AECL--10489

CA9200333

ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

DURABILITY PREDICTIONS FROM RATE OF DIFFUSION TESTING OF NORMAL PORTLAND CEMENT, FLY ASH, AND SLAG CONCRETE

PRÉDICTION DE LA RÉSISTANCE D'APRÈS LA VITESSE DE DIFFUSION ÉTABLIE PAR DES ESSAIS SUR DU BÉTON NORMAL À CIMENT PORTLAND, ESCARBILLES ET SCORIES

K.E. PHILIPOSE, R.F. FELDMAN and J.J. BEAUDOIN

Chalk River Laboratories
Laboratoires de Chalk River

Chalk River, Ontario K0J 1J0

September 1991 septembre

AECL Research

DURABILITY PREDICTIONS FROM RATE OF DIFFUSION TESTING OF NORMAL PORTLAND CEMENT, FLY ASH, AND SLAG CONCRETE

by

K.E. Philipose
AECL Research, Chalk River Laboratories

and

R.F. Feldman and J.J. Beaudoin
Institute for Research in Construction
National Research Council, Ottawa, Canada

Waste Management Systems
Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1J0

1991 September

AECL-10489

EACL Recherche

PRÉDICTION DE LA RÉSISTANCE D'APRÈS LA VITESSE DE DIFFUSION ÉTABLIE PAR DES ESSAIS SUR DU BÉTON NORMAL À CIMENT PORTLAND, ESCARBILLES ET SCORIES

par

K.E. Philipose
EACL Recherche, Laboratoires de Chalk River

et

R.F. Feldman et J.J. Beaudoin
Institut de Recherche en Construction
Conseil National de Recherches, Ottawa, Canada

RÉSUMÉ

On projette de construire un dépôt souterrain de déchets de faible radioactivité appelé IRUS (Intrusion-Resistant Underground Structure) (Dépôt Souterrain Anti-intrusion), aux Laboratoires de Chalk River. Ce concept repose en grande partie sur la résistance du béton pendant une durée de vie utile d'au moins 500 ans. Un programme de recherche est en cours; il comporte des essais de laboratoire pour concevoir un béton résistant et prédire sa durée de vie utile technologique.

La résistance du béton est fonction de sa résistance à la détérioration par des sources internes ou externes. Comme la vitesse de dégradation est fonction, dans une grande mesure, de la vitesse d'entrée des ions agressifs dans le béton, des essais de laboratoire sont en cours pour établir la vitesse de diffusion des chlorures et ions de sulfate. On expose 1 000 échantillons de béton et 500 échantillons de pâte au total, à vingt-cinq combinaisons différentes d'agents corrosifs dont le CO_2, à des températures de 22 et 45°C. On met au point une technique de mesure du profil de pénétration des ions et de détermination des facteurs régissant la diffusion des ions dans les divers bétons. Dans cette communication, on donne les premiers résultats du programme de recherche ainsi que les longévités prédites permettant de qualifier les bétons pour la construction du dépôt de déchets IRUS après 16 mois d'essais de diffusion sur des échantillons de laboratoire.

Systèmes de gestion des déchets
Laboratoires de Chalk River
Chalk River, Ontario, Canada KOJ 1J0

1991 septembre

AECL-10489

AECL Research

DURABILITY PREDICTIONS FROM RATE OF DIFFUSION TESTING OF NORMAL PORTLAND CEMENT, FLY ASH, AND SLAG CONCRETE

by

K.E. Philipose
AECL Research, Chalk River Laboratories

and

R.F. Feldman and J.J. Beaudoin
Institute for Research in Construction
National Research Council, Ottawa, Canada

ABSTRACT

A waste repository for the belowground disposal of low-level radioactive waste, labelled IRUS (Intrusion Resistant Underground Structure), is planned at the Chalk River Laboratories. It relies greatly on the durability of concrete for a minimum of 500 years of service life. A research program based on laboratory testing to design a durable concrete and predict its useful engineered service life is in progress.

The durability of concrete depends on its resistance to deterioration from both internal and external causes. Since the rate of degradation depends to a major extent on the rate of ingress of aggressive ions into concrete, laboratory testing is in progress to establish the diffusion rates of chlorides and sulphate ions. A total of 1000 concrete specimens and 500 paste specimens are being exposed at 22° and 45°C to twenty-five different combinations of corrosive agents, including CO_2. Procedures to measure the ionic penetration profile and to determine the factors controlling diffusion of ions in the various concretes have been developed. The paper presents the initial results from the research program and the longevity predictions to qualify concretes for the IRUS waste repository, based on 16 months of diffusion testing on laboratory specimens.

Waste Management Systems
Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1J0

1991 September

AECL-10489

CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Concrete durability depends on the quality of the concrete ingredients [1,2], their formulation, placement, and the service environment inside and outside of the repository; it is site dependent. AECL Research has identified various potential aggressive elements for a repository concrete for the disposal of low-level radioactive waste at Chalk River Laboratories, labelled as IRUS (Intrusion Resistant Underground Structure) [3]. Environmental factors considered include sulphate and chloride ion concentrations in groundwater, carbonation effects, leaching of concrete, freeze-thaw deterioration, influence of microcracking due to design loads on the structure and alkali-aggregate reaction.

A cross-section of the IRUS disposal facility after closure is given in Figure 1. The facility will be located in a free-draining sand dune, with the foundation of the repository placed one metre above the groundwater table. The walls of the repository will be made of 0.6-metre-thick reinforced concrete, and the roof will have a minimum thickness of one metre. The soil cover will place the repository concrete below the frost level. Since the vault and roof are major components of the engineered barriers against radionuclide migration, the durability of concrete is an important aspect of the disposal concept's integrity.

2. PROGRAM OBJECTIVES

The focus of this joint research program by AECL and the National Research Council is not on the development of a single highly durable concrete, but on a methodology that would assess the durability aspects of a wide variety of concrete types and qualities subjected to different exposure conditions. This program has the following main objectives:

1. Design a concrete formulation for an engineered service life of a minimum of 500 years, taking the IRUS repository site environment into consideration. The intended duration of this research is 30 months.

2. Continue studies on the durability aspects of concrete specimens under different exposure conditions and create a data base. Predict the longevity of concrete systems subjected to IRUS and other environmental conditions. This study is of a generic nature and is expected to last 6 to 10 years.

3. PREDICTION METHODOLOGY

To qualify a concrete for IRUS and predict its longevity, deleterious effects of all relevant degradation mechanisms are to be considered.

Figure 2 shows a concrete failure tree. Alkali-aggregate corrosion can be avoided by selecting inert aggregates. Deterioration due to freezing and thawing will not be significant for the IRUS structure, because it is buried below the freezing zone during its long service life. For the same reason, deterioration due to temperature changes and humidity changes can be considered insignificant. Micro-cracking of concrete due to design stresses can be important. In a study being jointly conducted by AECL and the National Research Council on "the effect of micro-cracking on reinforcement corrosion", it has been found that the microcracking due to design loads has a direct influence on the ionic ingress. The rate of ingress increased substantially with increased micro-cracking in the specimen. This effect is not considered in this report, because sufficient data is not yet available from the ongoing tests; however, it will be factored into the final concrete longevity predictions.

At present, the deleterious effects of all major degradation agents on IRUS concrete such as carbonation, leaching of calcium hydroxide and the chemical attack due to sulphates and chlorides are undergoing laboratory testing by exposing specimens to the simulated aggressive environment. It has been concluded that the diffusion of chloride ions into the concrete will be used as the rate-determining factor for the longevity predictions for the IRUS reinforced concrete, because the rate of penetration of chloride ions has been shown to be higher than other degradation processes, such as sulphate attack, carbonation, leaching, etc. Hence the initial longevity predictions are attempted, based entirely on the reinforcement corrosion (identified as the most aggressive failure mechanism) due to the diffusion of chloride ions into the concrete specimens. The IRUS repository is being designed with a 75 mm concrete cover over the reinforcing bars. When the chloride ions diffuse through a distance of 75 mm, they will come into contact with the bars and start the process of accelerated reinforcing steel corrosion. Once the steel corrosion has initiated, it will be only a short time before failure of the reinforced concrete vault may occur, since in a reinforced concrete structure failure of reinforcement would cause failure of the structure. For IRUS, a 75 mm depth of ionic ingress into concrete was selected as a conservative failure criteria for the preliminary longevity predictions.

Ionic ingress, in combination with other deleterious effects, can be considered for qualifying concrete for an engineered service life. Ionic ingress is a slow process, especially in the case of quality concrete systems. From the test results, it is clear that in quality concrete it will take many hundreds of years for the ions to reach the failure depth of 75 mm. Rate parameters are being established from short-term experimental data. Longevity of concrete systems can be predicted from equations developed either by statistical treatment of the data or by mathematical modelling. Confidence levels in these predictions will improve with the availability of longer-term data [3].

4. RESEARCH PROGRAM ON CONCRETE DURABILITY

The material testing is being done in five stages. In stage 1, five cement systems with 4 water-to-cement ratios presenting 4 levels of resistance to ionic diffusion were manufactured. These 20 concrete systems were exposed to 25 baths with different temperatures, ionic combinations and concentrations. Mix designs for test samples incorporated Normal Portland Cement, sulphate-resisting cement, fly ash, silica fume, slag and other additives. In stage 2, the specimens were characterized by determining the freeze-thaw resistance, porosity, and compressive strength. In stage 3, the specimens were exposed to aggressive ions and ion combinations in 25 baths containing salt solutions of various concentrations. Specimens were taken by cutting 12-mm slices from concrete prisms after various periods of exposure and the reaction front was established using microprobe analysis techniques. Details of sample preparation are described elsewhere [4]. A Cambridge Stereoscan S-250 Microscope was used for the examination, and a Tracor Northern TN 5500 Energy Dispersive X-Ray Analyser was used for the quantitative analysis. The system was calibrated using prepared paste specimens with known Cl^- concentrations. Calibrations were confirmed with an obsidian standard 0.36% Cl. EDAX analysis on several pieces gave 0.38% Cl, a difference of 5.5%. At each position along the profile, ion concentrations were expressed as mass percent of the paste. Values of 0.3% Cl and 3.0% of $SO_4^=$ were selected arbitrarily to establish the position of measured profiles of Cl and $SO_4^=$, so that its movement with time may be monitored. In stages 4 and 5, correlation of the data and longevity predictions are being attempted. The research program is in stage 4 at present, and results based on 16 months of testing are now available.

5. EXPERIMENTAL SET-UP

Binders

Normal Portland Cement (Type 10), sulphate-resisting cement (Type 50), silica fume and blast-furnace slag were used for the study. The oxide analyses of the binders are given in Table 1.

Aggregates

Unblended sand, consisting mainly of quartz and feldspar, was used. The potential alkali-reactivity of the sand was determined by accelerated mortar-bar tests, which monitored length change during two weeks' storage in 1 M NaOH solution at 80°C. The expansion of the specimens was well below the CSA A-5 (Cement) May, 1989 code-proposed limit of 0.1%, indicating innocuous aggregates.

Limestone coarse aggregate was also subjected to accelerated mortar-bar testing and the standard concrete prism test. The expansion of concrete prisms after 8 weeks was under 0.02%, compared to the code limit of 0.04%, and no further expansion was observed up to the present time (565 days) [4]. These results indicate that the aggregate is non-expansive and that the selected limestone aggregate for IRUS from Arnprior, Ontario, would be unlikely to show expansion in concrete even in the long-service-life term. The specimens were also subjected to a magnesium sulphate soundness test (loss in weight of 9.2% was well below the CSA A-23.1.5.3.4 limit of 16%), freeze-thaw cycling and petrographic evaluation, and the results were found to be satisfactory.

Concrete and Paste Systems

Table 2 shows the nomenclature and composition of the cement and paste systems. Two types of cement, the Normal Portland Cement (Type 10) and the sulphate-resisting cement (Type 50), were used for the study. System 4 contains fly ash and silica fume, replacing cement content by 30% and 5%, respectively. System 5 contains slag and silica fume, replacing the cement content by 75% and 3%, respectively, by weight. The concrete and paste systems were designed with a water-to-cement ratio varying from 0.35 to 0.6 by weight.

Concrete Specimens

For each concrete mix, two concrete prisms, 75x75x280 mm, were cast for the study. All sides of the specimen were sealed with wax, leaving one long side (280 mm) unwaxed, to allow unidirectional ingress of chloride and sulphate ions. Figure 3 shows a test specimen and the analysis sampling technique.

6. PHYSICAL TESTING

Compressive strengths of some of the test samples are shown in Table 3. The average compressive strengths were achieved by loading three paste cubes and concrete cylinders to destruction. Figure 4 shows the strength development of the cement paste systems. The results indicate the direct impact of water-to-cement ratio on the strength development. The strength increased in all test cases as the water-to-cement ratio decreased. The total porosity was evaluated using propan-1-ol as the displacement fluid, and microhardness measurements on paste systems 1 to 5. The porosity varies as low as 10% for system 5, to as high as 50% for system 1, increasing with the water-to-cement ratio within each system.

7. IONIC INGRESS AS A MEASURE OF DURABILITY

To evaluate the resistance of concrete systems to chemical attack, the rate of ingress of ions into concrete specimens must be established. For this evaluation, the depth of ion penetration was obtained from the ionic penetration profile data plotted versus the square root of time of exposure. This conforms to the requirement of a diffusion-based mechanistic model [5]. Figure 5 shows an example of ionic profiles. Concentrations of Cl along the sample from the exposure face are plotted for 3, 6, 9, and 12 months of exposure. Bath 13 contains 4.95 g/L of NaCl at 22°C, which represents a "worst-case scenario" for the IRUS repository. Bath 15 contains 49.5 g/L of NaCl at 22°C, which is 10 times more severe than the "worst-case scenario" expected during the service life-time for IRUS, and serves as an accelerated test condition. Bath 25 contains 88.75 g/L $Na_2SO_4^=$ and 49.47 g/L NaCl at 45°C, which represents a double ion bath at higher temperature and hence serves as a further accelerated test condition. Table 4 shows the laboratory data for three concrete systems containing Normal Portland Cement, fly ash and silica fume and slag concrete subjected to Bath 15. Lines 1 to 6 show data for five experimental points up to 16 months of testing. Line 7 is the value of ionic ingress corresponding to 500 years of exposure, obtained by linear regression analysis performed on each set of data. Line 8 indicates the correlation coefficients for each analysis. The correlation coefficient of 0.8 or above provides better confidence in the analysis of results. Table 5 shows the same array of data for the concrete systems subject to Cl^- ions in Bath 13. Sulphate results are not presented in detail because they are similar in nature to chloride results, but the rate of ingress is considerably lower.

Linear regression lines extrapolated to 500 years for systems 1, 4 and 5 subjected to Bath 13 (IRUS bath) are shown in Figure 6, and the same systems subjected to Bath 15 are shown in Figure 7. Tables 6 and 7 show the predicted longevity of the concrete systems based on 16 months of testing subjected to ionic concentrations in Baths 15 and 13.

8. DISCUSSION

Ionic profiles and depth-of-penetration measurements in concrete show that reasonably accurate results can be obtained and predictions of ingress made. But the difficulty in locating the reaction front of chloride ions in fly ash and slag concretes has resulted in some scatter in the experimental results. This is because the profiles are difficult to determine in dense concrete, as the rate of movement of the front is slow and the path of ionic ingress through the aggregates can be tortuous, leading to inconsistent results. However, the program is still in its initial stages and further collection of data during the next 4 to 5 years of research is expected to improve the consistency.

Fly ash and slag systems indicate superior resistance to ionic ingress, and a decrease in water-to-cement ratio enhances the resistance even further. This is consistent for both baths.

The slag system seems to have the highest resistance to ionic ingress. For System 5 with slag concrete (mixes 1, 2 and 4), penetration depths based on extrapolation to 500 years are less than 75 mm (the assumed failure depth). This may be partly due to the lower median pore diameter and porosity values, and perhaps due to the lower calcium hydroxide content of slag concretes. The calcium hydroxide contents for S5M1 and S1M1 are 0.0 and 8.5%, respectively, and it is possible that with higher calcium hydroxide content, chloride diffusion is increased due to enhanced calcium hydroxide solubility or calcium hydroxide-chloride formation.

The chlorides detected in the specimens during the measurements are both chemically and physically combined. Thus both chloro-aluminates and chlorides with different levels of attachments with C-S-H are present [6,7,8]. As a result, the concentration of chlorides measured is not related to the driving force of diffusion process, although it is clear from the correlation with square root of time that the process is diffusion controlled [4,9,10].

Even though the ionic concentration in Bath 15 is 10 times higher than in Bath 13, the corresponding measured increase in the depth of penetration of ions was only 1.5 to 3 times, indicating that, as expected, the rate of diffusion is not directly proportional to the ionic concentration.

The determination of chloride profiles (Figure 5) yields relatively high chloride content values for all systems measured. This is also true for slag systems, which differs in this regard from the results of other authors [11]. But the decrease in chloride content with depth of ingress is more rapid with slag systems than others, and this is consistent for all water-cement ratios. The profiles for sulphate ion ingress show features similar to that of chloride ion. Near the exposed surface of the specimen, the sulphate ion concentration is especially high for the slag cement S5M1, in the order of 7%, as compared to 4.5% for S1M1. The rate of ingress of sulphate ion in Bath 25 is again much higher for System 1 than for Systems 4 and 5; however, it is much lower than the rate of ingress of chloride ion [8]. The projected ingress of sulphate ion exposed to Bath 25 in System 5, Mix 2, is 22 mm after 500 years, based on 1 year of testing.

Longevity predictions in years for the concrete systems 1, 4, and 5 for the IRUS environment are shown in Table 7. The expected service life of the Normal Portland Cement system is 9 to 27 years, compared to 395 to 1974 years for the slag system, with a 90 percent confidence limit. These predictions clearly show the superior resistance of the slag system to ionic ingress in comparison with the other systems. Further, these initial results are indications that System 5 Mix 1, 2 and 4 would exceed the service life requirement of 500 years, whereas Systems 1 and 4 may not qualify.

It is clear that having data for only 16 months (5 data points) decreases the level of confidence of the computations. The confidence level will increase as longer-term data become available to validate the extrapolation being used to generate longevity predictions.

9. CONCLUSIONS

1. The rate of ingress of chloride ions into the three systems appears to be diffusion controlled.
2. The rates of ingress of chloride ions are decreased by the addition of fly ash, silica fume and blast-furnace slag to Type 50 cement.
3. The rate of ingress of chloride ions generally increases with the increasing water-to-cement ratio for the three systems.
4. The rate of ingress of sulphate ions is considerably lower than chloride ions for all systems.
5. Linear regression analysis of the limited data obtained by chloride exposure to concentrations 10-times higher than the maximum concentrations expected in the IRUS environment indicates penetration of chloride ion as low as 125 mm in 500 years.
6. Linear regression analysis of the limited data obtained by exposure of specimens to IRUS bath conditions indicates the time required for a 75 mm penetration (failure depth) can be over 1000 years (longevity assessment).

REFERENCES

1. A. Atkinson, D. Goult, and J.A. Hearne. "Assessment of the Long-Term Durability of Concrete in Radioactive Waste Repositories". Materials Research Society Symposia Proc., Vol. 50, pp. 229-236, 1986.

2. J.R. Clifton, and L.I. Knab. "Service Life of Concrete". U.S. Department of Commerce Report NISTIR 89-4086, p. 119, 1962 June.

3. K.E. Philipose. "500 Year Concrete for a Radioactive Waste Repository". AECL Report, AECL-9721, 1988 March.

4. R.F. Feldman, J.J. Beaudoin, and K.E. Philipose. "Durable Concrete for a Waste Repository - Ionic Ingress". Proceedings of the Scientific Basis for a Nuclear Waste Management XIII Symposia U, Materials Research Society Fall Meeting, Boston, 1989, Vol. 176, pp. 129-142.

5. R.F. Feldman, J.J. Beaudoin, and K.E. Philipose. "Effect of Cement Blends on Chloride and Sulphate Ion Diffusion in Concrete". Submitted for publication in Il Cemento, Rome, Italy.

6. R.D. Browne. Durability of Building Materials. Vol. 1, p. 113, 1982.

7. M. Colepardi, A. Marcialis, R. Turriziani. Il Cemento, Vol. 67, p.157, 1970.

8. C.L. Page, N.R. Short, A. El Tarras. Cem. and Con. Res., Vol. 11, p.395, 1981.

9. G.L. Kalousek, and E.J. Benton. J. Amer. Conc. Inst., Vol. 67, 187 (1970).

10. V.S. Ramachandran. Materials and Structures, Vol. 4, p.3, 1971.

11. D.M. Roy, A. Kumar, and J.P. Rhodes. "Diffusion of Chloride and Cesium Ions in Portland Cement Pastes and Mortars Containing Blast Furnace Slag and Fly Ash. Proc. 2nd Int. Conf. on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid 1986, A.C.I. SP 91-70, 1423-1444.

Table 1 - Oxide Analysis of Cements, Silica Fume and Slag

	Normal Portland Cement Type		Silica Fume	Slag
	10	50		
SiO_2	19.43	20.71	35.30	95.17
Al_2O_3	4.18	3.77	10.62	0.21
Fe_2O_3	3.20	4.36	0.58	0.13
CaO	61.21	62.46	36.94	0.23
MgO	4.09	3.35	13.32	0.15
Na_2O	0.45	0.35	-	0.10
K_2O	0.89	0.87	-	0.27
C				1.56
L-O-I	1.53	0.88	1.16	2.30
SO_3	3.93	2.46	1.41	2.30
Free Lime	1.15	0.70	-	-

Table 2 - Nomenclature and Composition of Cement Systems

		CEMENT		SLAG	FLY ASH	SILICA FUME	CURING TIME
S1	System 1	Type 10	100%	0	0	0	14 days
S4	System 4	Type 50	65%	0	30%	5%	56 days
S5	System 5	Type 50	22%	75%	0	3%	28 days

M1	Mix 1	0.35 w/c
M2	Mix 2	0.42 w/c
M3	Mix 3	0.50 w/c
M4	Mix 4	0.60 w/c

Table 3 - Compressive Strength of Paste and Concrete

Compressive Strength of Cement Paste					Compressive Strength at End of Curing Period		
Days	Mpa S=Systems M=Mix					Paste Mpa	Concrete Mpa
NPC Concrete (S1)							
	M1	M2	M3	M4	M1	49.0	41.6
1.0	37.7	25.5	17.1	11.5	M2	34.9	31.1
3.0	43.4	31.56	23.4	16.8	M4	26.7	26.1
7.0	49.0	34.9	26.7	19.0	M4	19.0	22.6
Fly Ash Concrete (S4)							
	M1	M2	M3	M4	M1	47.1	48.4
3.0	21.5	13.6	10.7	5.6	M2	35.9	39.0
14.0	38.6	27.5	21.1	14.1	M3	29.8	30.5
56.0	47.1	35.9	29.8	22.1	M4	22.1	31.3
Slag Concrete (S5)							
	M1	M2	M3	M4	M1	54.6	45.3
3.0	11.4	7.7	5.2	2.5	M2	42.2	36.1
14.0	46.1	34.6	25.3	18.6	M3	32.6	29.3
28.0	54.6	42.2	32.6	26.3	M4	26.3	20.0

Table 4 - Bath 15
Chloride Ion Ingress (mm) in Concretes as a Function of Time of Immersion

Line No.	Time Days	√Time Days	NPC (System 1) w/c Ratio				Fly Ash (System 4) w/c Ratio				Slag Concrete (System 5)			
			Mix 1	Mix 2	Mix 3	Mix 4	Mix 1	Mix 2	Mix 3	Mix 4	Mix 1	Mix 2	Mix 3	Mix 4
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	92	10	11.9	13.6	13.8	13.8	5.4	9.7	10.2	12.5	3.6	1.7	3.6	4.1
3	113	14	15.8	20.4	24.3	28.0	6.6	10.0	9.7	10.6	4.1	2.0	4.3	6.0
4	275	17	17.9	23.8	25.9	27.0	8.6	11.7	15.0	26.7	6.3	5.1	5.8	7.0
5	366	19	20.8	33.1	33.1	30.9	8.5	11.7	13.2	13.2	5.3	5.2	3.8	7.2
6	488	22	18.6	23.0	23.0	36.5	9.5	11.5	12.3	16.0	9.3	6.2	7.6	11.5
7	183000	427	395	557.3	640	710.6	186.7	227	258	340	158	125	25	200
			Linear Regression Analysis											
8	Corre. Coe.		0.96	0.92	0.98	0.98	0.98	0.91	0.89	0.72	0.95	0.94	0.91	0.97

Note: Lines 1 to 6, data for 5 experimental points up to 16 months (488 days) of testing.
Line 7, value of ionic ingress corresponding to 500 years of exposure obtained by linear regression analysis performed on each set of data.
Line 8, correlation coefficients for each analysis.

Table 5 - Bath 13 "IRUS"
Chloride Ion Ingress (mm) in Concretes as a Function of Time of Immersion

Line No.	Time Days	√Time Days	NPC (System 1) w/c Ratio				Fly Ash (System 4) w/c Ratio				Slag Concrete (System 5)			
			Mix 1 0.35	Mix 2 0.42	Mix 3 0.5	Mix 4 0.6	Mix 1 0.35	Mix 2 0.42	Mix 3 0.5	Mix 4 0.6	Mix 1 0.35	Mix 2 0.42	Mix 3 0.5	Mix 4 0.6
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	92	10	10.4	8.6	13.2	13.8	2.4	3.6	1.4	8.6	1.2	0.7	0.6	1.2
3	183	14	10.5	15.0	10.6	17.9	3.8	3.3	5.9	6.7	1.7	0.0	0.8	1.7
4	275	17	15.6	15.4	22.4	16.6	5.5	3.2	6.6	11.4	2.3	1.3	1.0	3.2
5	366	19	11.8	9.2	22.7	22.9	5.5	6.1	8.7	9.4	2.3	0.0	3.1	1.5
6	488	22	12.4	13.2	29.0	23.5	5.6	7.7	5.8	13.6	1.2	0.6	4.5	3.0
7	183000	427	251.5	249	540.4	452	120	132	156	236	35.3	4.4	77.4	54.5
			Linear Regression Analysis											
8	Corre. Coe.		0.87	0.79	0.96	0.97	0.98	0.92	0.87	0.93	0.74	0.28	0.83	0.84

Note: Lines 1 to 6, data for 5 experimental points up to 16 months (427 days) of testing.
Line 7, value of ionic ingress corresponding to 500 years of exposure obtained by linear regression analysis performed on each set of data.
Line 8, correlation coefficients for each analysis.

Table 6 - Longevity Prediction for Concrete Systems (Bath 15, 16 months of testing)

Cement System	Time in Years			
	Mix 1	Mix 2	Mix 3	Mix 4
NPC Concrete (S1)	17 (13)	9 (5)	7 (5)	6 (4)
Fly Ash + S.F. (S4)	80 (73)	53 (42)	41 (30)	23 (12)
Slag + S.F. (S5)	113 (98)	180 (161)	181 (155)	71 (62)

Table 7 - Longevity Prediction for Concrete Systems (IRUS Environment (Bath 13), 16 months of testing)

Cement System	Time in Years			
	Mix 1 v/c 0.35	Mix 2 v/c 0.42	Mix 3 v/c 0.5	Mix 4 v/c 0.6
NPC Concrete (S1)	43 (27)	43 (24)	10 (6)	13 (9)
Fly Ash + S.F. (S4)	197 (179)	151 (132)	116 (84)	50 (36)
Slag + S.F. (S5)	2282 (1974)	1526 (1286)	471 (395)	950 (831)

<u>NOTE:</u> Figures in brackets show longevity prediction with 90% confidence limit.

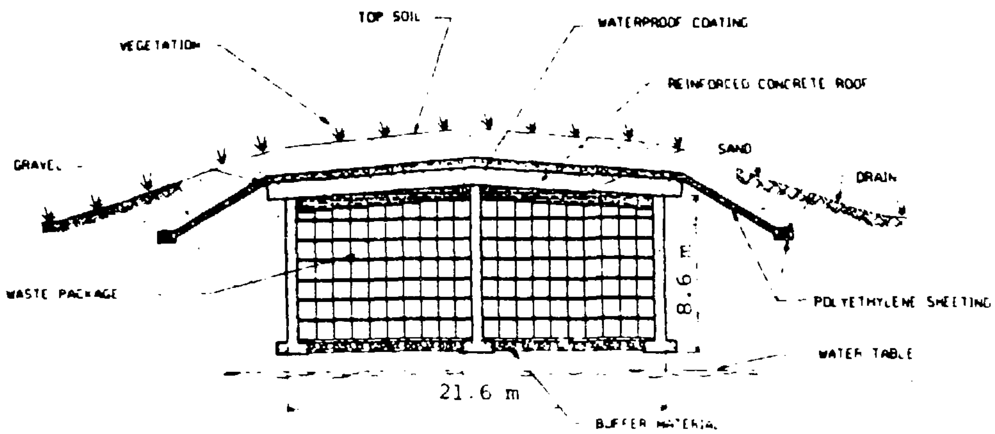


FIGURE 1: IRUS Disposal Facility (Cross-section)

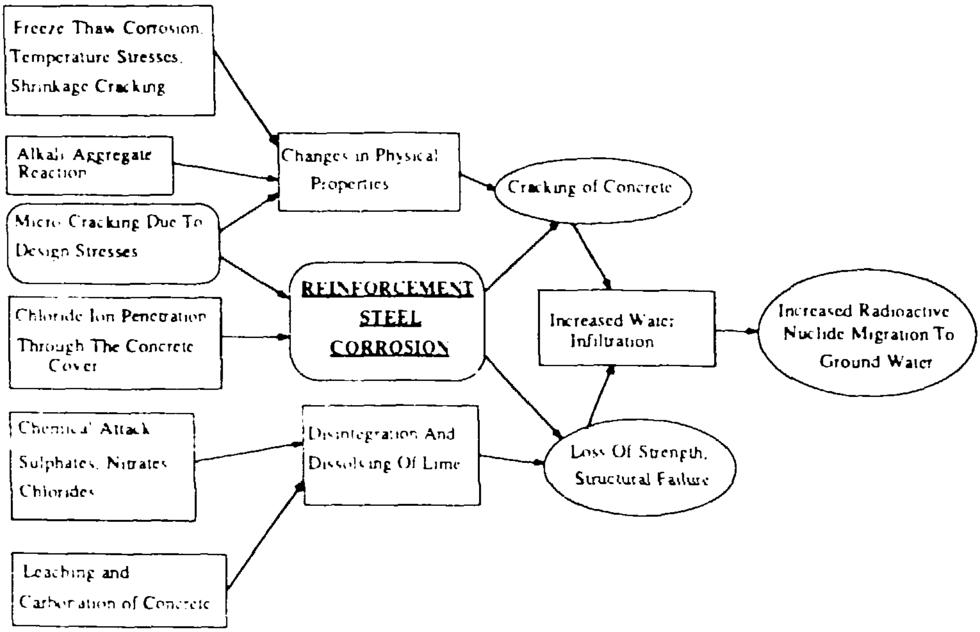


FIGURE 2 Concrete Failure Tree

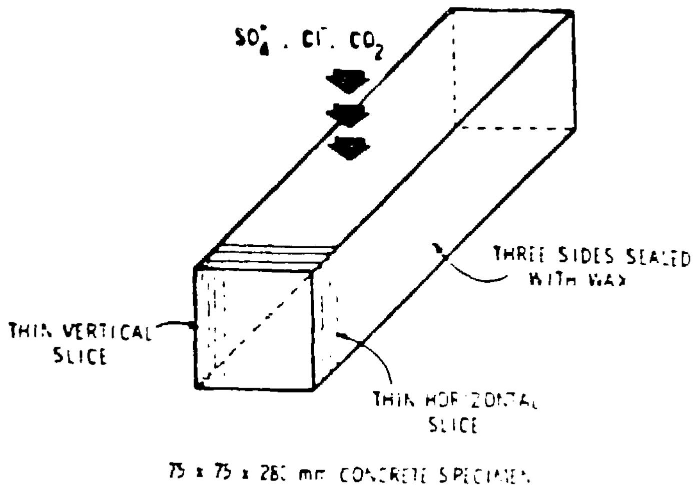


FIGURE 3: Concrete Test Specimen

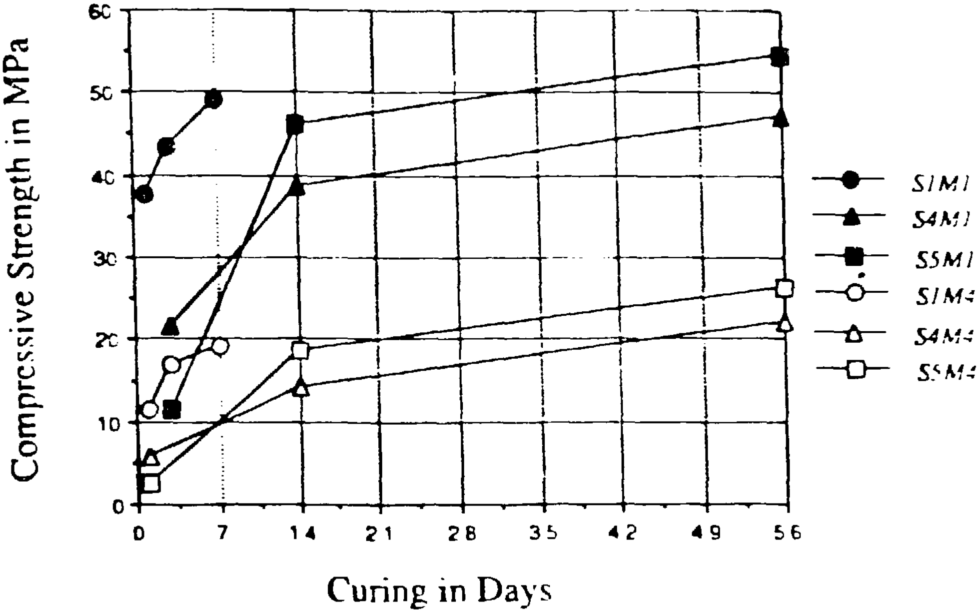


Figure 4: Strength Development of Paste Systems

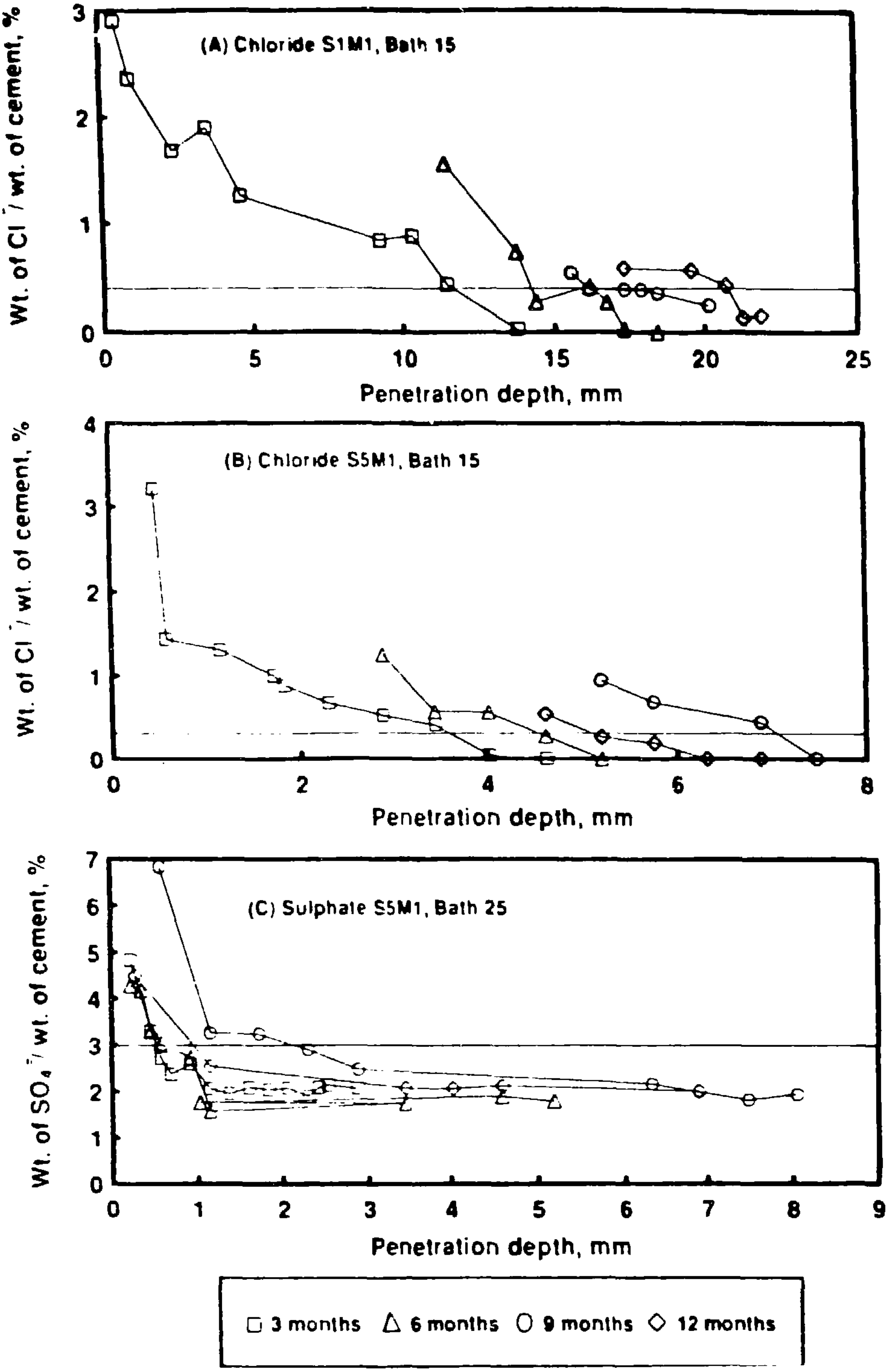


FIGURE 5: Ionic Profiles

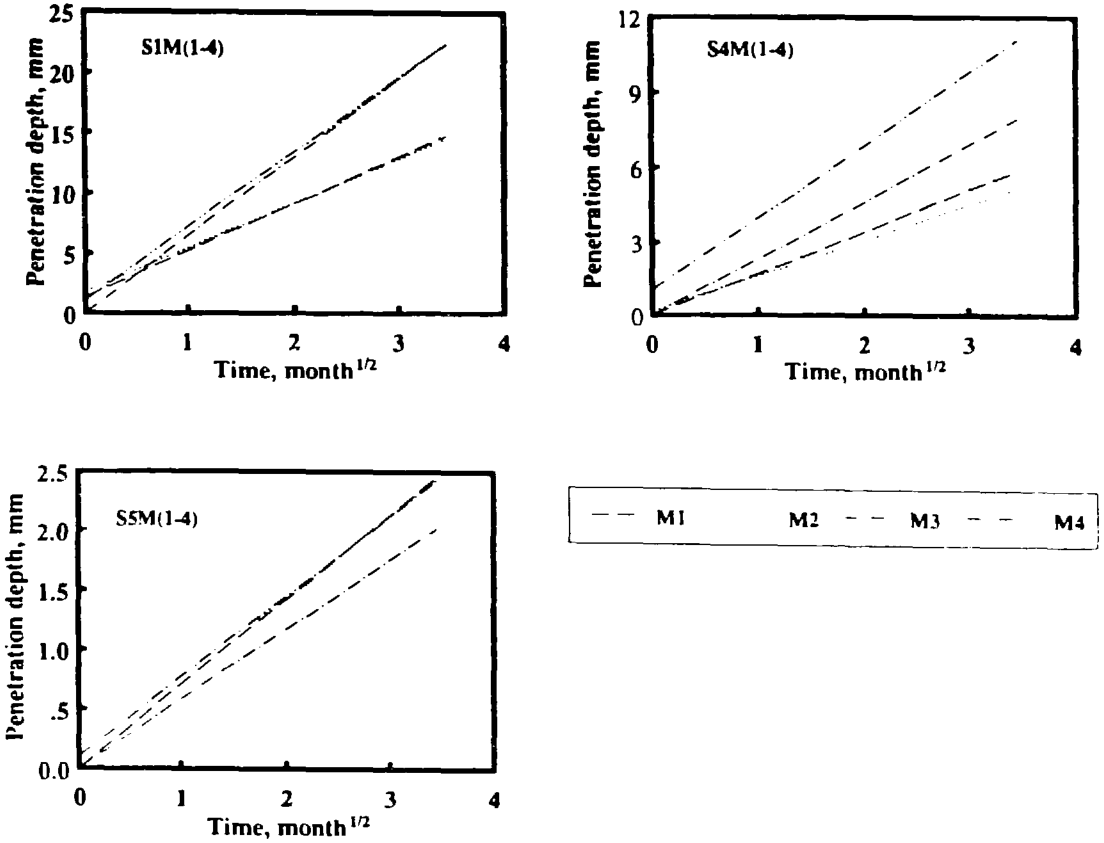
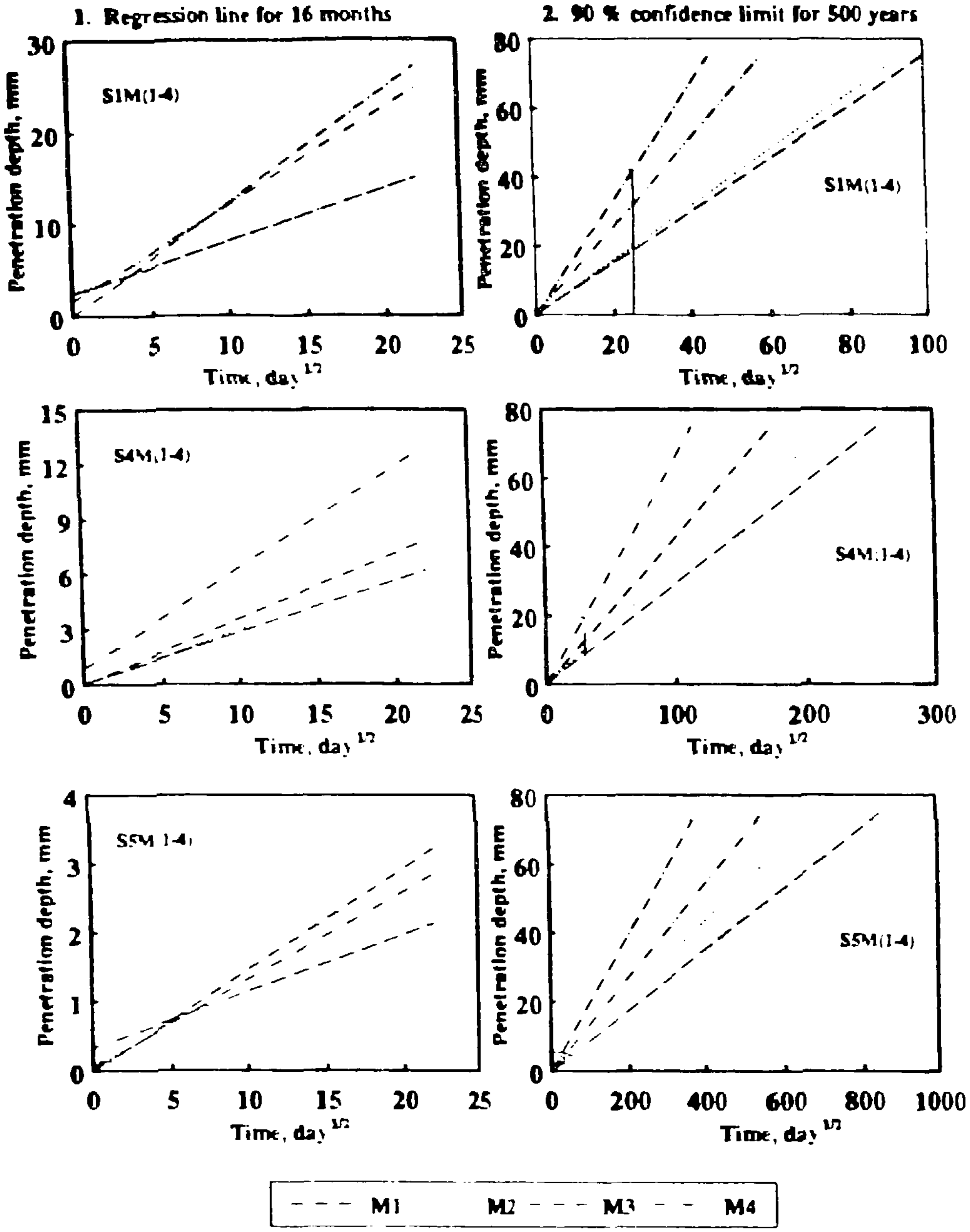


FIGURE 6: Penetration Depths of Chloride Ions vs Time$^{\frac{1}{2}}$ of Immersion in Bath 13. Regression Lines.



1. Regression line for 16 months

2. 90 % confidence limit for 500 years

Figure 7: Penetration Depths of Chloride ion versus Time$^{1/2}$ of Immersion in Bath 13

ISSN 0067-0367

To identify individual documents in the series we have assigned an AECL- number to each.

Please refer to the AECL- number when requesting additional copies of this document

from

Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada
K0J 1J0

Price: A

ISSN 0067-0367

Pour identifier les rapports individuels faisant partie de cette série nous avons assigné un numéro AECL- à chacun.

Veuillez faire mention du numéro AECL- si vous demandez d'autres exemplaires de ce rapport

au

Service de Distribution des Documents Officiels
Énergie atomique du Canada limitée
Chalk River, Ontario, Canada
K0J 1J0

Prix: A

2640-91