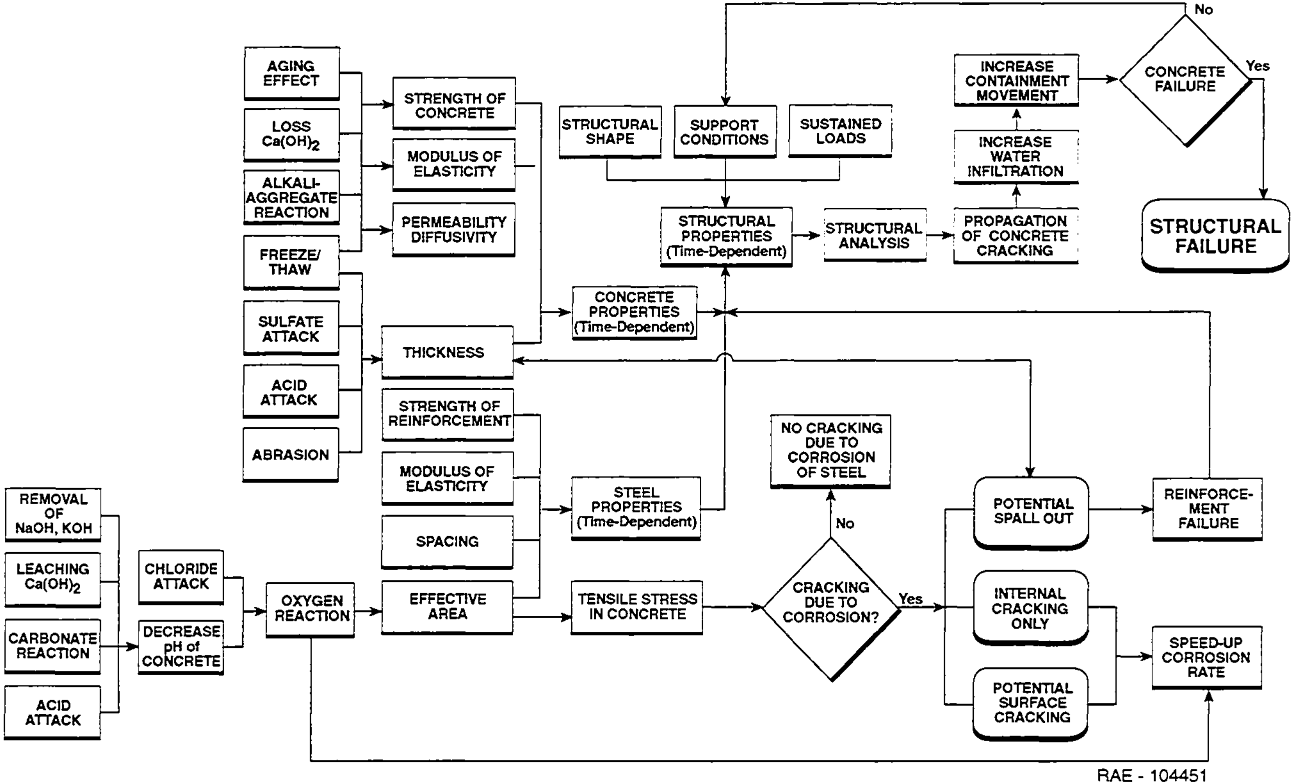

Fig. 2—Factors which influence integrity of reinforced concrete structures

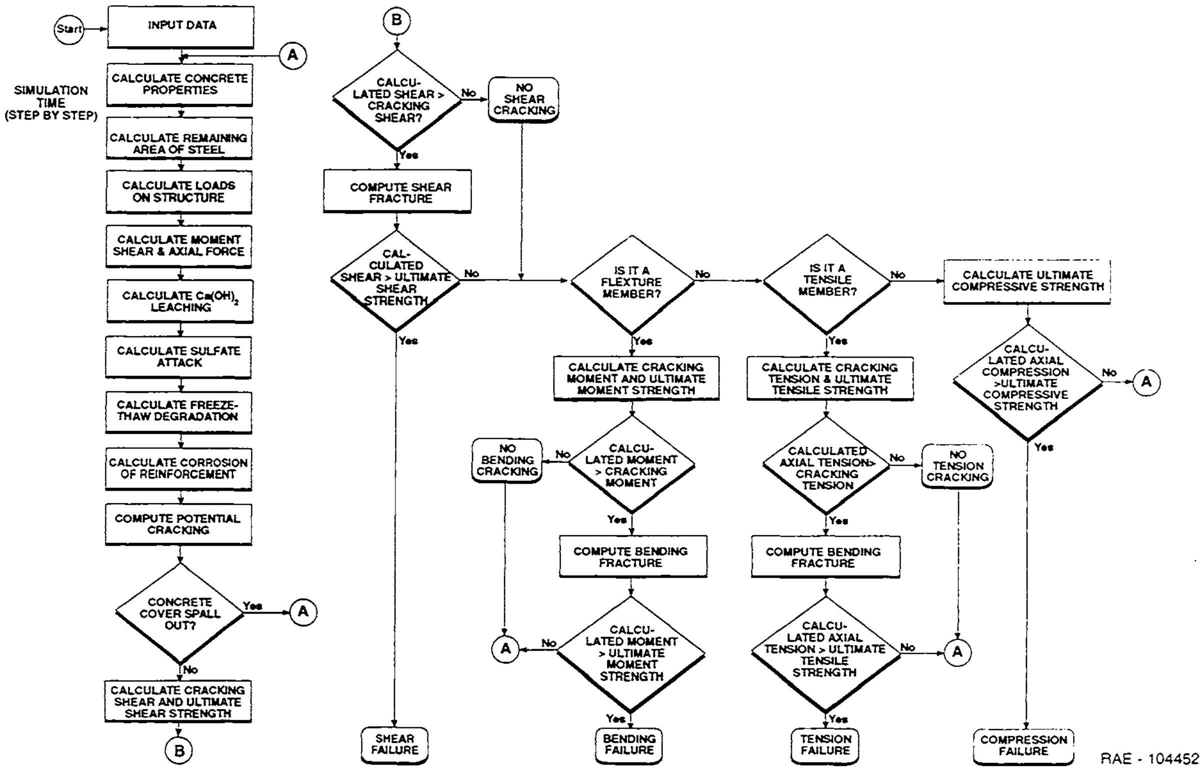

Fig. 3—Logic flow chart for computing degradation of reinforced concrete structures

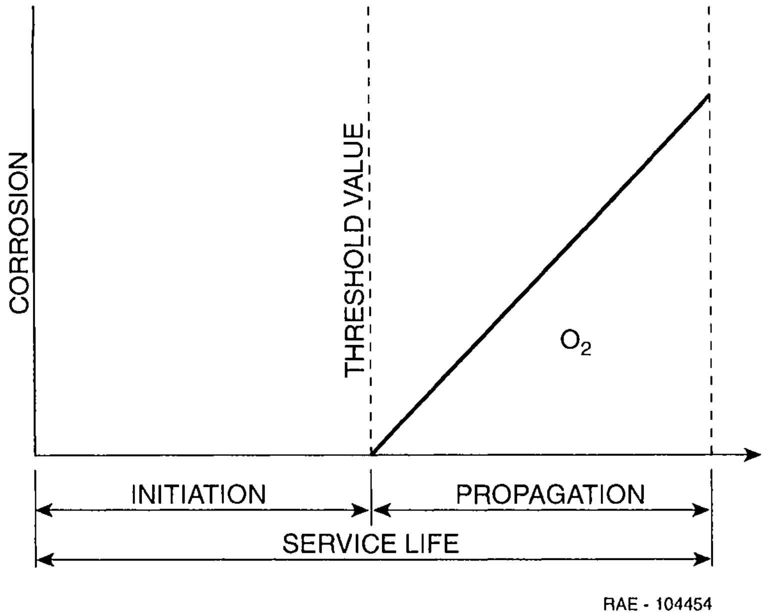

Fig. 4—Conceptual model of corrosion of reinforcement in concrete

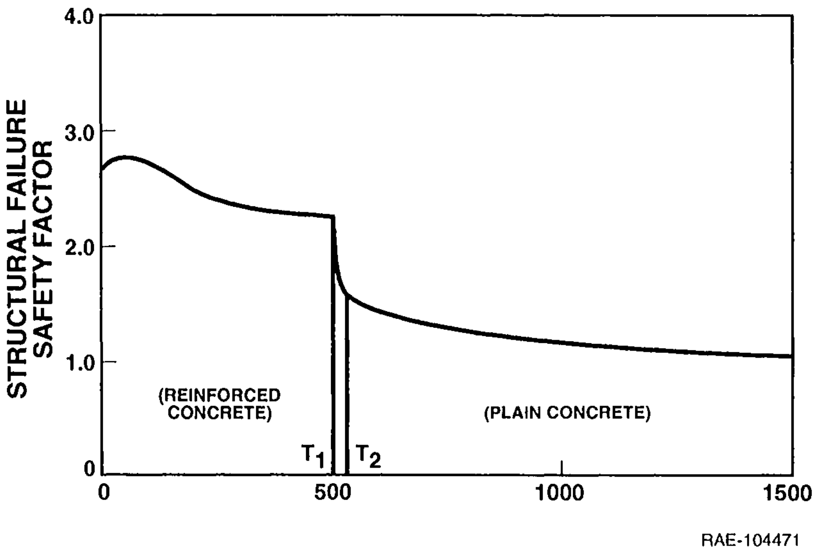

Fig. 5—Structural safety factor as function of time

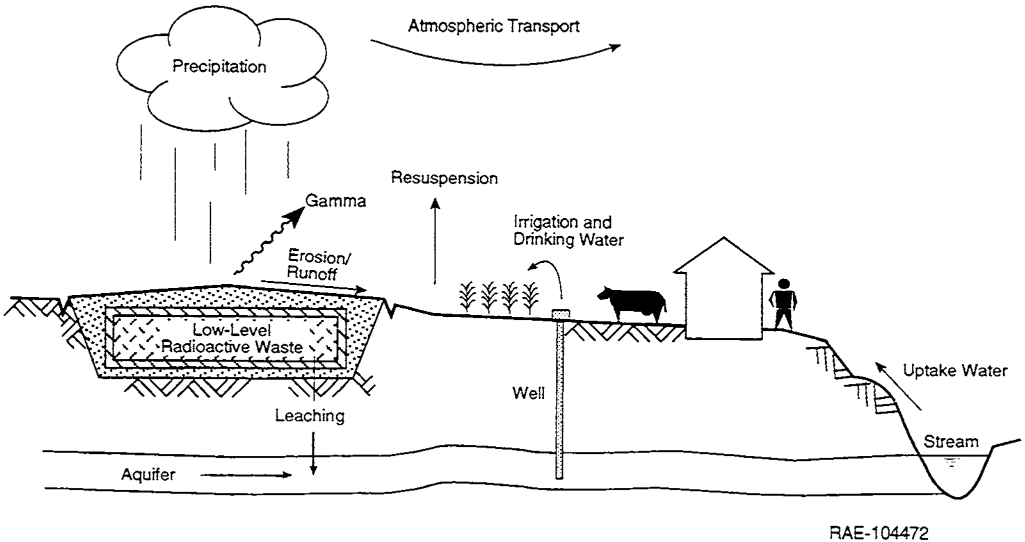

Fig. 6—Exposure pathways

SP 158-4

Testing and Evaluation of Durability of Concrete Barriers for Tumulus Disposal Facility for Low-Level Radioactive Waste

by J. H. Lee and D. M. Roy

Synopsis: The tumulus (an earthen mound) disposal concept can provide a major means for the disposal of low-level radioactive waste (LLRW) provided the concrete structure of the tumulus disposal units is designed and fabricated for the long-term durability.

The concrete used in an experimental disposal facility, Tumulus II was designed to have an excellent resistant to frost attack and a very low permeability to chloride ions. The present study reports numerous research results, including those from an accelerated alkali-aggregate reactivity test (Accelerated Concrete Core Method), which showed that a local coarse aggregate was potentially reactive to alkali. The reactivity to alkali was substantially reduced by incorporating 30 % fly ash (Class F) by weight of cement. Additional studies were performed on field concrete samples incorporating 9 % silica fume by weight of cement which showed effective reduction in alkali-aggregate reactivity.

Expansion mechanisms of the local coarse aggregate and reference alkali-carbonate reactive Pittsburg aggregate in concrete were studied by digesting the powdered aggregates under the accelerated test condition (1.0 N NaOH solution and 80 °C) and monitoring clay mineral phases in the aggregates with X-ray diffraction (XRD) analysis at various digestion ages. The results showed that transformation of non-expansible clay phase (chlorite) initially present in the coarse aggregates into expansible clay phases (vermiculites/smectites) could occur in a highly alkaline environment which is typical of many concrete pore solutions. The expansible clays thus formed are, at least in part, responsible for the expansion of concrete cores containing the local coarse aggregate and Pittsburg aggregate, as observed by the accelerated alkali-aggregate reactivity tests.

Keywords: Alkali-aggregate reactions; carbonate aggregates; concretes; durability; expansion; fly ash; portland cement type 1; portland cement type 2; radioactivity; silica fume

Dr. Della M. Roy is Professor Emerita of Materials Science at the Materials Research Laboratory of the Pennsylvania State University, University Park, PA 16802, USA. A Member of the National Academy of Engineering, she is author of some 300 research publications, recipient of the Jeppson Medal and Copeland Award of the American Ceramic Society, and a Fellow of American Concrete Institute, American Ceramic Society, American Association for the Advancement of Science, and Mineralogical Society of America.

Dr. Joon H. Lee is Staff Consultant with INTERA, Inc., Las Vegas, NV 89109, USA, and currently involved in evaluating performance of waste package and engineered barrier systems at the Performance Assessment Department of the Management and Operating (M&O) Contractor for the Yucca Mountain site characterization project. He received Ph.D. in Materials at the Materials Research Laboratory of the Pennsylvania State University, University Park, PA, and M.S. and B.E. both in Chemical Engineering from the University of Tennessee at Knoxville and Chung-Ang University, Seoul, Korea, respectively.

INTRODUCTION

This paper discusses the results and findings from the on-going investigation to test and evaluate the long-term durability of concrete engineered barriers used for the construction of experimental tumulus (an earthen mound) disposal facilities. The tumulus disposal concept can provide a major means for the disposal of low-level radioactive waste (LLRW) provided the concrete is designed and fabricated for long-term durability. In the disposal facility, large concrete vaults, in which a steel box containing solidified LLRW is placed and the remaining space is filled with grout/concrete before being sealed, are stacked two-level high on a large, high-quality concrete pad. Once the concrete pad is filled to capacity, it is completely covered with a three-layered tumuli of clay, gravel and soil. In this initial phase of the investigation, strength, freeze-thaw resistance, permeability (currently measured as rapid chloride permeability) and alkali-aggregate reaction have been identified as key properties that are important for the long-term durability. Compressive strength tests, freeze-thaw resistance tests and rapid chloride permeability tests were conducted on field concrete samples.

Although it is the most widely used standard method to test potential alkali-silica reactivity of siliceous aggregates, the ASTM C 227 method (Mortar-Bar Method) is not sufficiently sensitive and fails to detect potential alkali-carbonate reactive aggregates. Its failure in detecting the potential alkali-carbonate reactive aggregate is believed to be due to different expansion mechanisms of alkali-silica reactive aggregate [1] and alkali-carbonate reactive aggregate [2] in concrete. At the present time, the Canadian Standard Association Test Method CSA A23.2-14A (Concrete Prism Expansion Method) is the only standard test method with a high degree of confidence to detect potential alkali-carbonate reactive aggregates. One drawback of the concrete prism expansion method is its long test duration: the established maximum expansion limit is 0.025 % in one year for concrete subjected to moist environment for most of its service life [3]. An accelerated method (NBRI

Accelerated Mortar Bar Method) which was developed to test potential alkali-silica reactivity of siliceous aggregates by immersing mortar bars prepared from the aggregate to be tested, in 1.0 N NaOH solution at 80 °C for 14 days [4-6], was adopted to test potential alkali-carbonate reactivity of coarse aggregate in concrete by testing specimens cored from 28-day moist cured concrete block cast with the coarse aggregate to be tested. Among accelerated test methods published, the accelerated method used for the present study appears to be best correlated to the Canadian concrete prism expansion method [7]. The accelerated test (Accelerated Concrete Core Method) was used to study alkali-aggregate reactivity of a selected local coarse aggregate (dolomitic limestone) in concrete, which could be a major source of deterioration of the tumulus concrete barriers if the reactivity is above a certain level. The accelerated tests were run for concrete cores from laboratory-prepared samples containing the combination of the local coarse aggregate and four different fine aggregates: one local natural silica sand; one local manufactured dolomitic sand; a manufactured sand prepared from the coarse aggregate, having the same size distributions as the local natural sand; and reference non-reactive natural silica sand (Ottawa sand). They were compared with the behavior of reference alkali-carbonate reactive (Pittsburg quarry) and non-reactive (Nelson) aggregates. The effects of a local fly ash (Class F) on the reactivity of the local coarse aggregate were studied with the accelerated test for specimens cored from concrete blocks prepared in the laboratory by incorporating 30 % fly ash by weight of cement. Concrete cores from field concrete samples which were provided from Martin Marietta Energy Systems (MMES) were also tested by the accelerated test.

It has been known that the expansion of alkali-carbonate reactive aggregate in concrete is closely related to clay phases present in the aggregate [2,8-12]. One postulation for the expansion mechanisms of the aggregate in concrete was that initially dry clays inside the aggregate generate expansive action by absorbing moisture which reaches the clays through 'openings' that are provided as a result of dedolomitization reaction of some dolomite components in the aggregate [2,9-12]. X-ray diffraction (XRD) study of the acid-insoluble residue of Pittsburg quarry aggregate (dissolved in 4.0 M acetic acid) showed that, although they are not expansible, illite and chlorite are the major clay phases present [8]. In order to further elucidate the expansion mechanisms of the local coarse aggregate in reference to the Pittsburg aggregate, the powdered aggregates were digested under the accelerated test condition for various periods to expose clay phases of the aggregates to a highly alkaline environment (typical of many concrete pore solutions) and to accelerate their weathering. After being digested for various periods, the aggregate powders were dissolved in an acidic solution to remove carbonates, and the acid-insoluble residues were studied with XRD for clay phases.

MATERIALS

The component materials for the tumulus concrete were provided from local contractors in the Oak Ridge area in Tennessee. Chemical analyses and other properties of the cement, fly ash and coarse aggregate used for the experimental tumulus concrete are given in Table 1, and sieve size analysis and other properties of two local natural and manufactured fine aggregates in Table 2. As part of this investigation, MMES provided forty eight 6 x 12-in. cylinders and sixteen 3 x 3 x 11.25-in. beams of fly ash field concrete, cast from ready-mix trucks during the pouring of the experimental tumulus concrete (three cylinders and one beam from each truck load). In addition, nine 6 x 12-in. silica fume field concrete cylinders were also provided. Upon receipt, the field concrete samples were demolded and have been cured in fog room. Mix design characteristics of the field concretes are given in Table 3. Reference alkali-carbonate reactive aggregate (Pittsburg quarry aggregate) and reference non-reactive aggregate (Nelson aggregate) for laboratory tests were received from Ontario Ministry of Transportation, Ontario, Canada. The reactive nature of Pittsburg quarry aggregate is well documented [2,8-13]. Ottawa sand which is natural pure quartz sand and documented in ASTM C 778 was used as reference non-reactive fine aggregate. Nelson aggregate and Ottawa sand have been used as non-reactive references in a number of studies to develop and evaluate alkali-aggregate reactivity test methods [14-16].

TEST PROCEDURES

Compressive Strength Test

28-day compressive strength tests were conducted according to the procedures in ASTM C 39 on twenty one 6 x 12-in. fly ash field concrete cylinders from seven different sets (seven different ready-mix truckloads), three cylinders from each set.

Rapid Chloride Permeability Test

Following the procedures in AASHTO T 277, rapid chloride permeability tests were conducted on two specimens cored from one 6 x 12-in. fly ash field concrete cylinder and one specimen cored from one 6 x 12-in. silica fume field concrete cylinder. The specimens were 6 months old when tested.

Freeze-Thaw Test

Freeze-thaw tests were conducted on twelve 3 x 3 x 11.25-in. fly ash field concrete beams according to ASTM C 666 - Procedure A: Rapid Freezing and Thawing in Water. The concrete beams were 6 months old when tested. The optional length change measurement method was used as a measure for determining the degree of deterioration of the concrete beams due to the repeated freeze-thaw cycles. Length measurements were taken at every 20 freeze-thaw cycles. Seven readings were taken for each specimen, and all readings above and below two standard deviations from the mean were discarded. Then, the statistically 'cleaned' new mean was taken as the length of the specimen.

Accelerated Alkali-Aggregate Reactivity Test

Test procedures for the accelerated alkali-aggregate reactivity test (Accelerated Concrete Core Method) are described in detail in the original reference [7], and some modifications to specimen length measurement were made for the present study. The 3 x 6-in. concrete cylinder cast with coarse aggregate to be tested was continuously cured above water in a plastic container with a tight-fit cover at room temperature to the age of 28 days. At the end of the curing period the cylinder was cut at both ends to a length of about 2.75-in., and the both ends were ground with 240 grit SiC abrasive powder to ensure the surface smoothness which was needed to make accurate length measurements of specimens that were cored from the concrete cylinder. After the grinding, five specimens of about 0.8-in. diameter were cored from each concrete cylinder.

A simple comparator equipped with a dial indicator with graduations of 0.0001-in. was used for length measurements of specimens. The surface of the floor of the comparator, on which specimens are placed for length measurements, was finished to a surface roughness of about 30 micro-inches and has a mark to place specimens at the same position. When specimens were measured for their initial length after soaking the cored specimens in deionized water for four hours, the bottom of each specimen was marked, aligning with the mark on the comparator floor, and the point at which the contact point of the comparator touches the top of the specimen was also marked. By aligning those markings, it was ensured that length measurements of each specimen were taken every time at the exactly same point of the specimen. Seven length measurements were taken per specimen, and all measurements above and below two standard deviations from the mean were discarded. The statistically 'cleaned' new mean was used to calculate the length change of the specimen, and an average of length changes of five specimens was then used as the length change of the sample. The critical expansion limit established for a sample containing potential alkali-carbonate reactive aggregate is 0.162 % at 24 days. This limit was determined by correlating the expansion data from the accelerated test to those from the Canadian standard concrete prism test [7].

Digestion Study for Clay Minerals in Coarse Aggregates

Digestion of aggregate powder--To ensure a representative sampling, the coarse aggregates were crushed and thoroughly mixed, and those passing No. 4 sieve and retained on No. 8 sieve were used. Since a severe dry grinding could cause damage to clay minerals, the sampled aggregates were only coarsely ground. 10 g of the ground aggregate along with 30-40 g of concrete pieces which were remains from the concrete cylinder that contains the same coarse aggregate and non-reactive Ottawa sand and had been cored for the accelerated alkali-aggregate reactivity tests were digested in 1.0 N NaOH solution in a 150 mL tightly capped plastic bottle for 7 days, 14 days and 24 days in a 80 °C oven. Before being placed in the bottle, the concrete pieces were washed with running tap water to remove fine particles, thus reducing the addition of foreign materials to the aggregate powder. The inclusion of the concrete pieces was to supply other ions likely to be present in actual concrete pore solution. A total of six bottles was prepared, three bottles for 7-day, 14-day and 24-day digestion of the local coarse aggregate powder respectively and another three bottles for 7-day, 14-day and 24-day digestion of the reference reactive Pittsburg aggregate powder respectively. After a specified period of digestion, the digested aggregate powder was washed to remove excess salts by mixing with deionized water, centrifuging and decanting the clear supernatant liquid. The aggregate powder was then dried in a 80 °C oven and mixed thoroughly. A small portion of it was saved for XRD analysis.

Carbonate removal--Carbonates of both undigested and digested aggregate powders were removed by dissolving the powder in 1.0 M Na-acetate solution adjusted to pH 5. The dissolution was conducted in about 300 ml of the Na-acetate buffer solution in a beaker with a cover glass on it, and the solution was heated to 50 °C and stirred on a hot plate during the dissolution. After one day of dissolution, the residue was centrifuged and dissolved again in about 200 ml of the fresh Na-acetate buffer solution with heating and stirring. After the completion of dissolution, the residue was centrifuged and washed to remove excess salts by mixing with deionized water, centrifuging and decanting the clear supernatant liquid. The residue was then dried in an 80 °C oven and mixed thoroughly.

XRD analysis--Characterization of clay minerals in the residue was conducted using XRD analysis, utilizing a series of chemical and physical treatments to the residue. The residue was prepared as an oriented film on a glass slide for XRD analysis. The treatments utilized for the characterization of clay minerals by XRD analysis are well described in standard textbooks [17,18].

RESULTS AND DISCUSSION

Compressive Strength Tests

Results of compressive strength tests are given in Table 4. The 28-day strengths are an average of three cylinders per each set and exceed the design specification (minimum 4000 psi at 28 days). The results also show a good reproducibility with minimal variations among truckloads and from beginning to end.

Rapid Chloride Permeability Tests

Rapid chloride permeability test results are presented in Table 5. An average of 909 coulombs passed through the specimens cored from one 6-month old fly ash field concrete cylinder, and 175 coulombs through the specimen cored from one 6-month old silica fume field concrete cylinder. The results indicate that the rapid chloride permeability of both the fly ash and silica fume field concretes is rated as "very low", based on the criteria set forth in the AASHTO T 277 test method.

Freeze-Thaw Tests

The freeze-thaw test results measured at every 20 freeze-thaw cycles are given in Table 6. The percent length change is an average of twelve specimens. Although specimens showed different degrees of surface scaling, the results indicate essentially no length change of the specimens, values being within the measurement error. The maximum expansion limit suggested in ASTM C 666 is 0.1 % at any number of cycles during the test. The specimens were 6-month old when tested. The durability factor of the specimens can be estimated from the length change measurements using the correlation [19]

$$DF = \exp \{ \frac{1}{0.02016} [(0.2772 - d)^2 + 0.01613] \},$$

where DF = durability factor
d = length change (% per 100 cycles).

The correlation (correlation coefficient = 0.965) was developed based on results from the fundamental transverse frequency measurements and length change measurements on 196 samples (an average nine concrete specimens per sample) subjected to the freeze-thaw tests. The durability factor of the specimens, calculated from the correlation with d = - 0.0016 % per 100 cycles is 105 after 300 cycles, being interpreted as DF = 100 considering the measurement error. Therefore, it is concluded that the concrete was fabricated to have an adequate air-void system and have an excellent resistance to frost attack.