatively, place test specimens in a dessicator inside an oven that is able to maintain a temperature of  $50 \pm 2^\circ\text{C}$ . Control the RH in the dessicator with a saturated solution of potassium bromide. Do not allow test specimens to come in contact with the saturated salt solution.
- Remove the specimen from the pre-conditioning chamber and place it on the support device inside the sealable polyethylene container.
- Place the container at  $23 \pm 2^\circ\text{C}$  in an environmental chamber or oven for 15 days. The conditioning inside the sealed container results in spatial equilibration of the moisture distribution within the test specimens and has been found to provide internal relative humidities of 50 to 70%. This is similar to the lower values of RH typically found in field structures <sup>2,3</sup>.
- Store the specimen in the desiccator jar or a sealable polyethylene container until sorptivity testing.

## PROCEDURE

Once the specimens are conditioned as described above, the following procedure should be followed to prepare the specimens for testing. Two procedures to measure the sorption will be conducted. The selection of the appropriate procedure should be based on the type of exposure that the concrete will experience in the field.

### Preparation of Specimens for Measurements after Conditioning

- Conduct the absorption procedure at  $23 \pm 2^\circ\text{C}$  with tap water conditioned to the same temperature. If the experiment is continued for more than 3 days, saturated limewater shall be used instead of tap water. The limewater shall be prepared by dissolving sufficient calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) in distilled water to exceed the saturation concentration (1.65 mg/g of water).
- Remove the specimen from the container or bag and measure the mass of the conditioned test specimen to the nearest 0.1 g prior to sealing of side surfaces. Record this mass.
- Seal the sides of test specimens with a bituminous, epoxy, or other coating to prevent absorption of water into the sides and to prevent evaporation of internal water. Also cover the

---

<sup>2</sup> DeSouza S.J., Hooton R.D., Bickley J.A., "Evaluation of laboratory drying procedures relevant to field conditions for concrete sorptivity measurements," *Cement Concrete Aggr*, Vol. 19, No. 2, Dec 1997, pp. 59-63.

<sup>3</sup> DeSouza S.J., Hooton R.D., Bickley J.A., "A field test for evaluating high performance concrete covercrete quality," *Can J Civil Eng*, Vol. 25, No. 3, June 1998, pp. 551-556.

top of the specimen with the same material or with a bag attached with a rubber band. Strips of impermeable sheets, bituminous sheet, epoxy paint, vinyl electricians' tape, duct tape, or aluminum tape have been found to be effective for this purpose.

- Again measure the mass of the specimen with sides and the non-tested surface sealed and record the value as the initial mass for rate of absorption calculations.

## **Sorption Measurement Procedures**

### **Procedure A: Absorption by capillary suction (bottom surface exposure)**

This method allows the measurement of absorption where the surface exposed to the water is the bottom surface. Depending on the end use application of the concrete, absorption either against or with gravity may be a more appropriate measure. Procedure B will address the case of water in contact with the top surface of the concrete.

Fill the pan with tap water or saturated limewater as described above until the level is 1 to 3 mm above the top of the support device.

2. Record the time and immediately place the test surface of the specimen on the support device (see figure 12).
3. After  $60 \pm 2$  s, remove the test specimen from the container, stop the stopwatch, blot off any surface water with a dampened tissue or cloth, and measure the mass within 15 s.
4. Immediately replace the test surface of the specimen on the support device in contact with water and start the stopwatch
5. Repeat the procedure in steps 3 and 4 after total elapsed contact times of 5, 10, 20, 30, and 60 min ( $\pm 10$  s) from first contact of the specimen with water. Continue the measurements every hour up to 6 h and once a day up to 28 d from the first contact of the specimen with water. After blotting, dry the surface of the specimen and invert the specimen so that the wet surface does not come in contact with the balance pan. For measurements after the first 10 min, stopping the stopwatch while the specimen is not in contact with the water is not necessary.

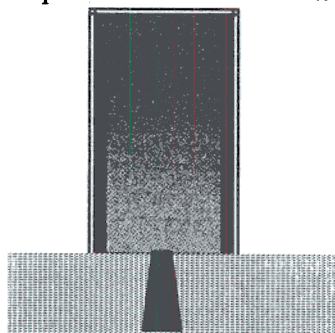


Figure 12. Schematic of Procedure A.

### **Procedure B: Absorption by ponding**

This method allows the measurement of absorption where the surface exposed to the water is the top surface. Thus, gravity will be an additional force to accelerate the penetration of the water into the specimen. Depending on the end use application of the concrete, absorption either



against or with gravity may be a more appropriate measure. For example, for the top surface of concrete pavements, absorption with gravity is perhaps more relevant.

1. Use strip caulk and duct tape to build a dam around the edge of the top of the specimen. Make sure that the caulk adheres tightly to the specimen. The dam should be about 10 mm in height. If the dam is built in such a way that it does not lay on the top of the specimen, the test surface area is equal to the top section of the specimen.
2. Again, determine the mass of the specimen with sides and bottom sealed, and with the dam on the top side. Record this value as the initial mass for rate of absorption calculations.
3. Fill the dam on top of the specimen with tap water up to the top of the dam and immediately record the time.
4. After  $60 \pm 2$  s, pour the water out of the test specimen, stop the stopwatch, and blot off any surface water with a dampened tissue or cloth and measure the mass within 15 s.
5. Immediately refill the dam on top of the specimen with water and restart the stopwatch.
6. Repeat steps 4 and 5 after total elapsed contact times of 5, 10, 20, 30, and 60 min ( $\pm 10$  s) from first contact of the specimen with water. Continue the measurements every hour up to 6 h and once a day up to 28 d from the first contact of the specimen with water. To avoid evaporation of the water when the measurements are longer than 1 h, cover the specimen loosely with plastic wrap.

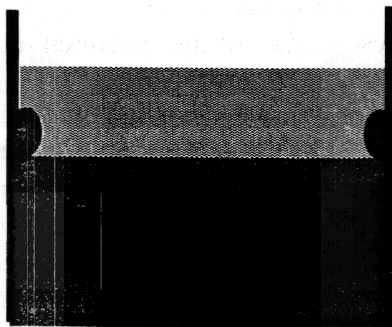


Figure 13. Schematic of Procedure B.

### Calculations

1. The initial rate of absorption,  $I$ , is the change in mass (g) divided by both the cross-sectional area of the test specimen ( $\text{mm}^2$ ) and the density of water at the temperature recorded. The density of water depends on its temperature. However, the effect of this variation with the temperature is not significant in this procedure, so the temperature measurement is not required. The density of the water could be assumed to be  $1.00 \text{ g/mL}$  ( $0.001 \text{ g/mm}^3$ ).
2. The initial water absorption ( $\text{mm/min}^{1/2}$ ) is defined as the slope of the line of  $I$  plotted against the square root of time ( $\text{min}^{1/2}$ ). Obtain this slope using least-squares, linear regression to establish the plot of  $I$  vs.  $\text{time}^{1/2}$ . Do not include the origin (measurement at 1 min) as a datum

point.<sup>4</sup> Use all the points in the regression until the plot shows a clear change of slope. If no portion of the curve  $I$  vs.  $\text{time}^{1/2}$  data is linear (a regression coefficient of less than 0.98) and the data show some systematic curvature, absorption cannot be determined. An example is given in Appendix A-1.

3. Obtain the water absorption at later age (after the line plotted in step 2 shows a change in slope) using least-squares, linear regression to determine the slope of the second portion of the plotted points for  $I$  vs.  $\text{time}^{1/2}$ . Include only points for times from 1 (to 7) d to 28 d. If no portion of the curve  $I$  vs.  $\text{time}^{1/2}$  data is linear (a regression coefficient of less than 0.98) and the data show some systematic curvature in the region, absorption at later age cannot be determined.

## Report

An example report is given in Appendix A-1. Report the following:

- Date sampled or date cast;
- Source of sample;
- Relevant background information on sample such as mixture proportions, curing history, type of finishing, and age, if available;
- Dimensions and dry mass of the test specimen;
- A plot of the absorption vs. square root of time;
- The average initial water absorption calculated to  $0.1 \text{ mm/min}^{1/2}$  and the individual absorption rates for the two specimens.
- If the initial water absorption could not be derived from all the data points as discussed in the calculation section, indicate which data points are omitted.
- Report the time (h) at which the slope of the line changes.
- The average later age water absorption calculated to  $0.1 \text{ mm/min}^{1/2}$  and the individual absorption rates of the two specimens tested.
- If the later age water absorption could not be derived from all the data points as discussed previously, indicate which data points were omitted.

---

<sup>4</sup> The initial change in mass up to 1 min is often higher than for subsequent time intervals in part because it corresponds to water absorbed on the outer surface in contact with the water and not absorbed inside the specimen (in the pores).

## APPENDIX A-1. EXAMPLE RATE OF ABSORPTION TEST

Cast Date: 3/2/99 Test Date: 3/14/00

Sample No. F-68

Concrete Mixture: 35% fly ash / w/cm = 0.45

Sample Conditioning: Cast, steam cured, test face = top surface

Sample: Age 378 days

Age at coring: NA

Mass of Conditioned disc: 750.5 g (prior to sealing sides)

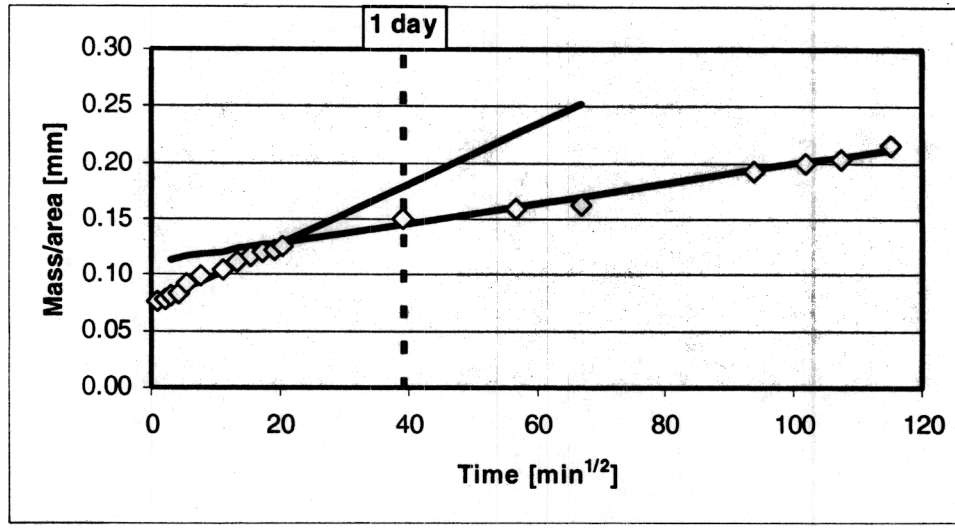
Diameter (mm): 101.6

Area: 8107.1 mm<sup>2</sup>

Thickness (mm): 50.8

Water temp: 20.7°C

Test Time		√Time	Mass	ΔMass	ΔMass/area = I
Days	min	[min <sup>1/2</sup> ]	[g]	[g]	[mm]
	0	0.0	761.83	0.00	0.0000
	1	1.0	762.45	0.62	0.0765
	5	2.2	762.46	0.63	0.0780
	10	3.2	762.48	0.65	0.0805
	20	4.5	762.50	0.67	0.0826
	30	5.5	762.57	0.74	0.0913
	60	7.7	762.63	0.80	0.0987
	120	11.0	762.68	0.85	0.1048
	180	13.4	762.73	0.90	0.1110
	240	15.5	762.77	0.94	0.1159
	300	17.3	762.81	0.98	0.1209
	360	19.0	762.82	0.99	0.1221
	420	20.5	762.84	1.01	0.1250
1	1537	39.2	763.05	1.22	0.1505
2	3220	56.7	763.12	1.29	0.1591
3	4475	66.9	763.15	1.32	0.1628
4	8793	93.8	763.39	1.56	0.1924
7	10370	101.8	763.45	1.62	0.1998
8	11540	107.4	763.48	1.65	0.2035
9	13225	115.0	763.58	1.75	0.2159



### EQUATION OF LINE:

Initial Absorption

$I = S \sqrt{t} + b$ . (points measured during the first day are used, excluding the point at origin)

$$S = 2.63 \times 10^{-3} \text{ mm}/\sqrt{\text{min.}} \quad b = 0.741 \times 10^{-2} \quad r = 0.98$$

Later age Absorption

$I = S \sqrt{t} + b$ . (points measured after the first day are used)

$$S = 0.877 \times 10^{-3} \text{ mm}/\sqrt{\text{min.}} \quad b = 0.11 \times 10^{-2} \quad r = 0.98$$

**THIS PAGE LEFT INTENTIONALLY BLANK**

## **APPENDIX B. CONCLIFE USER'S MANUAL**

### **INSTALLATION**

If installing CONCLIFE from a CD, access the CD-ROM drive and double click the INSTALL.BAT icon. If downloading CONCLIFE from the web, uncompress the zip file and double-click INSTALL.BAT. The installation program will give the user the option of changing the CONCLIFE program directory; if the default location is acceptable, press the **OK** button. Once installation is completed, start CONCLIFE by accessing it in the Start/Programs/CONCLIFE menu choice.

Minimum configuration required:

- Pentium™ P5<sup>5</sup> (80585) – 100 MHz Processor or better.
  - Windows 95/98™, Windows ME™, Windows 2000™, or Windows NT™ operating system.
- 64 Mb RAM  
SVGA (1024x768x8bpp) or higher resolution monitor.

### **MAIN CONCLIFE SCREENS**

CONCLIFE allows the user to create, conduct, and save numerous analyses, each called an “analysis set.” In each analysis set, the user specifies concrete material properties, environmental conditions, the sorptivity of the concrete over time, and the level of concrete spalling at which failure as defined by the user occurs. CONCLIFE then estimates the service life of the concrete based on deterioration from either sulfate attack or freeze-thaw. The CONCLIFE screens needed to complete these steps are shown in turn.

---

<sup>5</sup> Certain commercial products are identified to completely specify the research program. In no case does such identification imply endorsement by NIST or the FHWA or that the identified products are the best available for the purpose.

**Analysis**

Analysis set  
 Example analysis [v] [New] [Delete] [Set all to defaults]

Structure: ☒ Pavement ☐ Bridge deck

Sulfate attack | Freeze thaw

Input parameters

Elastic modulus	44.000000	GPa	Poisson's ratio	0.300000
Roughness factor	1.0000000000	[0,1]	Concrete porosity	14.000 %
Linear strain caused by one mole of ettringite formation	1.800000	$10^{-6}$ cubic meters/mole	External solution (rain) sulfate concentration	0.001000 M
Concrete fracture surface energy	10.000000	N/m		

Time of wetness

☒ Weather date Providence RI [v] [Use map...] ☐ Regular rainfall Rainfalls/yr 24.000000

☐ Use own Duration (hrs) 12.000000

[View weather data...] Concrete RH prior to rainfall 0.0 %

Sorptivity function

$S = 5.460000000 + 0.0027885600 t^{0.5000} \quad t \leq t_k$  [View...]

$S = 5.340000000 + 0.0089853600 t^{0.5000} \quad t > t_k$   $t_k = 7.00$  h

Measured concrete RH 60.0 % [Compute function...]

Service life

Failure criteria 0.050000 [Calculate] Service life: 64.8 years [View...]

m. of spalled concrete

Figure 14. CONCLIFE main window showing sulfate attack tab panel.

The **Analysis** window, shown in figure 14, has three main areas: the **Analysis set** section, the **Sulfate attack** tab panel, and the **Freeze-thaw** tab panel.

### Analysis Set Section

The **Analysis set** section maintains the database of CONCLIFE analysis sets. The drop-down box lists the current set of saved analyses. To create a new analysis set, press the **New** button; the user will be asked to enter a name for this new analysis. The **Delete** button will delete the currently displayed analysis (after asking for confirmation). The **Set all to defaults** button will set all of the sulfate attack *and* freeze-thaw parameter values in the currently displayed analysis set to their default values (after asking for confirmation).



Use the **Pavement** or **Bridge deck** button to specify whether a concrete pavement or bridge deck is being analyzed. This is an important distinction: because of the differences in their geometries and thermal boundary conditions, the temperature and time-of-wetness behavior of concrete pavements and bridge decks will be different, even when they are produced from the same materials and placed in the same geographical location. For example, departments of transportation often post “bridge freezes before road surface” signs because concrete suspended above ground freezes sooner than the same type of concrete in direct contact with the ground. CONCLIFE models this difference by maintaining separate pavement and bridge deck time-of-wetness files for each of the 13 sample geographical locations provided.

### **Sulfate Attack Tab Panel**

The **Sulfate attack** tab panel is divided into four major areas: **Input parameters**, **Time of wetness**, **Sorptivity function**, and **Service life**.

#### **Input Parameters**

The **Sulfate attack** tab panel uses a model based on the Atkinson and Hearne model,<sup>(7)</sup> which requires the following parameters, shown in the **Input parameters** section:

1. Measured elastic modulus of the concrete in GPa (default value is 44 GPa as measured on Rhode Island concrete) – the elastic modulus is the ratio of applied stress to the measured strain for the initial elastic region of the response obtained during a compression test.<sup>(19)</sup>
2. Geometrical factor to account for the roughness of the fracture path through the concrete (zero to one, one is the default<sup>(7)</sup>).
3. Linear strain caused by the reaction of sulfate ions to form one mole of ettringite (expressed in units of  $\text{m}^3/\text{mol} \times 10^{-6}$ , with a default value of  $1.8 \times 10^{-6}$ ,<sup>(7)</sup> equal to one-third of the bulk expansion caused by one mole of ettringite formation).
4. Concrete fracture surface energy (in N/m (or J/m<sup>2</sup>), default value is 10 N/m<sup>(7)</sup>).
5. Poisson’s ratio for the concrete (0.3 is the default value) – it is the ratio of the transverse contraction per unit dimension of a bar of uniform cross-section to its elongation per unit length, when subjected to a tensile stress; for concrete evaluated in compression,<sup>(19)</sup> it is the ratio of the transverse strain at the midheight of the specimen (expansion) to the longitudinal strain (compression).
6. Concrete porosity (percent, default value of 14 percent as measured on Rhode Island concrete).
7. Sulfate ion concentration of the solution (precipitation or condensation) to which the concrete is being exposed (in units of mol/liter, default value of 0.001 M) – measured sulfate ion concentrations in precipitation at a variety of geographical locations throughout the United States are available at the website of the National Atmospheric Deposition Program (<http://nadp.sws.uiuc.edu>).

CONCLIFE provides default values (as given above) for each of these parameters. However, whenever possible, users should use their own values from experimental measurements made on the concrete and/or environment under analysis.

## **Time of Wetness**

After specifying the concrete material properties, the user next selects in the **Time of wetness** section the environment to which the concrete is exposed. Environmental data can be specified in one of two ways. First, the user can select a typical time-of-wetness history from the **Weather data** drop-down box or by pressing the **Use map** button and selecting a city. These default time-of-wetness data files, generated from typical meteorological year data (TMY2DATA) files provided by the NREL,<sup>(5)</sup> are based on specific geometries for the pavements and bridge decks as shown in figure 9 and a specific set of thermal properties for the concrete and pavement subbase as provided in table 8. (See below for a description on how to change these default data on geometry and thermal properties.)

To view the weather data, press the **View weather data** button. This will display a histogram of the duration of each wetting event during the year for the geographical location currently shown in the weather data text box. These features will be discussed in more detail below.

A second, simpler model of environmental data can instead be specified by inputting “regular” rainfalls in the **Rainfalls/yr** and **Duration (h)** fields. In this case, specify the number of rainfalls per year, the duration of each rainfall, and the typical RH of the concrete just prior to the rainfall. Whether using the time-of-wetness histories or using the regular rainfall data, CONCLIFE uses these weather data to model the concrete’s sorption of water over time. Generally, when users have some idea of the geographical location of the concrete in question, they should utilize the weather data files to obtain a more accurate performance prediction.

## **Sorptivity Function**

The **Sorptivity function** section is used to input, view, and potentially generate the function describing the sorptivity of the concrete under analysis. Input the values that describe the concrete’s sorptivity over time (where time is measured in minutes and sorptivities in mm). As described in Reference (6), experimental sorptivity vs. time curves typically exhibit distinct behavior at early times and at later times. Both behaviors can be fit by a square root of time function with an intercept term. The nick-point time is the time when the sorptivity switches from the early-age behavior to the later-age behavior. The parameters describing the sorptivity can be determined either by (1) using an analysis tool outside of CONCLIFE, such as a spreadsheet, or (2) using the **Compute sorptivity function** window in CONCLIFE (accessed by pressing the **Compute function** button in the **Sorptivity function** section of the **Sulfate attack** tab panel). To compute a sorptivity from available measured experimental data, see the **Compute sorptivity function** section below. The user will also need to provide the measured concrete RH prior to sorptivity testing, as described in the sorptivity test provided in Appendix A. To view a graph of the current sorptivity function, press the **View** button.

## **Service Life**

In the **Service life** section, input the criteria for concrete failure (measured in terms of m-depth of spalled concrete). When users have input all parameters for the four sections, they should press the **Calculate** button to have CONCLIFE estimate the time required for spalling caused by

sulfate attack to reach this depth. The user may press the **View** button to view a graph of this spalling over time.

### Freeze-Thaw Tab Panel

Estimating freeze-thaw deterioration, the second degradation mechanism that CONCLIFE models, is analogous to that for sulfate attack. The **Freeze-thaw** tab panel, shown in figure 15, has the same four sections as the **Sulfate attack** tab panel: **Input parameters**, **Time of wetness**, **Sorptivity function**, and **Service life**.

**Analysis**

Analysis set  
 Example analysis [New] [Delete] [Set all to defaults]  
 Structure: ☒ Pavement ☐ Bridge deck

**Sulfate attack** **Freeze thaw**

**Input parameters**  
 Critical saturation: 0.85000000 (0-1) Air content: 2.00 %  
 Concrete porosity: 14.00 %

**Time of wetness**  
 Weather data: Providence RI [Use map...]  
☐ Use own [View weather data...]

**Sorptivity function**  
☒ Use sulfate attack sorptivity function [View...]  

$$S = 5.4600000000 + 0.0027885600 t^{0.5000} \quad t \leq t_k$$

$$S = 5.3400000000 + 0.0069653600 t^{0.5000} \quad t > t_k$$

$$t_k = 7.00 \text{ h}$$
 Measured concrete RH: 60.0 % [Compute function...]

**Service life**  
 Failure criteria: 0.05000 [Calculate] Service life: 67.0 years [View...]  
 m of spalled concrete

Figure 15. Freeze-thaw tab panel.

### **Input Parameters**

The freeze-thaw model is based on the work of Fagerlund,<sup>(8)</sup> and requires the following parameters:

1. Critical saturation (zero to one) of the air void system necessary to cause damage during a freezing event (default value of 0.85;<sup>(8)</sup> this value could be obtained by conducting freeze-thaw tests<sup>(20)</sup> on concretes of various saturation levels or assessing the change in saturation level during the freeze-thaw testing).
2. Concrete porosity (percent).
3. Concrete air void content (percent).

Input these values in their corresponding fields in the **Input parameters** section.

### **Time of Wetness**

The freeze-thaw model uses only the time-of-wetness data files generated from typical meteorological year data (TMY2DATA) files provided by the NREL,<sup>(5)</sup> not any user-specified constant values. Select a particular location from the **Weather data** drop-down box, or press the **Use map** button to select from the geographical map. See below for a description of how to create your own time-of-wetness files using a different geometry or thermal properties than the defaults provided above in figure 9 and table 8.

### **Sorptivity Function**

Values for the sorptivity function are input in the same fashion as for the sulfate attack model. To use the same function being used in the **Sulfate attack** tab panel, checkmark the **Use sulfate attack sorptivity function** box.

### **Service Life**

As with the sulfate attack model, failure is measured in terms of the depth of spalled concrete. After inputting this depth (in m) and verifying all other input parameters, calculate the estimated time for failure to be reached by pressing the **Calculate** button. A graph of this spalling can be viewed by pressing the **View** button.

## SUPPLEMENTARY CONCLIFE SCREENS

CONCLIFE also provides windows for: constructing new weather data files using your own concrete and environmental data; constructing sorptivity functions using laboratory data; and displaying weather data, sorptivity functions, and spalling over time.

### Edit Own Weather Data Window

In addition to the supplied weather data files in the **Sulfate attack** and **Freeze-thaw** tab panels, users can create their own weather data files based on their own data on the geometry of the concrete structure and the thermal properties of the concrete and the soil subbase. To access the **Generate own data** window (figure 16), checkmark the **Use own** box in the **Time of wetness** section of either model and press the **Edit** button that appears.

	Concrete	Sub-base
Thermal conductivity (J/Kg-C)	1.50	0.30
Heat capacity (W/m-C)	1,000.	800.
Density (Kg/m^3)	2,350.	1,600.
Emissivity	0.900	
Solar absorptivity	0.650	
Lower surface temperature (T)		3.0

Figure 16. Generate own data window.

Up to six weather data sets can be created for each city listed in the **Weather data** drop-down boxes of the **Sulfate attack** and **Freeze-thaw** tab panels. To create a new own-data set in the **Generate own data** window, select the set in the **Thermal set** drop-down box.

Be sure to name the set so that it is recognizable in future work. Edit the slab and subbase values for thickness (there is no subbase for a bridge deck) and thermal properties. When done, press the **Go** button to create the new weather data set (this may take up to 10 min). When the new set is created, it will appear as a choice in the **Own data** drop-down boxes in the **Sulfate attack** and **Freeze-thaw** tab panels; if the user doesn't press **Go**, the set will be saved in this **Generate own data** window but will *not* appear in the **Sulfate attack** and **Freeze-thaw** tab panels.

### Compute Sorptivity Function Window

If the user has sorptivity data generated from the developed laboratory test for sorptivity (Appendix A), CONCLIFE can estimate a sorptivity function based on these data. In the **Sorptivity function** section of either the **Sulfate attack** or **Freeze-thaw** tab panels, press the **Compute function** button to access the **Compute sorptivity function** window (shown in figure 17). Input the laboratory data in the spreadsheet on the left (clear any old data by pressing the **Clear** button), then press the **Compute function** button. If the computed sorptivity parameters are acceptable, press the **Use this function** button; the sorptivity values in the **Sulfate attack** tab panel will then be updated. Press the **Cancel** button to exit this screen without updating the sulfate attack sorptivity function.

Input your timeseries of sorptivity values (times in minutes and sorptivities in mm)

Observation	Time (min)	Sorptivity (mm)
001	1.000	1.0000
002	1.100	2.0000
003	1.300	4.0000
004	1.400	9.0000
005	1.500	12.0000
006	1.600	15.0000
007	1.700	17.0000
008	1.800	18.0000
009	1.900	21.0000
010	2.000	23.0000
011	0.000	0.0000
012	0.000	0.0000
013	0.000	0.0000
014	0.000	0.0000

Graph it Clear

Compute sorptivity function

Compute function

$S = \text{[ ]} + \text{[ ]} t^{0.5} \quad t \leq t_k$   
 $S = \text{[ ]} + \text{[ ]} t^{0.5} \quad t > t_k$   
 $t_k = \text{[ ]} \text{ h}$

Graph

Cancel Use this function

Figure 17. Screen for computing sorptivity function from measured data.

## Graphs and Maps

A number of graphs and maps are provided throughout CONCLIFE to aid in the understanding of the environmental data, of the sorptivity of concrete over time, and of the spalling of concrete over time.

### U.S. Map for Weather Locations

The weather location map, shown in figure 18, displays the cities for which CONCLIFE provides time-of-wetness data. Select sample weather data for a particular city by clicking on the city name. To access this map, press the **Use map** button in the **Time of wetness** section of either the **Sulfate attack** or the **Freeze-thaw** tab panels.

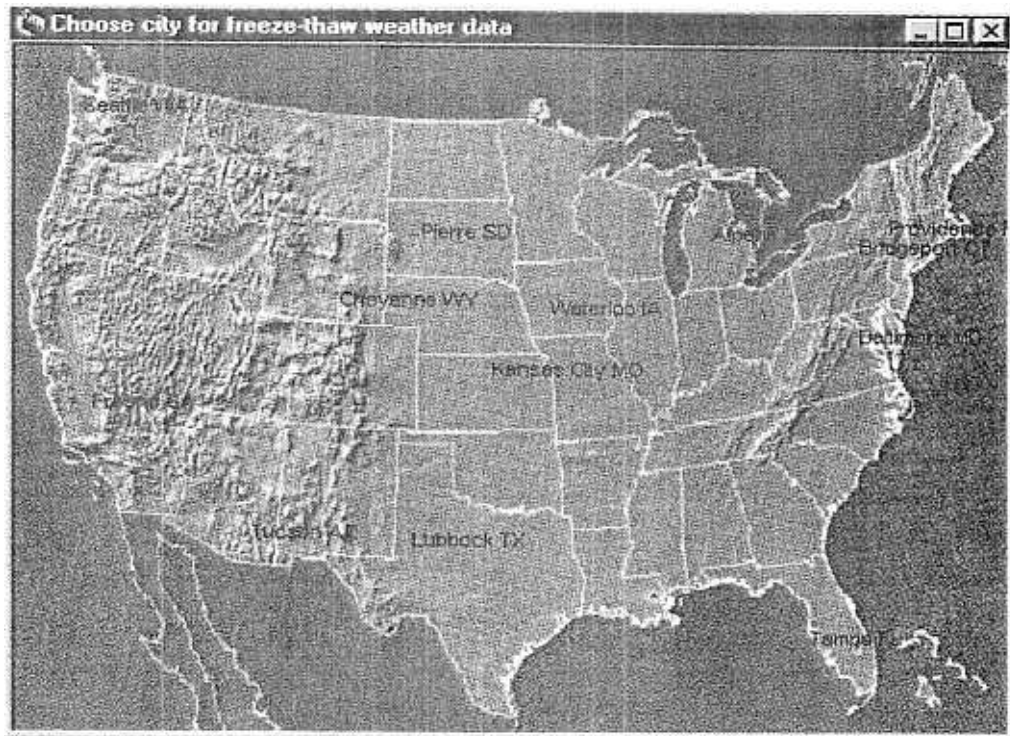


Figure 18. Map of weather data cities.



### Sorptivity Function Graph

A graph of the current sorptivity function (figure 19) can be viewed by pressing the **View** button in the **Sorptivity function** section of either the **Sulfate attack** or **Freeze-thaw** tab panels. The graph can be printed by selecting the **Print/Graph** selection from the menu.

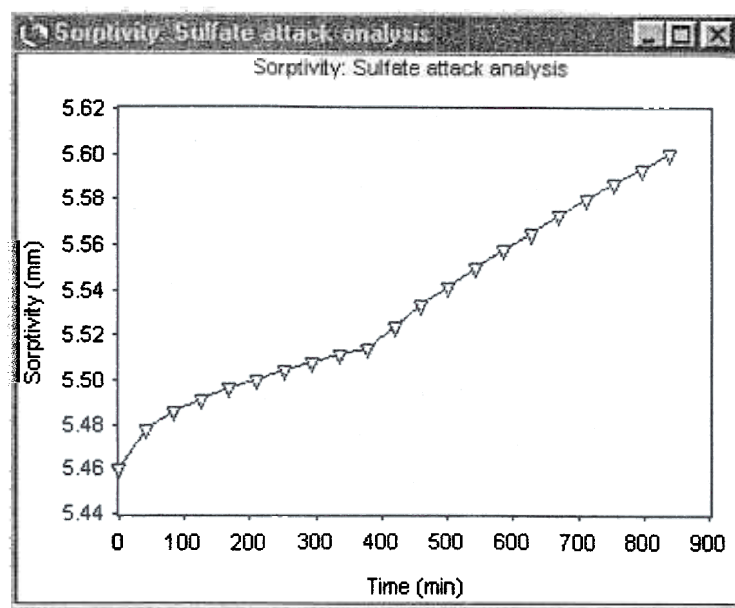


Figure 19. Graph of typical sorptivity function.

## Weather Data Graph

The time-of wetness data files he graphed pressing the **View weather data** button in the **Time of wetness** section of either the **Sulfate attack** or **Frost/thaw** tab panels. This graph, shown in figure 1, he printed by selecting **Print/Graph** from the **CONCLIF**

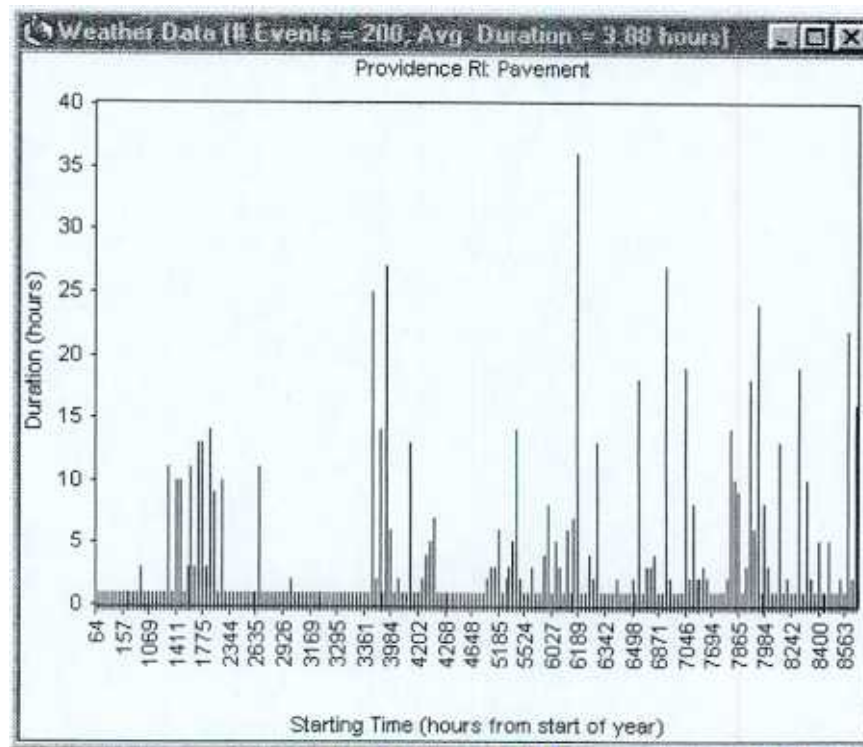


Figure 1. Time-of-wetness data for Interstate 95, Providence, RI

## Spalling Graph

A graph of estimated spalling over time (figure 21) can be viewed for either model by pressing the **View** button in the **Estimated failure** section. (The **View** button appears only if the service life has been estimated.) It can be observed that the spalling occurs as a series of discrete spalling events at various times during the service life of the concrete. To print this graph, select **Print/Graph** from the CONCLIFE menu.

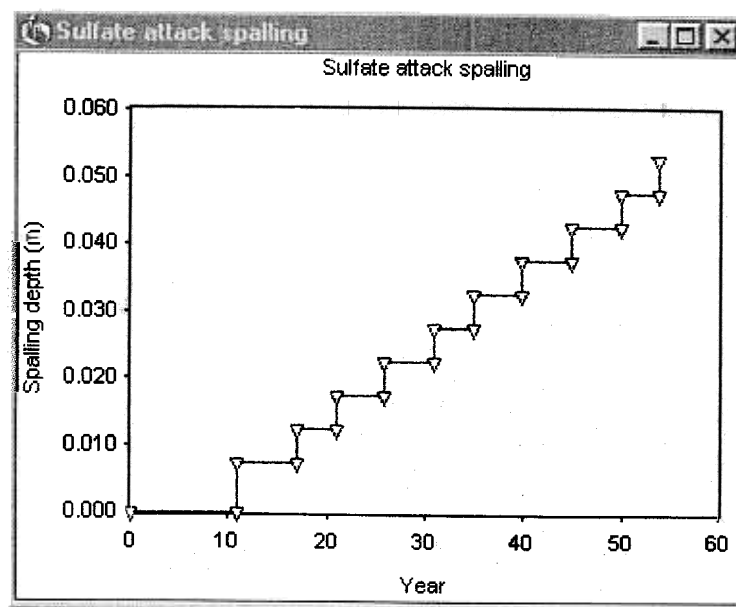


Figure 21. Graph of estimated spalling over time for a pavement in Providence, RI, exposed to sulfate attack.

## EXAMPLE ANALYSES

To illustrate the use of CONCLIFE, this section describes an analysis performed by NIST<sup>(6)</sup> that compared the predicted service lives of concrete pavements in Rhode Island and Missouri. The parameters and assumptions used in this analysis can be found in the analysis set “Example analysis” included with CONCLIFE.

NIST, with cooperation from the Rhode Island and Missouri Departments of Transportation (DOTs), measured and developed estimates of the material characteristics, structural geometries, and environmental conditions of sample concrete pavements in the two States, and then used CONCLIFE to estimate service lives. NIST first measured the elastic moduli and sorptivity coefficients of concrete cores obtained from the two States’ DOTs.<sup>(6)</sup> The measured values are shown in tables 6 and 7.

Air content of the concretes was assumed to be a marginal air void system with only 2 percent air. The sulfate concentration of the rainwater/condensation was estimated to be 0.001 mol/L, the concrete porosity to be 14 percent (based on measurements on the Rhode Island cores), and the critical saturation of the air void system necessary to cause freeze-thaw damage to be 0.85. Pavement “failure” in both States was defined as spalling in excess of 0.05 m. Figures 14 and 15 show these and the other values used in the CONCLIFE analysis of the Rhode Island pavement. Figures 22 and 23 show the corresponding screens for the Missouri Rt. 65 driving lane concrete. The resulting CONCLIFE estimates of the service lives are shown in table 9.



**Analysis**

Analysis set: **Example #1** [New] [Delete] [Set all to defaults]

Structure: ☒ Pavement ☐ Bridge deck

**Sulfate attack** | Freeze thaw

**Input parameters**

Elastic modulus	46.000000	GPa	Poisson's ratio	0.300000
Roughness factor	1.0000000000	[0,1]	Concrete porosity	14.000 %
Linear strain caused by one mole of ettringite formation	1.800000	$10^{-6}$ cubic meters/mole	External solution (rain) sulfate concentration	0.001000 M
Concrete fracture surface energy	10.000000	N/m		

**Time of wetness**

☒ Weather data: **Kansas City MO** [Use map...] ☐ Regular rainfall

☐ Use own

Rainfalls/yr: 24.000000  
Duration (hrs): 12.000000  
Concrete RH prior to rainfall: 0.0 %

[View weather data...]

**Sorptivity function**

$S = 0.0750000000 + 0.0032500 t^{0.5000} \quad t \leq t_k$  [View...]  
 $S = 0.0650000000 + 0.0039500 t^{0.5000} \quad t > t_k$   
 $t_k = 7.00 \text{ h}$

Measured concrete RH: 60.0 % [Compute function...]

**Service life**

Failure criteria: 0.050000 [Calculate] **Service life: > 99 years** [View...]  
 m of spalled concrete

Figure 22. CONCLIFE sulfate attack tab panel for concrete pavement from Missouri Rt. 65 driving lane.

Table 9. Predicted service lives for the concretes.<sup>(6)</sup>

Degradation Mode	Rhode Island	Missouri Rt. 65 Driving Lane	Missouri Rt. 13 Driving Lane
Sulfate attack	54.8 years	> 99 years	> 99 years
Freeze-thaw	67.0 years	> 99 years	> 99 years

The very low sorptivities of the Missouri concretes result in estimated sulfate attack and freeze-thaw service lives that exceed 99 years (the maximum computed lifetime in the CONCLIFE software). The higher  $I_0$  (early age) and  $S$  (later age) values for the Rhode Island concrete result in sulfate attack and freeze-thaw predicted service lives of about 55 years and 67 years,



**Analysis**

Analysis set:  
 Example #1 [New] [Delete] [Set all to defaults]

Structure: ☒ Pavement ☐ Bridge deck

**Sulfate attack** | Freeze thaw

Input parameters:  
 Critical saturation: 0.65000000 (0-1)      Air content: 2.00 %  
 Concrete porosity: 14.00 %

Time of wetness:  
 Weather data: Kansas City MO [Use map...]  
☐ Use own  
 [View weather data...]

Sorptivity function:  
☐ Use sulfate attack sorptivity function  

$$S = 0.07500000000 + 0.0032500 t^{0.5000} \quad t \leq t_k$$

$$S = 0.06500000000 + 0.0039500 t^{0.5000} \quad t > t_k$$

$$t_k = 7.00 \text{ h}$$
 [View...]  
 Measured concrete RH: 60.0 % [Compute function...]

Service life:  
 Failure criteria: 0.05000 [Calculate]      Service life: > 99 years [View...]  
 m of spalled concrete

CONC. fr

lan

R<sub>a</sub>

## REFERENCES

1. Basheer, P.A.M., Chidiac, S.E., and Long, A.E., "Predictive Models for Deterioration of Concrete Structures," *Construction and Building Materials*, Vol. 10 (1), 27-37, 1996.
2. Nilsson, L.O., "Interaction Between Microclimate and Concrete - A Prerequisite for Deterioration," *Construction and Building Materials*, Vol. 10 (5), 301-308, 1996.
3. Bentz, D.P., Clifton, J.R., Ferraris, C.F., and Garboczi, E.J., *Transport Properties and Durability of Concrete: Literature Review and Research Plan*, NISTIR 6395, U.S. Department of Commerce, September 1999.
4. Bentz, D.P., *A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks*, NISTIR 6551, U.S. Department of Commerce, August, 2000.
5. Marion, W., and Urban, K., *User's Manual for TMY2s: Typical Meteorological Years*, National Renewable Energy Laboratory, June 1995.
6. Bentz, D.P., Ehlen, M.A., Ferraris, C.F., and Garboczi, E.J., "Sorptivity-Based Service Life Predictions for Concrete Pavements," 7<sup>th</sup> International Conference on Concrete Pavements, Orlando, FL, September 2001.
7. Atkinson, A., and Hearne, J.A., *Mechanistic Model for the Durability of Concrete Barriers Exposed to Sulphate-Bearing Groundwaters*, MRS Symposium Proceedings, Vol. 176, 149-156, 1990.
8. Fagerlund, G., "Modeling the Service Life of Concrete Exposed to Frost," International Conference on Ion and Mass Transport in Cement-Based Materials, University of Toronto, October, 1999.
9. ASTM C215, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens," ASTM C215-97, Vol. 04.02, 1999.
10. ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM C1202-97, Vol. 04.02, 1999.
11. "Recommendation of TC 116-PCD: Tests for Gas Permeability of Concrete C. Determination of the Capillary Absorption of Water of Hardened Concrete," *Materials and Structures*, Vol. 32 (217), 178-179, 1999.
12. Howe, S., "The Great Tape Off," *Backpacker*, Vol. 29 (190-8), 59, 2000.
13. Martys, N., and Ferraris, C.F., "Capillary Transport in Mortars and Concretes," *Cement and Concrete Research*, Vol. 27 (5), 747-760, 1997.
14. Walton, G.N., *Thermal Analysis Research Program- Reference Manual*, NBSIR 83-2655, U.S. Department of Commerce, March 1983, Update 1985.
15. McCullough, B.F., and Rasmussen, R.O., *Fast-Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonded Concrete Overlays, Volume 1: Final Report*, FHWA-RD-98-167, Federal Highway Administration, 1997.
16. Schlangen, E., *Online Help/Manual module HEAT of FEMMASSE, 1990-2000*, FEMMASSE b.v., The Netherlands, 2000.
17. Holman, J.P., *Heat Transfer*, McGraw-Hill Book Company, New York, 1981.
18. Weast, R.C. (ed.), *CRC Handbook of Chemistry and Physics*, 63<sup>rd</sup> edition, 1983.
19. ASTM C469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," ASTM C469-94, Vol. 04.02, 2000.
20. ASTM C666, "Standard Test Method or Resistance of Concrete to Rapid Freezing and Thawing," ASTM C666-97, Vol. 04.02, 2000.



**THIS PAGE LEFT INTENTIONALLY BLANK**