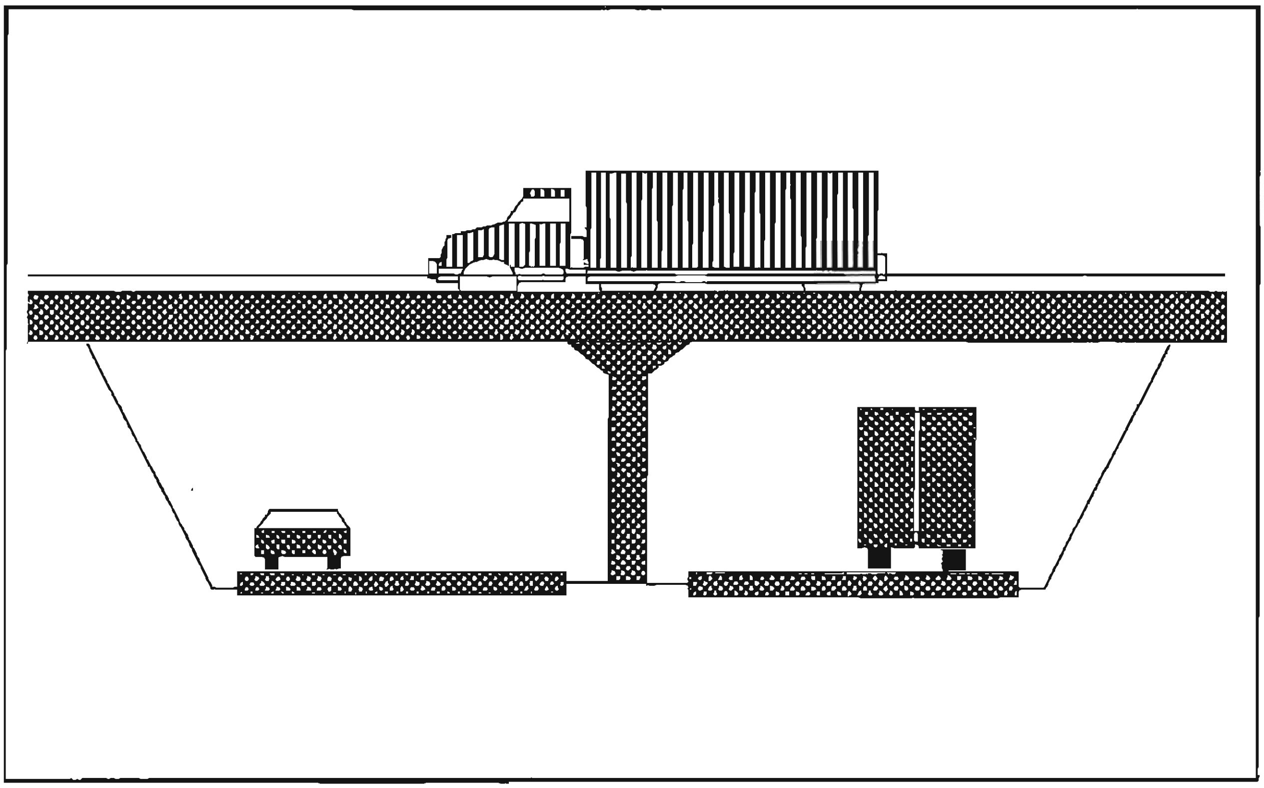
Report No. CDOT-DTD-R-92-7

CHLORCAL90

COLORADO DEPARTMENT OF HIGHWAYS
CHLORIDE CONTENT EVALUATION PROGRAM
FOR REINFORCED CONCRETE BRIDGE DECKS



by

Arne B.Riple and Bruce A. Suprenant

February 1992

Prepared in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CDOT-DTD-R-92-7		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code / 8. Performing Organization Report No.
CHLORIDE CONTENT PROGRAM FOR THE EVALUATION OF REINFORCED CONCRETE BRIDGE DECKS	5. June, 1992 6. File 80.06
7. Author(s) Arne B. Riple and Bruce A. Suprenant	8. CDOT-DTD-R-92-7
9. Performing Organization Name and Address University of Colorado Department of Civil Engineering Campus Box 428 Boulder, CO 80309	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation 4201 East Arkansas Avenue Denver, CO 80222	13. Type of Report and Period Covered Final Report 10/90 through 6/92 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U. S. Department of Transportation
Federal Highway Administration

16. Abstract

Reinforcing steel in concrete is protected by a passive layer that is destroyed when exposed to chlorides. To maintain a bare deck, deicing salts that contain chlorides are used to remove the snow and ice. The chlorides penetrate the concrete, destroy the passive layer surrounding the reinforcing, and help initiate corrosion of the rebar.

A computer program has been developed to calculate the chloride diffusion in concrete and to assist the engineer in analyzing existing bridge decks and future concrete repairs. The computer program calculates the diffusion coefficient, the applied surface chloride loads, and future chloride profiles based on chloride profiles from core tests.

The program can evaluate different deck designs including changes in concrete cover, chloride loads, concrete type, sealer application and life, and other variables. The program is user-friendly and operates on a 386PC with a VGA screen.

17. Key Words	18. Distribution Statement
chloride diffusion, bridge management, corrosion	No restrictions: This report is available to the public through the National Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	37	

Form DOT F 1700.7 (8-72)

INTRODUCTION

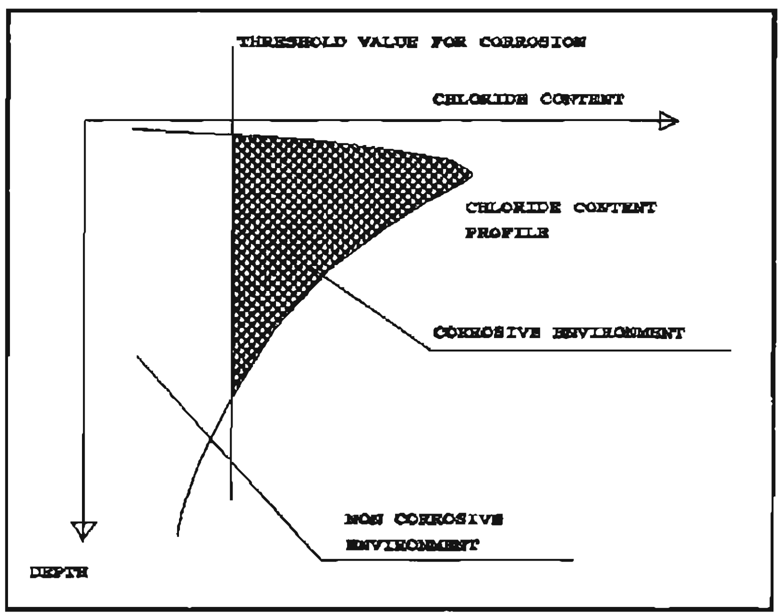
Corrosion of steel reinforcement, initiated by high chloride concentrations in the concrete, is a serious cause of degradation in concrete structures exposed to deicing salts and to a marine environment.

Steel embedded in concrete does not normally corrode, this is due to passivation of the steel. This passivation occurs because of reactions between oxygen and the alkaline environment in the concrete. A very thin, but impermeable layer of iron oxide is formed to protect the steel against corrosion.

Chloride ions are the most common degradation agent found to cause corrosion damage in today's concrete structures. High levels of chloride concentration are capable of breaking down the passivation layer surrounding the steel reinforcement, and corrosion may be initiated.

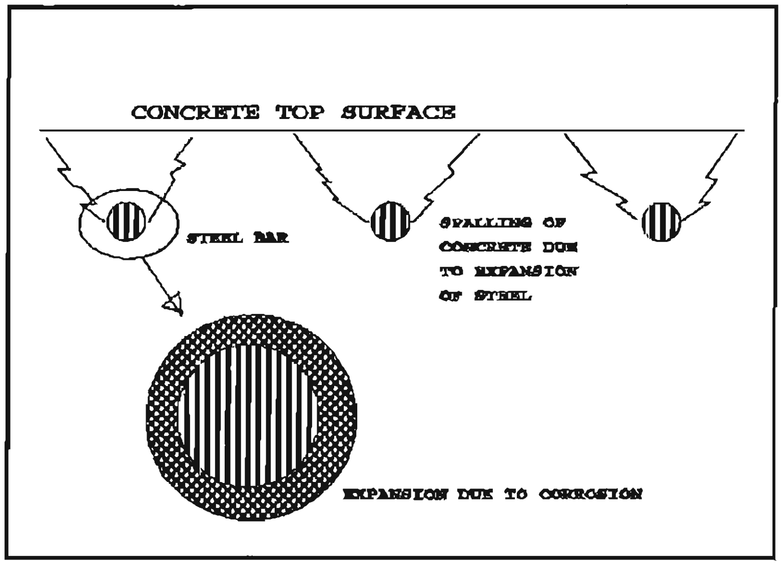
It is found that corrosion initiation occurs with chloride concentrations of about 1.4 pcy or approximately 0.03% chloride in concrete, Ref /4/.

As the chloride content at the rebar level reaches a threshold value for corrosion initiation, the steel will start to corrode. When the chloride level is below the threshold value, the steel will not corrode.



With large chloride concentrations at the top surface, the chloride level at the rebar level will increase with time, and eventually exceed the threshold value.

As the steel corrodes, the expansive forces generated by the rust have been estimated to reach 4700 psi, Ref/3/. These forces may be large enough to cause the concrete to crack at the steel - concrete interface.



CHLORIDE DIFFUSION

Researchers have found that diffusion of chloride ions through concrete corresponds well to Fick's Second Law of Diffusion.

$$\frac{\partial C}{\partial t} = \frac{D_e \partial^2 C}{\partial x^2} \tag{1}$$

C = *Chloride concentration at some distance* x

D_e = *Effective diffusion coefficient*

t = *Time*

Depending on the boundary conditions and load application of chloride, several possible solutions to this differential equation are possible. Two solutions are presented, and the differences in the application of chlorides should be noted.

A standard solution for a constant chloride source at the concrete surface is as follows, Ref/1/:

$$C_{(x,t)} = C_0 \left[1 - erf\left(\frac{x}{2\sqrt{D_e t}} \right) \right]$$

$C_{(x,t)}$ = *Chloride concentration at depth x after time t for an equilibrium concentration C_0 at the surface* (2)

erf = *e function*

For equation number (2), the solution is valid only for a constant chloride source at the concrete surface. This relationship is well suited for concrete structures exposed to seawater or other stationary (fixed) chloride sources.

For an instantaneous chloride source applied at the surface at time t = 0, a solution is given by, Ref/2/:

$$C_{(x,t)} = \frac{M}{\sqrt{\pi D_e t}} \exp\left(\frac{-x^2}{4 D_e t} \right)$$

$C_{(x,t)}$ = *Chloride concentration* (3)

M = *Amount of chloride deposited at time t = 0 at distance x = 0*

D_e = *Effective diffusion coefficient*

For concrete structures exposed to a single application of chloride, equation number (3) is appropriate. Using the method of superposition, equation number (3) is well suited for concrete structures exposed to repeated applications of chloride deposits, at the concrete surface, such as highway bridge decks.

DIFFUSION DUE TO REPEATED CHLORIDE APPLICATIONS

Diffusion in accordance with equation (3) is visualized in figure (4). The single chloride deposit will diffuse through the concrete, reducing the chloride concentration at the surface, at the same time the concentration is increased through the concrete depth.

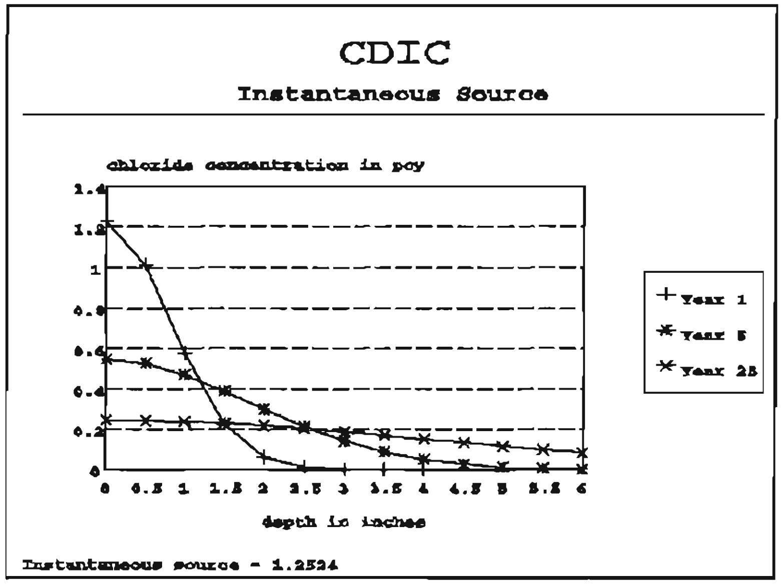


Figure 4

With repeated chloride applications, several single deposits may be superimpose to create the combined effects of all applications. Assuming equal deposits every year, the combined chloride concentration at the surface will increase with time. The rate of change will decrease with time, and will eventually reach an asymptotic limit. However, the time to reach this threshold limit is far beyond the expected service life of most concrete structures.

The increase in chloride concentration at the concrete surface is shown in figure (5).

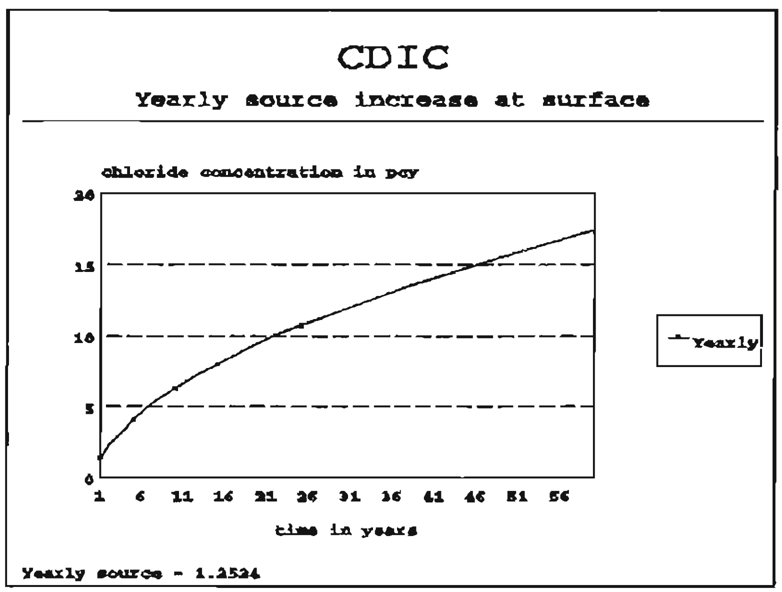


Figure 5

Figure (6) shows predicted chloride concentration curves for an equal amount of yearly repeated chloride application.

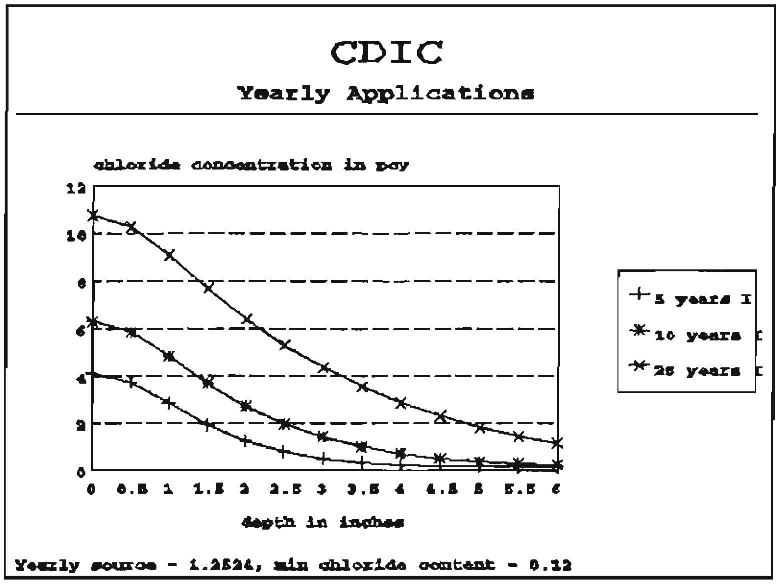


Figure 6

It must be noted that the effect of evaporation of chloride ions from the top surface is not included in the evaluation. From core tests, the maximum chloride concentration is commonly found at 0.5 inches below the top surface.

When running CHLORCAL90, the user inputs the chloride measurements from the concrete structure, and also the time between construction and chloride measurements.

CHLORIDE CONCENTRATIONS FROM CORE TESTS

For the practicing engineer, it's important to establish the parameters involved in the diffusion equations.

Depending on the concrete quality, specifically the porosity, the variation in the diffusion coefficient may be quite large. With little information about the actual diffusion rate of the concrete, and equally little information about the applied chloride source, the engineer must obtain chloride concentrations from field concrete samples.

The most common approach to establish this fundamental information is to sample core tests at 0.5 inch intervals to a depth of 6 to 8 inches in the concrete structure. The chloride concentrations at these levels will establish a chloride concentration profile through the concrete.

Be aware of the variation in chloride results when sampling the core tests. The variations may be due to inaccurate depth of the measurements, concrete porosity, or due to inaccuracy in the chloride concentration measurements. Due to this possible variance, 3 measurements at each level are recommended.

The measured chloride concentration profile must then be fitted to the applicable diffusion equation, and future profiles may then be calculated.

For the constant chloride source at the surface, the exact value for the effective diffusion can be established. For repeated chloride deposits at the surface, however, there are usually two unknowns, the diffusion coefficient and the application of chlorides. The parameters for the repeated chloride deposits must therefore be established by a numerical process.

CHLORCAL90, PERFORMANCE

CHLORCAL90 is developed to obtain the parameters from the measured chloride concentration profile. CHLORCAL90 also predicts future chloride concentration profiles based upon the results obtained from the chloride measurements. Also included in CHLORCAL90 is the evaluation of time to corrosion initiation, in accordance with the obtained diffusion parameters.

CHLORCAL90 calculates the effective diffusion coefficient De, and this may then be incorporated for prediction of future profiles. The user has the opportunity to specify three evaluation times, and CHLORCAL90 will display all three simultaneously to show the trend.

Because there are two unknowns, the diffusion coefficient De, and the yearly chloride deposit M, CHLORCAL90 uses a numerical routine to find a best fit curve.

The two parameters are found by fitting a curve through the minimum chloride concentration measurement, and each of the higher chloride measurements. The minimum sum of least square deviations is then selected for the best fit curve. However, this may not always give the best fit curve for the depth where the engineer is investigating.

To provide the engineer with more control of the curve fitting, CHLORCAL90 has a customizing routine, so that the predicted curve is more consistent within a particular area of interest in the measured chloride concentration profile.

When the diffusion parameters are obtained from the measured chloride concentration profile, the engineer may use these parameters to calculate new chloride predictions at selected time intervals. CHLORCAL90 also allows for input of individual chloride deposits each year. Inputting yearly individual chloride surface deposits provides the engineer with better control over the actual loading condition, and if some years have a different chloride application, this is easily incorporated.

Another advantage using the method of superposition of yearly applied chloride deposits is that sealers may easily be incorporated in the evaluation. Just as the engineer has the possibility of assigning different levels of chloride applications each year, CHLORCAL90 also incorporates the possibility of assigning different sealer capacities each year.

This gives the engineer a full range of features that can be implemented in the maintenance scheduling, and in evaluating the possible effects of preventive measurements that may be taken. Using this method, the engineer can perform trial designs by changing the parameters affecting the time to corrosion, the maintenance sequence, and the most economical maintenance or repair plan can be evaluated for the service life of the structure.

CHLORCAL90, THE COMPUTER PROGRAM

CHLORCAL90 was developed with the designer in mind. Several options are available for new bridge deck design. The designer has a powerful tool to evaluate several design options to optimize the overall design. Options such as use of sealers, variation of cover depth, and the use of several types of concrete are available.

While running the computer program, the user is in a menu driven environment. The user can move between menus and options as needed. The input values can be viewed at any time, and changes can be made to any value, or set of values.

Some of the parameters in the computer program are provided with default values, therefore the designer doesn't have to know the exact parameter value. These default values are based on statistical data.

A main function of CHLORCAL90 is to find the effective diffusion coefficient in an existing deck. This is based on chloride content tests evaluated at several depths within the concrete bridge deck.

When the chloride contents are known for the various depths, and the time period between construction of deck and the time when chloride content tests are taken, CHLORCAL90 evaluates the maximum and minimum chloride contents in the profile.

The maximum chloride content is usually found at a distance of approximately 0.5 inches from the top. Ref./4/.

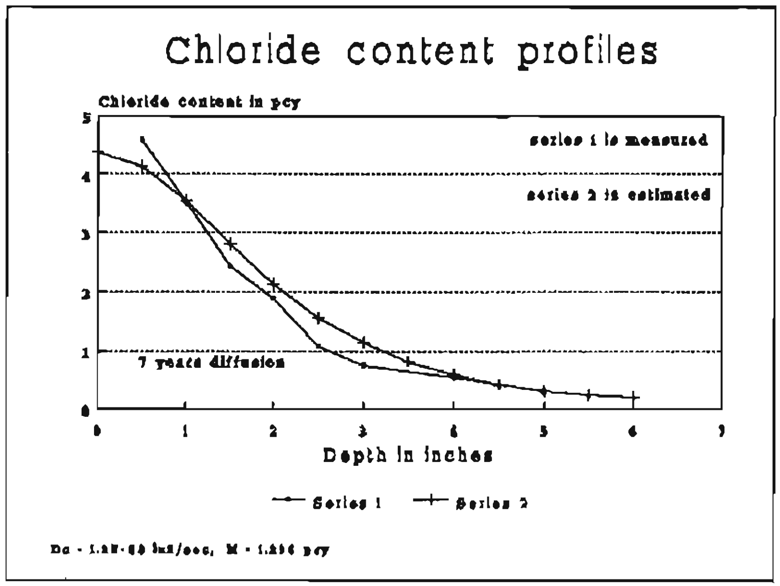
The minimum value is defined as the initial chloride content in the concrete mix. This is evident when the chloride content profile becomes vertical. CHLORCAL90 assigns a minimum value if the angular rate of change with respect to the vertical axis is less than 2.5 degrees.

A minimum value may not always be found. If an insufficient number of measurements are provided, the vertical portion of the curve will not be obvious. In this case, CHLORCAL90 assigns the minimum value to zero. The user may override this by assigning an initial chloride content value.

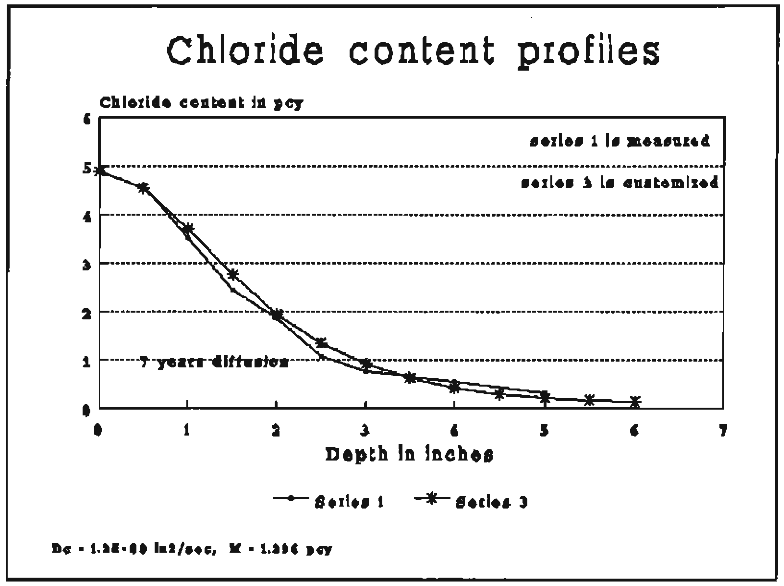
When evaluating the diffusion coefficient and average yearly applied chloride content, CHLORCAL90 uses a numerical procedure to find a unique solution that satisfies both the measured chloride contents and the diffusion equation.

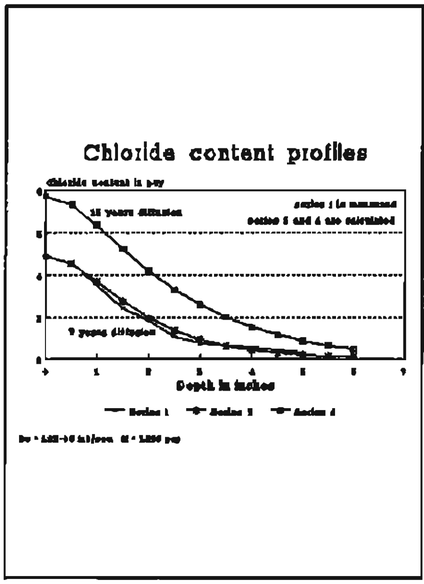
The procedure calculates the corresponding diffusion coefficient and chloride application that satisfies the chloride measurements. This calculation is performed for all chloride measurements for the deck. Using the calculated results, these chloride content values are compared with the measured chloride content values.

The difference in estimated chloride content and measured content is calculated for all applicable locations in the deck. Then the diffusion coefficient and corresponding chloride application that has the least sum of squared errors is selected.



The computer program can customize the calculated result to fit the curve to the measured chloride values in any desired region.





With the diffusion coefficient and the average yearly applied chloride concentration at the surface, new chloride content profiles can be calculated for future times.

The user must assign the following values to CHLORCAL90 :

- Diffusion coefficient.
- Yearly chloride application at surface.
- Minimum chloride concentration.
- Time to evaluation.
- Depth to reinforcement.
- Threshold value for initiation of corrosion.
- Sealer capacity.

The chloride content at the level of reinforcement will be calculated and simultaneously, the time to corrosion initiation will be estimated.

CHLORCAL90 calculates a set of chloride concentration values at 0.5 inch increments to a depth of 6.0 inches. These values will be presented in both tabular form and in graphical representation.

The future chloride content profiles will be presented for three different time evaluations as specified by the engineer. The three profiles shows how the chloride profile will increase with time.

The threshold limit is also shown for comparison with the profiles.

RUNNING CHLORCAL90

The engineer enters CHLORCAL90 by typing " CC90 ".

A title page will be displayed. To continue, the user must press <ENTER>. CHLORCAL90 will then display an introduction of the program features. After the introduction, the main menu will be displayed.

From the main menu, the user has the opportunity to evaluate the diffusion coefficient in an existing deck, evaluate new chloride content profiles, select a help menu that provides information on the applicable features in the program, or to exit the program.

Evaluation of diffusion coefficient in existing deck:

The diffusion coefficient for a concrete bridge deck is a main consideration in the evaluation of the chloride content at any level in the deck. The diffusion coefficient is a measure of the rate that the chloride ions migrate from the top surface of the concrete through the deck. The higher the diffusion coefficient, the faster the chloride content will reach the threshold value of corrosion at the rebar level.

As the threshold value of corrosion is reached at the level of the reinforcing steel, the corrosion of steel will initiate. The time to initiation of corrosion is usually the most important engineering parameter. This time to initiation of corrosion is the mean value for the steel actually located at the design level. However, based upon statistical data, the steel is placed with a standard deviation of 0.5 inches, Ref./4/. On a given bridge, 16% of the steel will have cover depths of 0.4 inches less than average cover, and about 2.5% will be less than the average cover by 0.8 inches or more. This deviation will make some of the steel corrode at an earlier stage, and some of the steel at a later stage.

To evaluate the diffusion coefficient in an existing deck, chloride content tests from the deck must be taken. The chloride content is usually found for each half inch increment to a depth of 6 inches. This produces a good chloride content profile through the concrete deck.

Because of a coefficient of variation in measured chloride content of 30%, 6 cores per bridge deck should be used, Ref./3/. The results needs to be interpreted, some measurements may need to be discarded, before averaging the chloride content at the individual depths.

This chloride content profile must be available to the engineer before attempting to evaluate the diffusion coefficient with CHLORCAL90. It is also necessary to know the time from construction of the bridge deck to the time the chloride content tests are taken.

The chloride content profile, and the time interval between construction and core tests are the only two parameters needed to start the evaluation for the diffusion coefficient and the average yearly applied chloride.

Assigning values:

When selecting the number for evaluation of diffusion coefficient in an existing deck, the user is prompted with a new menu, menu 1.1. The user will then select the number corresponding to the action wanted.

```
MENU 1.1

EVALUATION OF DIFFUSION COEFFICIENT IN EXISTING DECK DESIGN
************************************************************
Assign Chloride Content values.

Assign Time between Construction and Evaluation.

Assign Distance to Reinforcement.

Assign Minimum Chloride Content.

View Assigned Values.

Perform Calculations and View Results.
************************************************************
```

As the user enters the action number, a new menu or action is displayed on the screen.

Assigning Chloride content values:

Selecting this action, with the intention of entering the chloride content values found in the core tests, the user enters an interactive window where the arrow keys can be used to move between input locations.

The user must input the depth of the measurement and the corresponding chloride content. The values must be given for half-inch or full inch locations, but need not be given for consecutive increments.

Half-inch increments are commonly given to a depth of 5 to 6 inches, but as the depth increases, full inch increments may provide sufficient accuracy.

The input values shall start with the lowest depth measurement and then increase in depth, i.e. from 0.5 inches to 4 inches. The depth must be given in inches and the chloride content in pounds per cubic yard, pcy.

Example:

Depth	Chloride Content
0.0	4.9
0.5	4.6
1.0	3.52
1.5	2.76
2.0	1.88
2.5	1.08
3.0	0.76
4.0	0.56
5.0	0.32

The user may change these values at any time by moving to the actual number and pressing <ENTER>, the space turns blank, and a number may be entered.

It is unnecessary to fill in all possible depths, CHLORCAL90 automatically stops evaluating the measurements at the first depth that is entered as zero after the set of depth increments.

The user may start with the first value as 0.0, and then increase with 0.5 inch increments, as shown above. However, if the first value is smaller than the maximum value, this is then neglected by the computer program, since this does not correspond to a theoretical diffusion curve.

The reason for smaller values at the top surface is the evaporation of chlorides to the air. The computer program works on the curve below the maximum chloride concentration.

Assigning time to evaluation:

Selecting this action in menu 1.1, the user is prompted for the time to evaluation in years. This value is the number of years between the construction of the bridge deck, and the time the core tests were taken for analysis of chloride content.

Assigning distance to reinforcement:

Selecting this action in menu 1.1, the user is prompted for the depth of concrete cover. This depth is the value from the top surface of the bridge deck to the design depth of the top layer of reinforcement.

Assigning minimum chloride content in the deck:

Selecting this action in menu 1.1, the user is prompted for the initial or minimum chloride content value in the deck. This value corresponds to any chloride content within the mix, resulting from admixtures or aggregates.

The initial chloride content is evident in the chloride profile from the core tests if the chloride content profile flattens out, is vertical, and does not decrease from one depth to the next.

If the profile is not deep enough, there may still be an initial chloride content value, but this value may be unknown unless the designer knows or can calculate the chloride content in the concrete mix.

Unless the user specifies a minimum value, the CHLORCAL90 will calculate the value based upon the entered profile. If there is no indication of a minimum value, the minimum value will be set equal to zero.

If the user specifies a minimum value, this value will override any value calculated by CHLORCAL90.

View assigned values:

When selecting action 5 in menu 1.1, the screen will display all assigned values for the user to check for any input errors. If any errors are detected, simply return to menu 1.1 and select any action that needs to be corrected or altered.

Performing calculations:

To perform the calculations with the values assigned and displayed, simply select this action in menu 1.1.

As this action is selected, CHLORCAL90 calculates the diffusion coefficient in the concrete deck and also the corresponding yearly application of chloride.

After the calculations are performed, the screen will display the assigned values and the calculated results.

The results will automatically be presented after the calculations are completed. The first presentation will be a review of input parameters and the calculated parameters.

Also CHLORCAL90 presents a graphical representation of the measured chloride contents and the calculated chloride content profile based upon the estimated parameters.

Then having viewed and compared the actual measurements to the estimated, the engineer has the option to customize the curve.

If desired, the user may then select to enter the customizing procedure and enter multiplication factors for the diffusion coefficient and/or the chloride application. If using a multiplication factor of 1.0, the values would remain unchanged.

After entering the multiplication factors, a new graph is displayed showing the original graph and the customized profile. The user may choose to keep the customized profile by saving the values before exiting the routine.

The user must select to save the values if these values are to be used to estimate future chloride profiles. Once the new customized values are saved, the original values are deleted.

The user may choose to change the multiplication factors as many times as needed to provide a good fit to the measured values.

Evaluation of chloride content profiles in new and existing decks:

To evaluate a chloride content profile at a future time, the engineer need to know the chloride concentration applied at the bridge deck surface, the diffusion coefficient, and the time of interest.

To evaluate the chloride content at the level of the reinforcement, the engineer also needs to know the cover depth of the reinforcement. To assess the corrosion of the steel, the threshold value of chloride concentration for corrosion initiation must be known or assumed.

If the engineer is interested in evaluating the chloride content profile in an existing deck, the diffusion coefficient and the applied chloride concentration should be evaluated in part one before advancing to part two of the computer program. Also the initial chloride content must be evaluated in part one.

The values obtained from part one can then be applied in this section by selecting those corresponding values while assigning the new parameters needed to calculate future chloride content profiles.

To evaluate chloride content profiles in new deck designs, the above mentioned values must be known or assumed. If the values are unknown, the chloride content profiles can be evaluated using default values for different types of concrete. The engineer can then evaluate the time to corrosion with different cover depths to the reinforcing steel.

To proceed with the evaluation, the user of CHLORCAL90 must assign values for diffusion coefficient, chloride content application, minimum (initial) chloride content in the concrete, time to evaluation, and depth to reinforcement.

Assigning values:

While entering the section for evaluation of new chloride content profiles, menu 2.1 is displayed. The user will then select the action number for the specific parameter to be assigned or altered.

After assigning the values, the user can view the entered values, and can correct or alter any number before performing the analyses.

After completion of an analysis, new numbers can be entered for new designs and further analyses.

MENU 2.1: EVALUATION OF CHLORIDE CONTENT PROFILES

****

Assign Diffusion Coefficient.

Assign Time of Evaluation.

Assign Yearly Chloride Applications on Deck.

Assign Minimum Chloride Concentration in Deck.

Assign Depth to Evaluation Point.

Assign Threshold Value for Corrosion Initiation.

Assign sealer capacity.

View Current Assigned Values.

Perform Analysis and View results.

****

Assigning diffusion coefficient:

After entering the action code, an interactive menu will be displayed on the screen. Several options are available when selecting the diffusion coefficient.

The user has the opportunity to select the value obtained from the previous evaluation of an existing deck, or can select default values based upon concrete mix type.

The user also has the opportunity to assign a new value or to return to the previous menu.

When selecting default values, CHLORCAL90 will return to the previous menu. When selecting a new value to be assigned, the user will be prompted for the value to be input.

Assigning time to evaluation:

The time to evaluation is the time period between construction of the bridge deck and the time to be evaluated. When using the diffusion coefficient obtained from an existing deck, the time period is still the time between construction and chloride measurements, and not between chloride tests and a future evaluation time.

When selecting this action, the user enters an interactive menu, and may move with the arrow keys to select the appropriate input location.

The user may enter 3 times to be evaluated. Press <ENTER> at the time selection, and the cursor will move to a blank space for the user to input the time in years.

The user can change these enter time values.

Assign chloride application at the surface:

After entering the action code, the screen displays an interactive menu, where the user has several choices. Use the arrow keys to move between input locations and press <ENTER> to select.

The user may choose to select the value established in the previous analysis, input a new value, or input a profile of yearly applications.

To be consistent with the chloride content values from the core tests, the chloride values must be input in pcy.

When entering a profile of yearly applications, the screen displays a new interactive menu.

CHLORCAL90 interprets the inputs as an array of chloride applications. The user therefore has the option to change any chloride application in any year. This is done by selecting the profile option.

The user may specify up to 60 years of yearly chloride applications.

Assigning minimum chloride content:

The minimum chloride content value corresponds to the initial chloride content in the concrete mix due to admixtures or aggregates.

The minimum value may be transferred from the calculations of an existing deck in part one or a default value of zero can be entered. The user may also input a known minimum value.

Assign depth to evaluation point:

The depth to the evaluation point is usually the cover depth to the top layer of the reinforcing steel. However, any value the can be entered.

As the user enters the action code, CHLORCAL90 prompts for a the depth in inches.

Assign threshold value for corrosion initiation:

Having entered the action code, CHLORCAL90 will display an interactive menu, and the user may select to use the default value of 1.4 pcy or enter a new value.

Assigning sealers:

The user has the opportunity to enter sealer capacities to reduce the effective amount of chloride entering the concrete.

Displayed on the screen is an interactive menu which the user may use to assign a constant value to be applied every year. The user may also choose to assign a sealer profile that has a certain life cycle.

For this case, the user must specify the sealer life, the number of sealer applications, and the sealer efficiency during the sealer life.

The user has a third option, to enter a new profile or to change the previously established sealer data.

The user must specify the reduction capacity as a fraction. To reduce the applied chloride with 40 %, the user must enter the value 0.4 when prompted for the sealer reduction capacity.

A sealer may have a profile as follows:

Year	Reduction capacity
1	0.8
2	0.6
3	0.4
4	0.2
5	0.0

If the sealer was applied every 4 years, for 10 times, the total number of years with a sealer would be 40. CHLORCAL90 will assign the correct sequence of values for the 40 year time period.

On the menu screen choose to select a sealer, then enter sealer life and number of applications. The screen will then display an interactive menu for the sealer values to be input. Assign values for the actual sealer profile from year 1.

After assigning the values, a new screen will show the complete sealer profile, and the user may choose to change any values if needed.

View assigned values:

After assigning all parameters, the user has the option of viewing the assigned values before performing the analyses.

After viewing the assigned values, the user may correct or alter any value before performing the analysis.

Performing analysis:

When entering this action, CHLORCAL90 uses the assigned values to calculate the chloride content at the depth requested. In addition to this, a chloride content profile is calculated in one-half inch increments to a depth of 6 inches.

The chloride content at the requested depth will be compared to the threshold value for corrosion initiation and a time to corrosion initiation will be calculated.

Having performed the analysis, CHLORCAL90 presents the results automatically.

The results are displayed on separate pages on the screen. First a summary of assigned values and then the calculated values at the requested depth are displayed.

After the tabular chloride content profiles are presented, a graphical presentation of the chloride profiles will be presented.

METHOD OF ANALYSIS.

Establishing diffusion coefficient from a chloride concentration profile and a constant chloride source:

An equivalent expression to equation (2) is given by ref./7/, and used by West and Hime, ref/3/, in their prediction of future chloride concentration profiles .

$$U = \frac{C_{max}-C_x}{C_{max}-C_{min}} = erf\left[\frac{x}{\sqrt{4D_e t}}\right]$$

C_{max} = *Maximum concentration at surface*

C_{min} = *Minimum concentration within concrete* **(4)**

C_x = *Concentration at distance x*

t = *time*

D_e = *Effective diffusion coefficient*

$$p = \frac{x}{\sqrt{4D_e t}}$$

$$erf(p) = 1-\frac{1}{(1+a_1p+a_2p^2+a_3p^3+a_4p^4)^4}$$ **(5)**

$a_1 = 0.278393$

$a_2 = 0.230389$

$a_3 = 0.000972$

$a_4 = 0.078108$

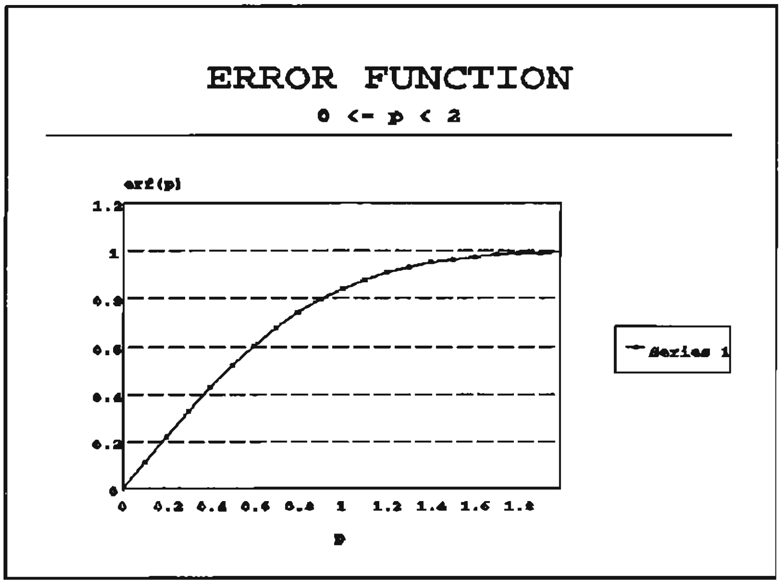


Figure 10

Sequence of calculations:

1. Calculate U between surface and first measurement.
2. Find p in erf(p) by numerical solution, using equation (5), or through figure (2), ref /8/.
3. Solve for De.
4. Repeat calculations 1-3 for top half of chloride measurements.
5. Calculate average De.

Establishing diffusion coefficient from a chloride concentration profile and repeated chloride deposit:

Two unknown parameters in equation (3), effective diffusion and yearly repeated deposit, makes the analysis somewhat more involved than for a constant chloride source.

Sequence of calculations:

1. Find an initial prediction of D_e based upon a constant chloride source.

2. Solve for yearly applied source, M, such that predicted chloride concentration equals chloride measurement at upper measurement. First assumption may be M = Cmax. If predicted chloride concentration is larger than measured, reduce value of M. Predict new chloride concentration value and compare to measured value, proceed until predicted equals measured.

3. Keeping M constant, use initial assumption of D_e to find chloride concentration at the lowest measurement location. Compare predicted chloride concentration to measured. If predicted value is less than measured, increase diffusion rate. Predict new chloride concentration value and compare to measured value, proceed until predicted equals measured.

4. Repeat steps 2 and 3 until the predicted and measured values are equal for both upper and lower location, such that the same diffusion parameters are used for both predictions.

5. Repeat steps 2,3 and 4 for all measurements, performing the calculations between the lowest chloride measurement and all above measurements. The upper measurement shall be moved one measurement down for each cycle.

6. Find the best fitting curve based upon the sum of least squares. Find the deviations between the predicted chloride concentration and the actual chloride concentration at each level, square the deviation and add all squared deviations. Perform this check for all combinations of M and D_e. Select the smallest sum as the best fit curve.

7. Allow for customizing of chloride concentration profile using multiplication factors for M and D_e. Have the program plot the measured chloride concentration profile, the original predicted profile, and the customized profile. The user may then check if customized profile fits the measured values better for a certain profile length.

8. Have the program save the customized parameters if found to be superior to the original prediction.

Establish future predictions of chloride concentration profiles using constant chloride source at surface:

Future profiles may be established using equations (4) and (5), all parameters are now known, and the solution is straight forward.

The solution of time to corrosion at specific depth may be solved using the same numerical procedure used to solve for D_e.

Establish future predictions of chloride concentration profiles using yearly repeated chloride deposits:

The method of superposition must be utilized to solve for more than one chloride deposit.

1. For time = t years, find chloride concentration profile due to first deposit using t years in equation (3).

2. For next deposit, find the chloride concentration profile using t-1 years.

3. Repeat 1-2 for all yearly deposits, and add the chloride concentrations at all 0.5 inch intervals to produce the combined chloride concentration profile.

4. The time to corrosion initiation can be found by finding the year where the chloride concentration at the steel reinforcement depth is greater than the threshold value. This gives the time to corrosion by a margin of 1 year. Print out the chloride content at that specific year to find if the concentration is close to the threshold value.

5. Sealers may be applied for each year by using a multiplication factor for the effective chloride deposit in accordance with the actual sealing capacity.

EXAMPLES

Five bridge decks have been selected for evaluation with the computer program and the results from the analyses will be presented as examples. All core tests were taken during the fall of 1991.

Concrete	Road	Str.No	Year	Near	Project
Flyash+ Asphalt	C470	F16MD	86	Kipling st.	IXFU 470-1(36)
Flyash	SH157	D16DG	88	Boulder over BN RR	FCU 157-1(14)
Portland + Asphalt	119	D16CP	74	E. over Longmont	RS 0119(20)
Portland	I-70	F19AR	62	Near Strasburg	I-70-4(29)322
Portland	I-25	F17GT	76	Quincy over I-25	I-25-4(19)201

ROAD C-470:

Depth in inches	Chloride content	Chloride content %
0.5	0.003	0.014
1.0	0.002	0.004
1.5	0.002	0.002
2.0	0.004	0.002
2.5	0.002	0.002
3.0	0.002	0.002
3.5	0.002	0.003

As the chloride content profile shows, the values are low and consistent. The threshold value for corrosion initiation is 0.03%, and the values are well below this threshold.

The constant amount of chlorides over the depth range, shows that the diffusion of chlorides have been minimal, and that the chlorides present are from the concrete mix.

The asphalt layer on top of the concrete has been a very efficient sealer.

Note however that the top layer of the concrete has some higher chloride values in one sample, this may be due to cracking in the asphalt layer, with the resulting diffusion of chlorides expected at this location.

ROAD SH 157:

Depth in inches	Chloride content%	Chloride content%	Average Chloride content %
0.0-0.5	0.300	0.255	0.278
0.5-1.0	0.213	0.232	0.223
1.0-1.5	0.067	0.088	0.078
1.5-2.0	0.010	0.021	0.016
2.0-2.5	0.009	0.005	0.007
2.5-3.0	0.002	0.002	0.002
3.0-3.5	0.002	0.002	0.002

As the chloride values are provided at intervals between half-inch increments, these will be recalculated for half in increments. Also as the chloride content values are given in percent, these will be converted into pounds per cubic yard (pcy).

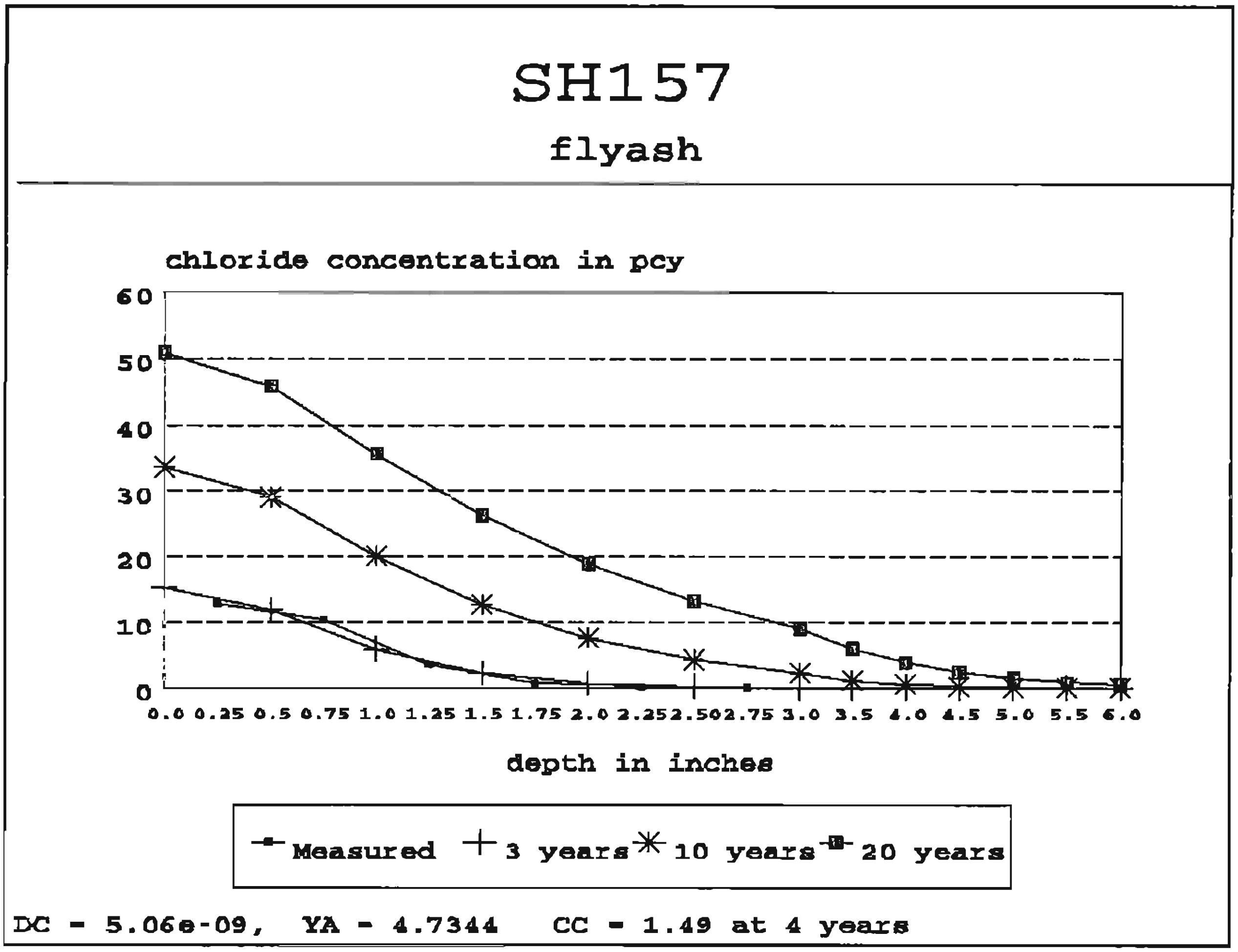
Depth in inches	Chloride content %	Chloride content pcy
0.5	0.2505	11.69
1.0	0.1505	7.023
1.5	0.0470	2.193
2.0	0.0115	0.537
2.5	0.0045	0.210
3.0	0.0020	0.093
3.5	0.0020	0.093

Evaluating the chloride content values at 1.5 inch cover depth, the chloride content is above the threshold limit of 1.4 pcy. At 2 inches, however, the chloride content is below the threshold level.

The steel may have an average cover depth of 2 inches, therefore may not be in danger of corroding. However, some steel may already have started to corrode due to the standard deviation of concrete cover of 0.5 inches.

The diffusion of chlorides will increase the chloride content at all levels and at the rebar level, will within a few years, increase above the threshold value.

The analyses completed with CHLORCAL90 provides the following results:



The following parameters have been established:

Diffusion coefficient	=	5.06e-09	in^2/sec
Yearly application	=	4.7344	pcy
Time to corrosion init.	=	4	years
Chloride content	=	1.49	pcy
28 day strength	=	5375	psi

ROAD 119:

Depth in inches	Chloride content%	Chloride content%
0.5	0.005	0.004
1.0	0.002	0.005
1.5	0.003	0.002
2.0	0.002	0.006
2.5	0.005	0.003
3.0	0.003	0.002
3.5	0.002	0.009

As can be seen from the chloride content, the values are low and consistent. The threshold value for corrosion initiation is 0.03%, and the values are well below this threshold.

The constant amount of chlorides over the depth range, shows that the diffusion of chlorides have been minimal, and that the chlorides present is from the concrete mix.

The asphalt layer on top of the concrete has been a very efficient sealer.

ROAD I-70:

Depth in inches	Chloride content%	Chloride content%	Average Chloride content %
0.0-0.5	0.140	0.062	0.101
0.5-1.0	0.156	0.246	0.201
1.0-1.5	0.105	0.220	0.163
1.5-2.0	0.049	0.109	0.079
2.0-2.5	0.011	0.022	0.017
2.5-3.0	0.002	0.004	0.003
3.0-3.5	0.002	0.002	0.002

As the values are provided at intervals between half-inch increments, these will be recalculated for half in increments. As for the chloride content values given in percent, these will be transformed into pcy.

Note that there is quite a difference in the chloride contents between the two samples. If more samples had been available, it might have been possible to exclude a sample from the averaging process. With two samples, the average value is selected to show the calculations with CHLORCAL90.

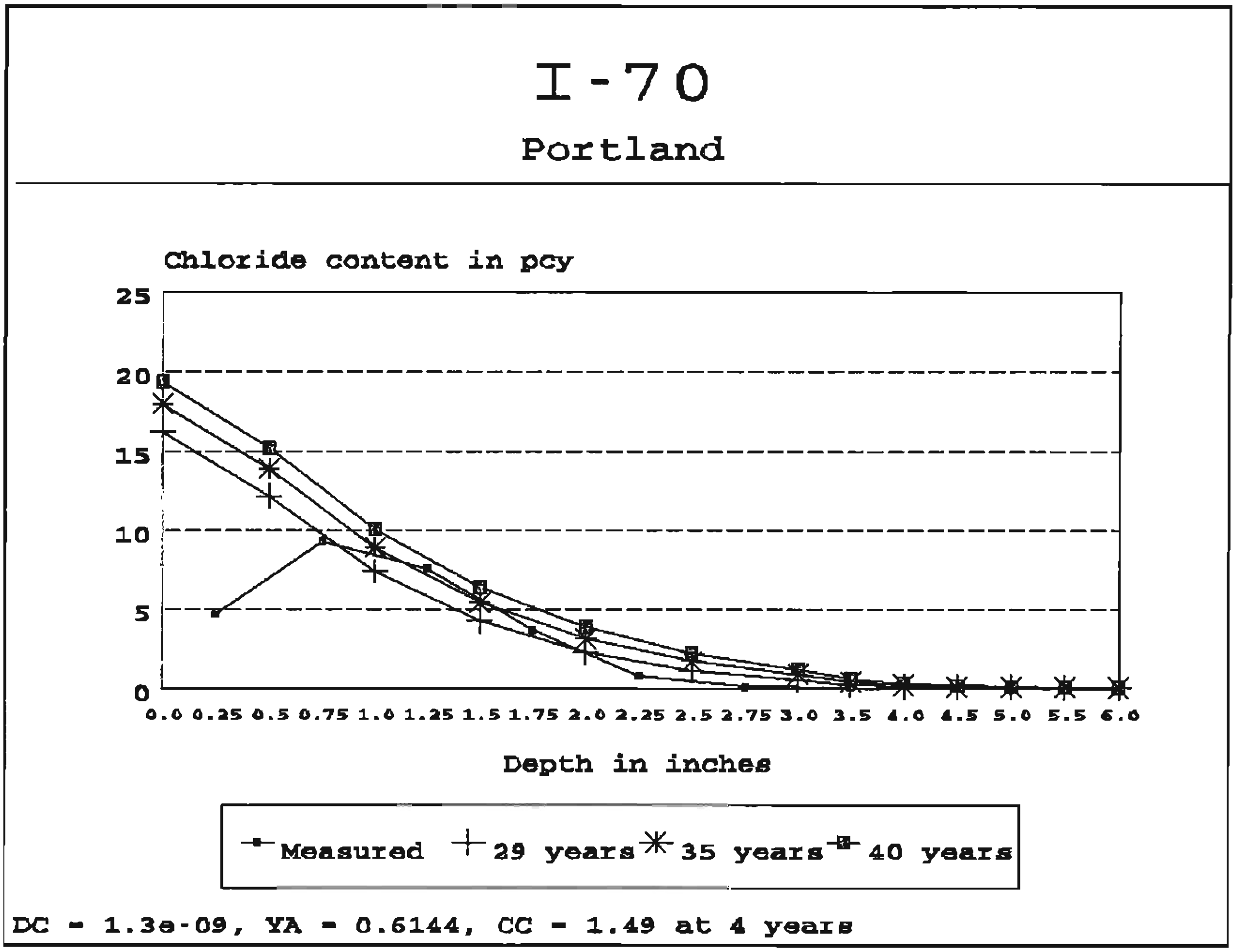
Note that for the chloride content value at 0.5 inches, the value is linearly extrapolated with respect to the values at 0.75 inches and at 1.0 inches. This is due to the fact that the chloride content at 0.0-0.5 inches is below that for 0.5-1.0 inches. The value at 0.5 inches could have easily been left out from the analyses, as the result would be negligibly different.

Depth in inches	Chloride content %	Chloride content pcy
0.5	0.220	10.26
1.0	0.182	8.493
1.5	0.121	5.647
2.0	0.048	2.240
2.5	0.010	0.467
3.0	0.0025	0.117
3.5	0.0020	0.093

Evaluating the chloride content values, it may be seen that at 2.0 inch cover depth, the chloride content is above the threshold limit of 1.4 pcy.

The steel may have an average cover depth of 2 inches, therefore may be within the danger level of corrosion initiation.

The analyses completed with CHLORCAL90 provide the following results:



The following parameters have been established:

Diffusion coefficient	=	1.30e-09	in^2/sec
Yearly application	=	0.6144	pcy
Time to corrosion init.	=	23	years
Chloride content	=	1.49	pcy
28 day strength	=	3475	psi

ROAD I-25:

Depth in inches	Chloride content%	Chloride content%	Average Chloride content %
0.0-0.5	0.339	0.382	0.361
0.5-1.0	0.196	0.163	0.180
1.0-1.5	0.077	0.080	0.079
1.5-2.0	0.031	0.042	0.037
2.0-2.5	0.009	0.023	0.016
2.5-3.0	0.010	0.012	0.011
3.0-3.5		0.002	0.002

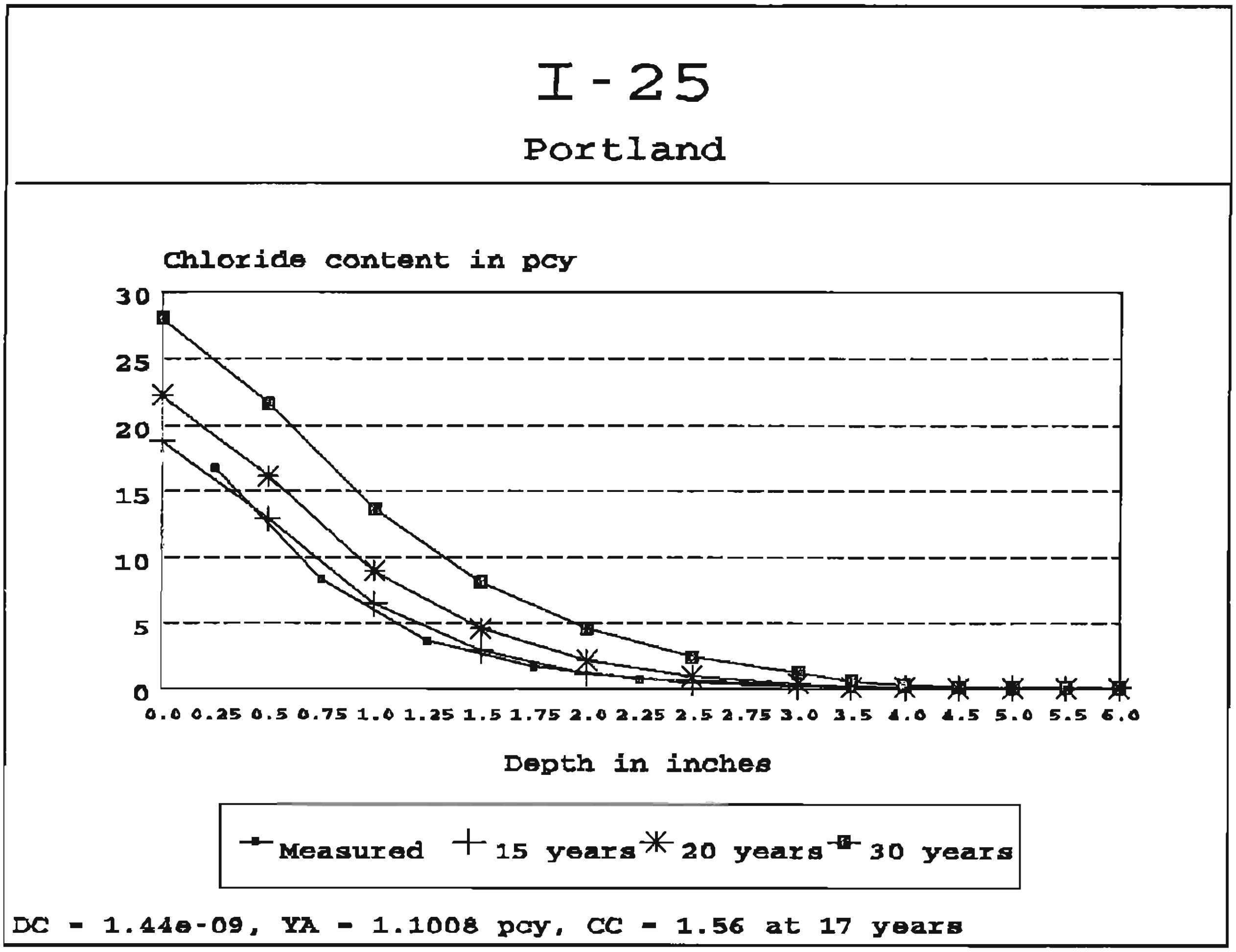
As the values are given at intervals between half-inch increments, these will be recalculated for half in increments. As for the chloride content values given in percent, these will be transformed into pcy.

Depth in inches	Chloride content %	Chloride content pcy
0.5	0.271	12.65
1.0	0.130	6.067
1.5	0.058	2.707
2.0	0.027	1.260
2.5	0.014	0.653
3.0	0.007	0.327
3.5	0.002	0.093

Evaluating the chloride content values, it may be seen that at 2.0 inch cover depth, the chloride content is very close to the threshold limit of 1.4 pcy.

The steel may have an average cover depth of 2 inches, therefore the steel is within the danger level of corrosion initiation.

The analyses completed with CHLORCAL90 give the following results:



The following parameters have been established:

Diffusion coefficient	**=**	**1.44e-09**	**in^2/sec**
Yearly application	**=**	**1.1008**	**pcy**
Time to corrosion init.	**=**	**17**	**years**
Chloride content	**=**	**1.56**	**pcy**
28 day strength	**=**	**6480**	**psi**

REFERENCES

1. R.D.Browne.
"Mechanisms of Corrosion of Steel in Relation to Design, Inspection, and Repair of Offshore and Coastal Structures."
Special Publication SP-65, ACI, Detroit, MI 1980.

2. Diffusion Equations.

3. R.E.West and W.G.Hime.
"Chloride profiles in salty concrete."
National Association of Corrosion Engineers, March 1985.

4. J.M.J.M.Bijen.
"Maintenance and repair of concrete structures."
HERON, Vol.34, No.2, Delft University of Technology, Delft, The Netherlands 1989.

5. M.Funahashi.
"Predicting Corrosion-Free Service Life of a Concrete Structure in a Chloride Environment."
ACI Materials Journal, Vol.87, No.6, 1990.

6. P.D.Cady and R.E.Weyers.
"Chloride Penetration and the Deterioration of Concrete Bridge Decks."
American Society for Testing and Materials, Vol.5, No.2, 1983.

7. F.C.Olson and O.T.Shultz.
"Temperatures in Solids During Heating or Cooling."
Industrial and Engineering Chemistry, Vol. 34, 1942.

8. "Technical Formulae"
Kurt Gieck, Heilbronn/N, Germany, 1985.

9. S.Mindess and J.F.Young.
"Concrete."
Prentice-Hall, Englewood Cliffs, New Jersey 07632, 1981.

10. P.D.Cady and R.E.Weyers.
"Deterioration Rates of Concrete Bridge Decks."
Journal of Transportation Engineering, Vol.110, No.1, 1984.