# DEVELOPMENT OF HIGH INTEGRITY, MAXIMUM DURABILITY CONCRETE STRUCTURES FOR LLW DISPOSAL FACILITIES

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## ABSTRACT

A number of disposal facilities for Low-Level Radioactive Wastes have been planned for the Savannah River Site operated by the Department of Energy near Aiken, SC. Design has been completed for disposal vaults for several waste classifications and construction is nearly complete or well underway on some facilities. Specific design criteria varies somewhat for each waste classification. All disposal units have been designed as below-grade concrete vaults, although the majority will be above ground for many years before being encapsulated with earth at final closure. Some classes of vaults have a minimum required service life of 100 years. All vaults utilize concrete containing a unique blend of cement, blast furnace slag and pozzolan. The design synthesizes the properties of the concrete mix with carefully planned design details and construction methodologies to (1) eliminate uncontrolled cracking; (2) minimize leakage potential; and (3) maximize durability. The first of these vaults will become operational in 1992.

## PURPOSE

This paper describes the materials, methods, and conceptual design of the concrete structures to enhance durability/service life and to meet specific performance objectives as derived from DOE Orders 5820.2A and 5480.11 and proposed EPA Regulation 40 CFR 193 in the disposal of containerized wastes. This paper also discusses the results to date of the quality of completed construction and a summary of methods presently being proposed for service life prediction.

The complex subject of cement-concrete chemistry as well as the processes associated with attack by sulfates, chlorides, freeze-thaw action and other primary degradation mechanisms are treated in many scholarly journals and reference texts and are not within the scope of this paper.

## BACKGROUND

Below-ground vaults are being planned as alternatives to shallow land disposal for low-level radioactive waste (LLW) at Savannah River Site (SRS). Reinforced concrete is the predominant material used in the construction of the vaults. Other principal elements of the SRS disposal facilities but not included in the scope of this paper include flexible membrane liners for certain waste classifications, permeable drainage layers under and beside the vaults, and engineered clay caps over the vault complexes.

The design criteria for all structures requires that cracking be controlled to an absolute minimum to reduce leakage potential. The design criteria for certain of the LLW facilities also contains a requirement for 100-year minimum service life.

Construction Technology Laboratories, Inc. (CTL), Skokie, Il. was engaged to assist in the development and testing of the most suitable concrete mix to help meet these objectives. The principal CTL investigator was Mr. Steven H. Gebler.

In addition to the determination of proper mix materials it was recognized that design details and construction methodologies were of major importance. Engineering judgement further dictated that the design incorporate *all* cost-viable practical measures to enhance structural durability within the limits of available materials and usual construction practices. Construction of the initial vaults is by Bechtel Savannah River, Inc. under the direction of Mr. W. J. Harper.

The corrosion environment at the Savannah River Site is not aggressive. The concentrations of sulfates and chlorides are very low in the soils and ground water. While there are sub-freezing temperatures each winter, rarely do they occur for many days in succession or persist for more than a few hours.

The potential for chemical attack on the concrete from waste leachates is very low. Only solid or grout-stabilized (solidified) wastes are disposed of in those vaults without flexible membrane liners on the interior. Each vault is protected by roof and walls against rainwater infiltration and provided with a leachate/leakage detection and removal system effectively minimizing the dwell time of any free liquids that might inadvertently enter the vaults.

## LEAKAGE POTENTIAL

Properly cured ordinary Portland Cement concretes with water/cement ratios of 0.45 or lower have been determined by numerous investigators to have permeabilities of approximately $1 \times 10^{-9}$ cm/sec where cracking is absent. This is 1 to 2 orders of magnitude better than clay liners or caps which are required by EPA acceptance criteria (1) to have a permeability, i.e., hydraulic conductivity, no higher than $1 \times 10^{-7}$ cm/sec. Thus, a 1 m thickness of ordinary concrete would have a permeability 100 times less than a 1 m thickness of acceptable clay and probably at least ten (10) times less than the best that is practical to achieve in clay (1).

Further, investigators for the Netherlands Delta Barrier Project (2 and 3) found that slag-cement concrete had a chloride transport permeability five (5) times less than that for ordinary Portland Cement concrete. This is consistent with the findings of numerous other investigators (10).

Despite the hydraulic barrier posed by well constructed concrete, it is not an acceptable substitute for a barrier of clay by EPA regulations. Most likely this is because concrete usually cracks or contains other discontinuities and/or is of doubtful long-term durability. Even a very small crack that was not anticipated and provided with waterstop can increase the hydraulic transport properties of a slab or wall by orders of magnitude.

## SERVICE LIFE

Service life of a structure is defined as the period of time during which all functions intended in the design are fulfilled within a given environment. The need for increased emphasis on durability of concrete structures during design is becoming increasingly obvious as evidenced by numerous articles by leading authorities in the design professions. With the need for long term durability in such structures as those for containment of radioactive wastes it appears very probable that a minimum service life will increasingly become an integral part of the design requirement along with the customary strength requirements. Already, the regulations governing LLW disposal typically contain service life requirements of 100, 300, or 500 years, for example.

Various methods of predicting service life have been proposed or are under development. Most methods proposed in the United States have focused on either the durability of the concrete mix material alone or combined with corrosion of the steel reinforcing. None have been published dealing with the effects of such degradation mechanisms as volume change cracking or carbonation.

NUREG/CR--5542 (4), recently published, is a review of mathematical models that predict concrete material properties over long time periods. It also discusses the recognized degradation mechanisms and concludes that "cracking is the one degradation process that is most difficult to predict and can have the greatest impact on performance."

One approach to predicting service life receiving considerable attention is the Barrier code (Shuman, et al., 1989). However, it neglects several degradation mechanisms. In Europe, in addition to concern for material degradation, there has apparently been more interest in the functioning of the structure as a whole as indicated by Fagerlund (5), Somerville (6) and van Schaik (3).

Corrosion of steel reinforcement is recognized as a major issue among the various degradation mechanisms. One of the most important models for predicting the effect on service life of reinforcement corrosion is that proposed by Tuutti, 1982.

Service life expectancy studies are being performed on each SRS vault type utilizing the Barrier code. Results are expected in 1992. Pending the results of these studies and based on comparisons with the conclusions reported in Refs. 2 and 3, plus the relatively mild environment for the SRS vaults, service life predicted for the vaults is expected to comfortably exceed 500 years.

## MIX DEVELOPMENT

Laboratory investigations, field trials and the construction of a full size test wall formed the basis of selection of the design mix. Compressive strength, usually of primary importance in reinforced concrete design, was not a major concern. Structural design calculations were based on a minimum compressive strength of 2.758 X $10^7$ N/$m^2$ (4000 psi) at 90 days.

The design mix selected utilizes a unique blend of cement, ground granulated blast furnace slag (GGBS) and flyash (pozzolan) in combination with a low water-cement ratio and a superplasticizer to achieve high workability, high durability, low permeability, low volume change concrete.

The design mix is in close agreement with the recommendations in Refs. 7, 8 and 9 as well as being quite similar to the 200-year-life mix reported in Refs. 2 and 3. The design mix has a water-cement ratio of 0.45 and contains 240 kg (530 lbs.) of cementitious materials, i.e., cement content, per cubic yard of concrete as follows:

| | | |
|---|---|---|
| (a) Portland Cement-Type II | - | 56.7 kg (125 lbs.) |
| (b) GGBS | - | 122.0 kg (270 lbs.) |
| (c) Flyash | - | 61.2 kg (135 lbs.) |
| Total | | 240.4 kg (530 lbs.) |

The mix is pre-cooled to 18.3°C (65°F) maximum placement temperature with the use of liquid nitrogen. Pre-cooling not only reduced hydration rate and peak temperature, but also lowered the water demand for the mix. The mix utilizes locally available sand and 1.9 x $10^{-2}$m (3/4-in.) maximum coarse aggregate. The locally available aggregate tends to be angular and somewhat harsh. Larger aggregate might have been advantageous in further reducing shrinkage properties. However, suitable larger aggregate is not locally available. Air entrainment and superplasticizer were used to enhance and prolong workability. Only chloride-free admixtures are permitted to minimize the potential for corrosion of steel reinforcement. The concrete was supplied by an off-site batch plant over 16 km (10 miles) distant from the construction site. This extended supply line was a reason for serious concern in obtaining a satisfactory, uniform product with reliable and timely delivery, considering potential for traffic tie-ups and high temperature summertime conditions.

Slag (GGBS) was found to be beneficial in lowering heat evolution, reducing permeability and improving workability. Van Schaik (3) reports chloride permeability as reduced by a factor of 5 using a 30 percent cement/70 percent slag mix when compared with a 100 percent cement mix.

Flyash was found to be helpful in reducing shrinkage as well as improving workability, cohesiveness and resistance to sulfate attack. Slag and flyash together also help to reduce the potential for early thermal cracking by lowering and delaying the peak hydration temperature and by slowing the post-peak cooling process.

The runner-up mix contained 30 percent cement and 70 percent slag with no flyash and exhibited very similar physical test properties to the optimum mix which was chosen because of superior overall workability and cohesiveness.

The Test Wall is 8.6 m (28 feet) in height, 0.6 m (24 inches) in thickness and 18.3 m (60 feet) in length and includes zones of three different concrete mixes including the design mix selected. It was completed in January, 1991, and is periodically inspected for cracking or other changes. Core samples were taken after 3 months and subjected to petrographic examination by CTL. The design mix matrix was found to be excellent with very little indication of incomplete hydration. It is planned that the Test Wall remain permanently in place providing a long-term source of sampling and testing to determine the rate of degradation continuing even after permanent closure of the burial ground estimated to occur around the year 2020.

## CONCRETE PROPERTIES

The minimum required compressive strength of 2.758 x $10^7$ N/$m^2$ (4000 psi) at 90 days was easily achieved. The strength gain is most dramatic between 7 and 14 days. Compressive strengths at various ages are as shown in Table I.

The peak hydration temperature was generally reached on the fifth day except during very cold weather. The peak

### TABLE I

Compressive Strength of Concrete at Various Ages

| | Median Strength | | Strength Range | |
|---|---|---|---|---|
| Age - Days | N/$m^2$ x $10^7$ | (psi) | N/$m^2$ x $10^7$ | (psi) |
| 7 | 1.034 | 1500 | 0.483-1.724 | 700 - 2500 |
| 10 | 1.862 | 2700 | 1.379-2.413 | 2000 - 3500 |
| 14 | 3.103 | 4500 | 2.758-3.448 | 4000 - 5000 |
| 28 | 3.930 | 5700 | 3.448-4.482 | 5000 - 6500 |
| 56 | 4.482 | 6500 | 4.137-5.171 | 6000 - 7500 |
| 90 | 4.964 | 7200 | 4.482-5.654 | 6500 - 8200 |

temperatures and times to peak are summarized in Table II. After peaking, the concrete cooled to ambient temperature at a rate of approximately 1.7°C (3°F) per day. This generally resulted in full dissipation of heat of hydration at a concrete age of approximately 10 to 12 days. The insulation provided by plywood forms plus insulating blankets limited the temperature differential between interior and exterior in most instances to less than 2.8°C (5°F) and in every instance to less than 5.6°C (10°F).

By comparison, ordinary Portland Cement concrete generally has a much higher peak hydration temperature, e.g., 52° - 56°C (125° - 150°F) internally, at much earlier age, would cool at a much greater rate, and would gain strength more rapidly for the first few days but have a lower strength after approximately 10 days. Potential for early thermal cracking is significantly increased with ordinary Portland Cement concrete in those situations where forms are stripped early and curing water applied causing rapid surface cooling.

## DURABILITY

In planning for a structure of maximum durability, several factors are of paramount importance. A proper concrete mix is essential, of course. However, also of great importance are such factors as structural design details, construction methods, and quality control at both the batch plant and the construction site.

### TABLE II

Peak Hydration Temperatures of Concrete

| Mean Ambient Temperature | Range of Peak Concrete Hydration Temperatures | Approximate No. of Days to Peak |
|---|---|---|
| 7.2° - 10.0°C<br>(45° - 50°F) | 18.3° - 23.9°C<br>(65° -75°F) | 7 - 12 |
| 10.0° - 12.7°C<br>(50° - 55°F) | 23.9° - 29.4°C<br>(75° - 85°F) | 5 - 10 |
| 12.7° - 18.3°C<br>(55° - 65°F) | 29.4° - 35.0°C<br>(85° -95°F) | 5 -8 |
| 18.3° - 23.9°C<br>(65° - 75°F) | 35.0° - 37.8°C<br>(95° - 100°F) | 5 -7 |
| 23.9° - 29.4°C<br>(75° - 85°F) | 37.8° - 40.6°C<br>(100° - 105°F) | 5 |
| 29.4° - 35.0°C<br>(85° - 95°F) | 40.6° - 43.3°C<br>(105° - 110°F) | 5 |

A long-recognized major influence on concrete durability is its permeability. Low permeability is a pre-requisite for high durability concrete. Low permeability is in turn caused primarily by low water-cement ratio, proper cement type and content, proper compaction (vibration) and proper curing. Slag-cement concrete very similar to that developed for the SRS vaults was found to have a permeability to chloride penetration five (5) times less than for ordinary Portland Cement concrete (2,3).

High durability concrete cannot be achieved with proper design and material selection alone. It is also imperative that construction be of high quality and fully recognized as such by the project criteria. Other than high-quality, low-permeability concrete, and adequate cover for corrosion protection of steel reinforcement, the major durability concern is for the control of cracking.

Corrosion protection for reinforcement is provided by .060 m (2 1/2 inches) of cover with high-quality, low- permeability concrete. The concentration of chlorides in the SRS soils and environment is very small so there is no justification for epoxy coated reinforcement. Moreover, recent observations, particularly in Florida and mostly unpublished, indicate a noticeable increase in shrinkage cracking where epoxy coated reinforcement is used.

The maximum corrosion protection in such a mild chloride exposure is provided by the high pH, passivating zone provided naturally by high quality, low permeability concrete. For long-life structures exposed to the elements for several years before covering with earth, SRS vault concrete surfaces are coated to protect against carbonation attack.

In the design of the Eastern Scheldt Storm Surge Barrier (2,3) elimination of cracking was considered to be the greatest single factor in achieving a service life of 200 years in an aggressive, high chloride exposure. Walton, et al. (4) indicates that a future NUREG publication will assess the impact of cracking on concrete durability.

## CRACKING

The most important factors affecting cracking in concrete members 0.46 m (18 inches) or more in thickness, i.e., mass concrete, are the volume changes resulting from thermal and moisture changes. Other volume changes such as alkali-aggregate expansion are not considered of primary importance. Neither is flexural stress in properly reinforced members. References 8 and 9 discuss in detail the phenomena associated with cracking. Particular emphasis therein is placed on the need to reduce restraint to volume change and to control peak concrete temperatures.

Vault walls are typically 0.6 m (24 inches) thick and 7 to 9 m (23-29 feet) high. Thicknesses for roofs and base slabs are from 0.75 to 1 m (30 to 36 inches). Slab-on-grade floors are 0.3 m (12 inches) thick.

Reference 8 states "The change in volume can be minimized by such measures as reducing cement content, replacing part of the cement with pozzolans, pre-cooling, post-cooling, and insulation to control the rate of heat absorbed or lost." It also stresses the need to reduce restraint to volume change as well as reducing the rate at which volume change takes place such as when cooling after hydration.

The need to minimize drying shrinkage has long been recognized as of major importance in controlling cracking. Major steps required to minimize drying shrinkage cracking *include* reducing water content to a minimum, an adequate system of contraction joints, proper reinforcement, moist curing and protection against rapid drying shock.

Volume change due to thermal changes, drying shrinkage or other cause would not result in cracking if there was no restraint. However, all concrete elements are restrained to some degree, either externally by the adjacent footings, walls, foundation soil or rock, etc. or internally by different parts of the element itself.

Internal restraint is caused by surface cooling while the interior temperature remains high. When this thermal differential exceeds 35°F, there is high likelihood of surface cracking. Once begun, these cracks propagate much more rapidly under subsequent temperature drops or drying shrinkage.

Major design or construction measures incorporated to minimize cracking in the vaults include the following:

1. Contraction control joints are provided at spacings no greater than 8.25 m (27 feet). Joints are detailed and constructed with great care to assure proper performance. At least 50 percent of reinforcing steel is interrupted at the joint. For best performance, the bars are terminated only .025 m (1 inch) from the joint. The joint section is further purposefully weakened by plastic embedments to promote a controlled crack.
2. Walls are poured full height in a single lift to minimize base restraint. Footings and mats are protected from drying shrinkage until each respective wall is constructed. This suggests that the footings should not be poured too long before walls are constructed and should be covered until then.
3. Reinforcing is uncoated in lieu of epoxy coated to enhance concrete bonding and ability to control shrinkage cracks. It is felt that the lack of chemical bond of concrete to epoxy reduces the ability to effectively control initial cracking.
4. Form ties for walls include a threaded rod interior section which is left in place after forms are stripped to reduce the "stress riser" effects that are present when removable tapered ties are used creating open thruwall holes.
5. Wall forms are left in place for seven (7) days minimum to enhance curing, provide necessary strength, and to protect against premature cooling or drying. Form removal is followed immediately by application of curing membrane to prevent rapid drying and to prolong the curing period.
6. Insulating blankets are provided over forms or slab/mat surfaces to minimize temperature differential within the concrete and thereby to minimize internal restraint. Insulating also delays the post-hydration cool-down providing more time for strength gain. Temperature differentials from interior to exterior are monitored for at least 14 days by embedded thermocouples to confirm gradual cool-down.

Concrete cracks when the stress exceeds the tensile strength. Since the volume change stress is caused by cooling or by drying shrinkage operating on a restrained element, it is very desirable to:

a. Reduce restraint by measures 1, 2, 5 and 6, above.
b. Reduce the shrinkage volume-change tendency by minimizing the water content.
c. Reduce the thermal volume change tendency by minimizing the cement content, using flyash, slag and low-heat cement, by pre-cooling the mix, and by being careful not to cure the concrete with cold water until the surface has cooled sufficiently.
d. Delay cool-down and/or drying out (by measures 5 and 6 above) while the concrete is gaining strength. This is most important during the first 14 days.

## WATERSTOPS

Contraction control joints promote controlled cracks which are sealed by waterstops as are construction joints. Waterstops for vaults with a required minimum service life of 100 years are of High Density Polyethylene (HDPE). Waterstops for other vaults are of PVC because of its ready availability and lesser cost. Rigorous quality control during construction is required to accurately locate and anchor these along with other joint elements during pouring.

## RESULTS

Results to date have been excellent. All surfaces have been inspected at monthly intervals for presence of cracks and other defects. Foundation mats and floor slabs are completely free of uncontrolled cracks. Over 600 m (2000 linear feet) of walls have been constructed and only four (4) wall cracks (vertical) have been noted thus far. Two (2) of these occurred within 0.1 m (4 inches) of a control joint and were likely due to termination of reinforcing steel too far from the joint. The other two (2) cracks in walls occurred along vertical rows of form ties and were probably due to base restraint caused by failure to protect and prevent premature drying shrinkage of the strip footings. Two (2) minor cracks were also noted in the 300 m (1100 linear feet) of wall strip footings constructed thus far.

The four (4) wall cracks will be grouted with flexible foam to assure their watertight integrity. A small number of surface discontinuities were also noted in walls. These were generally 0.3 to 1.31 m (1 to 4 feet) in length, and either horizontal or inclined less than 45°. They were found to be very shallow, ie., less than 0.01 m (1/2 inch) deep and probably due to plastic settlement of the fresh concrete. They were considered to be of no structural significance and do not require grouting.

Very minor honeycombing was noted and surface "bugholes" were well within acceptable limits. The precooling of the concrete during batching plus the use of extended life superplasticizer negated the lengthy (35-45 minute) travel time from batch plant to site so that lack of uniformity of delivered concrete was not a major problem. Approximately 10 percent of the truckloads required additional superplasticizer to be added at the jobsite to maintain specified slump.

The contraction control joints worked very well even where pour length reached 45 m (150 feet) without an intermediate construction joint. However, a few problems were noted in the initial stages of construction requiring a stronger emphasis on the necessity of careful attention to all details of joint construction.

## CONCLUSIONS

An assessment of all of the available data thus far indicates that the vault concrete is exceptionally sound and almost crack-free. The low-to-very low peak hydration temperatures combined with the gradual cool down after hydration suggest a minimum cracking potential from thermal stresses both initially and over the life of the structures. Although volume change due to drying shrinkage is inevitable, it has been reduced considerably below that expected with ordinary Portland Cement mixes. Of perhaps greater importance is the fact that the construction and protection practices employed delayed the onset of drying shrinkage until the concrete had obtained high strength and much improved resistance to cracking from drying shrinkage.

Even though high compressive strength was not a requisite for the concrete, the high strengths that actually resulted are very re-assuring that the finished structures are also very sound and durable.

It is hoped that on-going surveillance on not only the Test Wall but the vault structures themselves will be conducted to confirm the soundness of the materials and designs employed. Data for rate of carbonation attack, especially, should prove of great value in future evaluation of long-life containment facilities.

## REFERENCES

1. Requirements of Hazardous Waste Landfill Design, Construction and Closure, US EPA/625/4-89/022 (1989)
2. T. MONNIER AND J. M. VAN GEEST, "Durability Testing", Proceedings of the Delta Barrier Symposium, Rotterdam (1982)
3. H. VAN SCHAIK, "Durability and Corrosion," Proceedings of the Delta Barrier Symposium, Rotterdam (1982)
4. J. C. WALTON, et al., "Models for Estimation of Service Life of Concrete Barriers in Low-Level Radioactive Waste Disposal," NUREG/CR-5542 (1990)
5. G. F. FAGERLUND, "Service Life of Concrete Structures, " Proceedings of Contemporary European Concrete Research, Stockholm (1981)
6. G. SOMERVILLE, "The Design Life of Concrete Structures," Paper to Institution of Structural Engineers, London (1986)
7. R. H. DENSON, et al., "Recommendations to the NRC for Review Criteria for Alternative Methods of Low-Level Radioactive Waste Disposal, Below-Ground Vaults", NUREG/CR-5041, Vol. 1 (1989)
8. "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete", ACI 207.2R, ACI Materials Journal (May-June 1990)
9. "Control of Cracking in Concrete Structures", ACI 224R-80 (Rev. 1984), ACI Manual of Standard Practice
10. R. F. FELDMAN, "Proceedings of the Fifth International Symposium on Concrete Technology", Monterry (1981)

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