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# CONCRETE LONGEVITY OVERVIEW[a]

Wallace Chang, Envirosphere Company
Berlinda Morreale, Idaho National Engineering Laboratory
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415
208-526-9165 (Fax) or (208) 526-0511

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## ABSTRACT

A number of compact host states and unaffiliated states are currently selecting appropriate disposal technology and construction materials for their planned low-level radioactive waste (LLW) disposal facilities. Concrete is one of the candidate materials under consideration for the construction of LLW disposal facilities because of its strength, durability, abundant availability, and relatively low cost. The LLW disposal facilities must maintain intruder barrier integrity for up to 500 years, without active maintenance after the first 100 years. The ability of concrete to survive for such a long time as a construction material is a critical issue. This report provides a basic understanding of the composition and workings of concrete as a structural material in LLW disposal facilities and a description of degradation factors and state-of-the-art mitigative measures available to preserve the durability and longevity of concrete. Neither the paper nor the report is intended to be a design guidance document, and neither addresses using cement as a waste solidification agent.

## INTRODUCTION

The Low-Level Radioactive Waste Policy Act of 1980 (P.L. 96-573) and the Low-Level Radioactive Waste Policy Amendments Act (the Act) of 1985 (P.L. 99-240) require each state to be responsible for the disposal of low-level radioactive waste (LLW) generated within its borders. The Act establishes a method to enable states to form multi-state compact regions, and a framework within which a "host" state can be selected to provide the required LLW disposal facility for the entire compact region. To date, 13 states (host states and unaffiliated states) are engaged in siting, developing, and constructing low-level radioactive waste disposal facilities.

The legislation also directs the U.S. Department of Energy (DOE) to provide technical assistance to compact regions, host states, and unaffiliated states. Such assistance includes preparing technical guidelines for alternative technologies to be used in disposing of LLW. Accordingly, the DOE established the National Low-Level Waste Management Program to provide this technical assistance.

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A number of host states and unaffiliated states are now selecting the appropriate disposal technology and construction materials for their LLW disposal facilities. Concrete is expected to be used in constructing these facilities because of its strength, durability, abundant availability, and relatively low cost. The LLW disposal facilities are required to function as intruder barriers, without active maintenance, for at least 500 years. The ability of concrete to survive as a construction material for such a long time is an important issue. Representatives of participating states have, therefore, requested technical assistance from DOE in investigating the use of concrete in constructing a LLW disposal facility. This paper provides a basic understanding of: the use of concrete as a structural material in LLW disposal facilities; the nature and relative importance of factors that may limit the structure's durability and longevity; and methods for mitigating the degradation factors.

In building a LLW disposal facility, the engineered structure, backfill, and cover are the components that generally use concrete. Each of the currently proposed disposal alternatives incorporates an engineered structure, backfill, and disposal unit cover in its design. Concrete used for constructing engineered structures may be used with or without steel reinforcement.

Backfill material is used to fill voids between waste packages, space around the waste packages, and space within the surrounding engineered structure. Backfill provides lateral support to the disposed waste packages, the engineered structure walls, and the cover. The disposal unit cover may be simply a layer of earthen material placed over the engineered structure; however, more recent disposal unit cover designs incorporate a multilayered design consisting of layers of various materials such as gravel, sand, clay, and geotextile membranes. The purpose of the cover is to direct surface water and percolating rainwater away from the buried waste packages, and to protect the structure from the effects of natural phenomena. Concrete may also be used as one of the many layers to function as an inadvertent intruder barrier.

The scope of this paper covers degradation factors and mitigative measures applicable to Portland cement concrete and blended hydraulic cement concrete. Specialty concretes such as sulphur polymer, aluminate, and asphalt concrete are not covered in this study.

Based on the research conducted for this study, two facts are evident. Concrete-type structures have maintained a high degree of integrity for centuries; while limited data are available to confirm the longevity of concrete structures built with the more modern formulation, a large amount of research and development activities were conducted to continuously improve the strength and durability of modern concrete. This information is available in technical papers in trade journals, and in industrial codes and guidelines published by engineering societies such as the American Concrete Institute (ACI), the Portland Cement Association (PCA), the American Society of Mechanical Engineers (ASME), the American Society of Testing and Materials (ASTM), the National Institute of Standards and Technology (NIST), and the National Ready-Mixed Concrete Association.

Concrete is a versatile structural building material, manufactured by mixing cement, aggregates, water, and admixtures. Cement, when mixed with water, reacts to form a cohesive mixture which binds together the aggregates (i.e., sand, stone and gravel) to form concrete. Admixtures are added to the mixture immediately before or after mixing to produce concrete with the desired properties. Initially, this cement, water, and aggregate mixture is soft and can be molded into any form. The working time of concrete, under favorable conditions (i.e., the proper ambient temperature, humidity, and water-to-cement ratio) is limited to about 90 minutes before the mixture begins to stiffen. This mixture starts to solidify as the water in the mixture begins to combine chemically with cement. The initial solidification of the paste is referred to as the "setting of cement," and, under favorable conditions, occurs within 3 to 4 hours after mixing. The settling and hardening process in concrete is called hydration. Temperatures above freezing and adequate moisture are required to promote hydration during this early period. Cement requires sufficient moisture to fully hydrate and to reach full final strength. To ensure that the hydration process functions properly, additional water may be sprayed onto the concrete surface after the surface of the concrete structure becomes rigid. This process is called curing.

The ingredients in concrete other than cement, water, and aggregates are called admixtures; they are added to the mixture immediately before or during mixing, to control certain properties of concrete, such as consistency, setting time, strength development, amount of hydration heat and the reactivity with alkali in aggregates. The most common and commercially available materials used as admixtures include finely ground granulated blast-furnace slag, fly ash, and silica fume.

Degradation factors that may limit the use of concrete in these components and limit the durability and longevity required of these components are discussed in the following sections.

## FACTORS AFFECTING CONCRETE LONGEVITY

Five categories of degradation factors generally considered to be the most deleterious are sulfate attack, chloride attack, leaching, alkali-aggregate reaction, and freeze-thaw damage.

Sulfate Attack--Among the most common and destructive factors affecting concrete are sulfates in soil, groundwater, or seawater. The degradation caused by sulfate varies from minor surface erosion to complete loss of structural strength leading to total structural failure of the concrete. The ability of concrete to withstand sulfate attack depends on the sulfate concentration level, the quality of the concrete, and the chemical compatibility between the concrete and its sulfate environment.

The most commonly found sulfate salts in soils are sodium sulfate, calcium sulfate, and magnesium sulfate. Sulfates are also found naturally in rocks and mineral deposits. The deteriorating effects of sulfate salt are the results of reactions with the hardened cement in concrete. No deleterious reactions have been reported between sulfate salts and the aggregates.

Chemical reactions occur when sulfate is in contact with cement. These reactions are complex and may lead to one or more degradation mechanisms, depending on the types of sulfates and their concentration levels.

The subject of sulfate attack and methods of increasing concrete resistance to sulfate attack have been researched extensively for more than 50 years. Numerous methods can be used to minimize sulfate attack or to improve concrete's resistance to sulfate. Sulfate problems can be avoided by taking proper precautions. Prior to determining the composition and design of a concrete structure, local soil and water samples should be taken and analyzed to determine their sulfate concentration levels. The American Concrete Institute (ACI) has provided specific guidance for selecting cements and admixtures for various sulfate environments in the ACI Guide for Durable Concrete[1] and ACI 350 report, Environmental Engineering for Concrete Structures.[2] Mitigative measures for improving concrete resistance to sulfate, as recommended in various reports include

- Use of sulfate-resistant cement
- Use of admixtures
- Good drainage
- Use of protective coatings.

The combined application of the aforementioned mitigative measures can greatly reduce or eliminate the consequences of future sulfate attack. Although mitigative measures such as the use of sulfate-resistant cement, low water-to-cement ratio, and low permeability concrete have been developed only within the last several decades, it is likely that their effectiveness to preserve concrete longevity can be extended to over several hundred years.

Chloride Attack--Chloride ions are common in nature, and they exist in soil in the form of chloride salts such as calcium chloride, magnesium chloride, and sodium chloride. They are also found in igneous rocks and sedimentary rocks. Particularly high levels of chloride ions are found in evaporates. In arid regions of the United States, the soil usually contains high chloride concentrations because of the high evaporation rate. Precipitation close to the oceans contains some amount of chloride salt. Other sources include the sodium chloride used as a deicer and/or dust suppressants. Chlorides such as magnesium chloride and aluminum chloride react with lime to form unstable and water soluble compounds. Other chlorides, such as sodium chloride and potassium chloride, do not react with lime or other components of cement. These metal chlorides alone are generally harmless, but in concentrated solutions, they tend to leach lime from concrete.

Concrete, due to its highly alkaline nature (pH exceeding 12.5), normally provides a protected environment for embedded reinforcing steel. The alkaline environment results in the formation of a tightly adhering film that passivates the steel and protects it from corrosion. However, the introduction of chloride ions into the concrete reduces the alkalinity of the concrete and breaks down the protective film layer, allowing oxygen infiltration and contact with the embedded steel rebars. The presence of oxygen and the depassivated steel permits an electrochemical process that eventually corrodes the steel reinforcement, which is followed by structural failure.

There are several mitigative measures that can be used to minimize chloride-induced corrosion and to improve concrete resistance to the penetration of chlorides. Penetration of chlorides through the walls of a soil-covered engineered structure of a LLW disposal facility is a very slow process. This process can be further delayed by using a combination of the mitigative methods discussed in ACI 222.[3] These methods fall into three categories:

1. Application of appropriate design and construction practices to maximize the protection of the steel reinforcement
2. Application of treatment on external concrete surfaces to exclude chloride infiltration
3. Application of protective coating to the reinforcing steel.

Leaching--Leaching is the removal by water of soluble compounds from concrete. It affects concrete structures that are buried in soil where there is groundwater flow. Portland cement itself contains a large amount of water soluble compounds, with alkali salts being the most soluble, followed by calcium oxide, which comprises more than 60% by weight of the cement mixture. The hydration of cement leads to formation of calcium hydroxide, which is also known as free lime. This material is readily soluble in water, particularly when there is dissolved carbon dioxide in the water.

The most elementary yet direct measure to mitigate the effects of leaching on concrete is to simply prevent direct contact between the structure and the groundwater. This can be achieved by locating the structure in an arid region, or by placing it above the groundwater table and providing adequate drainage around the structure.

When required, however, other measures can be taken to increase concrete's resistance to leaching. These include:

1. Increasing the thickness of concrete to impede water infiltration and the leaching of core material
2. Using leach resistant cement such as those containing increased quantities of pozzolan and blast furnace slag
3. Improving the quality of concrete by using aggregates with low porosity
4. Increasing water-tightness and compactness in the production of concrete.

Alkali-aggregate--"Alkali-aggregate reaction" is a term used to describe the expansion reaction involving alkalis in the cement and minerals found in the aggregates. Aggregates are sand, stone, and gravel used in making concrete. Alkali-aggregate reactions are different from the other degradation factors because they do not depend on the external infusion of aggressive carbonate solution or solutions containing salt or acid into the concrete. All of the reactive components usually are contained in the concrete itself. For this reason, the degree of alkali-aggregate reaction in concrete usually is controllable and can be prevented by adjusting the ingredients used in the cement mixture and by careful choice of quality aggregates. The deleterious effects of alkali-aggregate reactions include small internal cracks in cement paste around the affected aggregate particles.[4] Although these cracks seldom cause serious structural failures, they do increase the permeability of concrete to water infiltration, leading to structural failure through other degradative mechanisms.

The ACI Guide to Durable Concrete contains detailed guidance on methods for preventing alkali-aggregate reaction. The best method is to avoid using reactive aggregates, if they can be identified. There are a number of methods for identifying reactive aggregates.

One source for identifying aggregate reactivity is the aggregate's past performance record. The service records of concrete structures provide the best information for the selection of aggregates. When an aggregate has been used extensively with cements of different compositions, including those of high- and low-alkali contents, and if the structure maintains good service records, it can be assumed that the aggregate's reactivity is low.

It is often necessary to use aggregates from new supply sources, or a combination from several sources where such service records are not available. It then becomes necessary to conduct laboratory tests to identify reactive types and the potential for concrete degradation.

The other method for reducing the potential of alkali-aggregate reactions is to mix aggregates with low-alkali cement. Low-alkali cements are readily available and can be purchased in accordance with ASTM C-150 optional requirements. The obvious method of mitigating the alkali-aggregate problem is to keep the concrete dry through careful site planning and with special attention to the local drainage system.

Freeze-Thaw--Freeze-thaw damage (sometimes called frost damage), as applied to concrete, is caused by exposing concrete structures to temperatures fluctuating above and below the freezing point. Freeze-thaw damage is a serious problem for exposed concrete structures, particularly those located in the northern regions of the United States, where several freeze-thaw cycles may occur during a single winter season. In general, a freeze-thaw cycle is said to have occurred if the air temperatures crossed the freezing point at any time, or fluctuated several times, during a 24-hour period. The annual frequency of freeze-thaw cycles in the United States varies from 20 cycles to 100 cycles per year.

The effects of freeze-thaw cycles on underground facilities with a soil cover are determined by the extent of the ground penetration of the freezing temperatures. The depth of soil that can be affected by freezing temperatures is called frost depth. Essentially, the entire United States experiences some degree of ground freezing. The degradation mechanism of frost damage has been intensely researched for the last 50 years. One hypothesis is that, during the freeze-thaw process, the increased volume of ice crystals generates internal hydraulic pressure to cause cracking.

The impact of freeze-thaw damage on LLW disposal facility depends largely on its design. An abovegrade facility without a disposal unit cover will be subject to freeze-thaw cycles according to the changing seasons and fluctuating air temperatures. Facilities placed at sufficient depth below ground, or covered with a sufficiently thick earthen cover, would be protected from the impact of changes in air temperature. A review of current host state disposal facility designs indicates that all of the disposal facilities will be located below grade, partially below grade, or will be covered with a temporary cover during construction. Structures buried below the frostline (the depth below which the ground does not freeze) are not affected by the freeze-thaw phenomenon.

There are a number of other known degradation factors, which, in a normal service environment, would have little or no effect on concrete structures. However, the cumulative effects of these factors over the long service life required for a LLW disposal facility may have an impact on the overall performance of the concrete structure. These factors include erosion and abrasion, carbonation, acid attack, irradiation and biodegradation.

## SUMMARY

This paper has identified the engineered structure, the backfill, and the disposal unit cover as the three components of a LLW disposal facility that will most likely use concrete. A review of the NRC's 10 CFR 61 regulation reveals that only the components of a LLW disposal facility designed to serve as intruder barriers are required to have a life of 500 years.

Several Agreement States have promulgated more explicit regulations than 10 CFR 61 on the performance period and requirements for the engineered structure at a LLW disposal facility. However, the intent of these state regulations remain the same as 10 CFR 61, that is to ensure structural stability and recognizability during the designated performance period.

For concrete, structural stability may be influenced by degradation mechanisms. The degradation mechanism and mitigative measures for five major degradative factors have been described. These are sulfate and chloride attack, leaching, alkali-aggregate interaction and freeze-thaw cycles. Most, or nearly all, degradation factors require the presence of moisture or water as a medium to transport aggressive chemicals into the concrete matrix and to carry degradation products out of the concrete. The key, therefore, to minimizing degradative effects on the longevity of concrete is to delay groundwater contact with the LLW structure. Some of the mitigative measures that are common to most of the degradation factors include those found in Table I.

One other important factor that will improve the longevity of concrete is quality. The long-term performance of concrete is often controlled by the level of its quality. Based on currently available information, concrete can be formulated to provide long-term, durable services as required at a LLW disposal facility.

**Table I.** Concrete formulations suitable for mitigating the effects of the five major degradation factors

| Degradative Factors | Mitigative Measures |
|---|---|
| 1. Sulfate Attack | Use Type II Portland cement for negligible or moderate exposure. Use Type V Portland cement for severe exposure. Use Type V Portland cement plus pozzolan for very severe exposure. Maximum water-cement ratio should not exceed 0.50 for moderate exposure and 0.45 for severe and very severe exposure. |
| 2. Chloride Attack Corrosion of Reinforcing Steel | Use Type I cement with tricalcium aluminate less than 10 percent. Use pozzolans to reduce permeability. Maximum water-cement ratio should not exceed 0.40. Use high range water-reducing admixture, air entraining mixture to improve workability and durability. Concrete cover over rebar, 3 in. minimum. Limit chlorides to 0.15 percent by weight of cement. Use epoxy-coated steel reinforcement. |
| 3. Leaching | Use Type I cement with tricalcium aluminate less than 10 percent. Maximum water-cement ratio should not exceed 0.45. Use air entraining admixtures and pozzolans to improve water-tightness and durability. |
| 4. Alkali-Aggregate Reactions | Use Type II low-alkali cement. Fly ash Class F may be used in lieu of low-alkali cement. Avoid reactive aggregates. |
| 5. Freeze-Thaw | Maximum water-cement ratio should not exceed 0.50, 0.45 and 0.40 for negligible, moderate and severe exposure respectively.<br>Use air entrainment 4 to 6 percent for moderate exposure and 5 to 7 percent for severe exposure. |

However, such long-term services can be obtained only if the concrete is prepared in accordance with a set of carefully defined specifications, supplemented with good construction practices in the field.

In summary, all degradation mechanisms can be prevented or mitigated using presently available techniques, and by the proper choice of materials, designs, or operation.[5]

# REFERENCES

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