Resources and Required Reading:
Concrete Pipe Handbook, Chapter 6 Durability Considerations
You Should Know No. 119 – Fire in Storm Sewer is Not Unusual – Which Pipe to Choose?
You Should Know No. 128 – A Case in Point
You Should Know No. 133 – Abrasion Affects Durability in Some Drainage Pipe
You Should Know No. 140 – Should Laser Video Inspection Be Required?
Design Data 25 - Life Cycle Cost Analysis
ACPA Brochure: Least Cost Analysis, Resource #07-130
ACPA Brochure: The Infrastructure is Collapsing Brochure, Resource #07-128
Buried Facts – Pipe Material Durability
CP Info – Precast Concrete Pipe Durability
CP Info – Cracks in Installed Reinforced Concrete Pipe
ASTM C76 - Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe
ASTM C33 - Standard Specification for Concrete Aggregates
ASTM C150 - Standard Specification for Portland Cement
ASTM C1131 - Standard of Practice for Least Cost (Life Cycle) Analysis of Concrete Culvert, Storm Sewer and Sanitary Sewer Systems

Overview
This course covers the durability and design life issues that can affect reinforced concrete pipe. If engineered properly, reinforced concrete pipe system will provide a 100-year plus service life. It is important to understand the issues that can affect the service life of reinforced concrete pipe to ensure that the service life of the pipe is achieved. If a system is not engineered correctly and conditions exist that reduce the service life of reinforced concrete pipe are not addressed, they can lead to pipe failure. If a pipe fails due to existing conditions that were not adequately addressed, reinforced concrete pipe will more than likely receive part of the blame regardless if it is warranted or not.

Meaning of Durability:
- Webster’s Dictionary defines durable as “able to exist for a long time without significant deterioration”
- Durability is defined by the CSA (Canadian Standards Association) as, “the ability of a building or any of its components to perform its required function over an intended period of time.”
- The American Concrete Institute (ACI) Committee 201 Durability of Concrete defines durability of Portland cement concrete as, “the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration.”

Durability of a pipe material is concerned with life expectancy, or the endurance characteristics of the material. It should be noted that a material might indeed last 2000 years; however just
because the material still exists, does not mean that it is still capable of performing its engineering purpose.

**Durability of a pipe system** is the capability of the pipe system to continue to perform its engineering (structural and hydraulic) functions for an economically acceptable period of time.

When considering durability in respect to a pipe or pipe system, one should consider that for a pipe system:

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\text{Durability} = \text{Economic} + \text{Structural} + \text{Hydraulic Performance}
\]

**Proven Record of Durability**

While no material at this time has proven to be completely inert to chemical action and physical deterioration, concrete under normal conditions has a very long life. Concrete pipe has a proven record of performance.

The Cloacae Maxim or “Greatest Sewer” initially constructed around 600 BC by the Romans, was one of the world’s earliest systems built to drain marshes and remove waste from Rome. While not precast concrete pipe, Roman’s used natural cement concrete to create conduits in Rome, parts of which are still in use today and in excellent condition after 2000 years of service.

The oldest known concrete sanitary sewer in the United States is a 6-inch diameter pipe installed in 1842 in Mohawk, New York, which is still in operation today.

**Why Durability Matters?**

Since most of the reinforced concrete pipe that is installed is part of a bigger engineered system, the pipe component of the system should be designed to last as long as, or longer than the designed service life of the project. With the Federal Highway Administration program Highways for Life pushing for a design life of 50 years for pavements and 100 years for bridges; culverts and storm water systems should be designed so that their service life should not adversely impact pavement, bridges or any other component of an engineered highway system.

**Factors Influencing Concrete Durability**

**Concrete Compressive Strength**

For reinforced concrete pipe, compressive strengths normally range from 400 psi to 6000 psi and are required by ASTM standards. The compressive strength relates to the structural aspects of concrete pipe and not directly to the durability of the material and are attained in a short period of time. While most concrete design strengths refer to 28 day compressive strengths, it is not uncommon for the 28 day test to substantially exceed specified design strengths.

Compressive strengths are a function of aggregates, cement, mix design, manufacturing process and curing procedures. Higher strength usually corresponds to overall higher quality, greater abrasion resistance, lower permeability and greater resistance to weathering and chemical attack.

**Density**

The density of reinforced concrete pipe ranges from 145 to 155 pounds per cubic foot. The higher densities are achieved by greater consolidation of concrete, higher specific gravity aggregates, or by a combination of the two. Usually the higher the density, the greater the concrete “durability.”

**Absorption**
Absorption is an indicator of the pore structure and used to check the density and imperviousness of the concrete. Like the compressive strength, the absorption can be greatly influenced by both the aggregate and the manufacturing process. ASTM C 76 specifies a maximum allowable absorption of 8.5% or 9%, depending on the test method used, for reinforced concrete pipe.

**Cement Content and Type**

Typical minimum cementitious content allowed by ASTM C 76 is 5 sacks (470 lbs) per cubic yard of concrete. Note: cementitious material is sometimes referred to in units of sacks, (1 sack = 94 lbs.). Type II cement is typically used in the manufacture of reinforced concrete pipe. The key to proper cementitious content is proper design of the mix considering the material properties, manufacturing and curing process. Usually increased cement content relates to lower adsorption, higher compressive strength and increased resistance to weathering, freeze-thaw and some chemical environments. However, increased cement content can also increase the probability of shrinking and cracking.

**Aggregate Characteristics**

Both course and fine aggregates for reinforced concrete pipe meet the requirements of ASTM C33, except for gradation. Gradation is established by the pipe manufacturer to provide compatibility with a particular manufacturing process to achieve optimum concrete strength and control permeability.

**Low Water/Cement (W/C) Ratios**

Low (W/C) ratios are one of the trademarks of quality concrete pipe with a corresponding high compressive strength as a function of the low W/C ratio. Typical precast concrete pipe have W/C ratios that range from 0.33 to 0.45, with 0.52 being the maximum allowed by ASTM C 76. Low W/C ratio results in reduced permeability and increased strength.

**Concrete Cover over the Reinforcement**

Minimum cover over the reinforcing steel is specified in ASTM standards. These minimum covers represent a balance between structural efficiency and durability. Assuming that both structural adequacy and proper crack control are achieved, greater durability is provided against a variety of aggressive conditions by a thicker concrete cover.

**Admixtures**

A wide range of admixtures have been developed to enhance the engineering properties of concrete pipe. Admixtures can provide some of the following benefits: adequate workability while reducing water in the mix; retarding or accelerating the setting time of the concrete; reducing adherence of concrete to forms used in the manufacturing process and increase freeze-thaw and weathering resistance.

**Chemical and Physical Factors**

**Fire**

Fire can melt and even burn other piping materials such as metal and plastic, but not concrete pipe.

**Acids**

When in contact with Portland cement concrete, acid will attack the exposed surface and be neutralized by the alkalinity of the concrete.

*Two* types of possible acidic attacks:
Biochemical which occurs in a sanitary sewer. The acid involved is always sulfuric (H2SO4) and the attack is confined to the interior, unsubmerged perimeter part of the pipe.

Effluents that are acidic in nature. Attack is confined to the wetted interior surface of the pipe.

Sulfates
Sodium, magnesium and calcium sulfates in soil, groundwater or effluent can react with Portland cement. This primarily occurs in alkali soils of the west/southwest and mostly affects cast-in-place structure.

Chlorides
The most significant action of chlorides is corrosion of steel in reinforced concrete. The concrete protects the embedded steel against corrosion under conditions that would be highly corrosive to bare steel.

Freeze-Thaw and Weathering
The damage is caused by water penetrating into concrete interstices and freezing, which generates stresses in the concrete. The stresses can cause cracking if the concrete does not have sufficient strength to resist the introduce stresses.

Velocity Abrasion
This is not caused by velocity alone, unless approach velocities of 40 feet per second or greater are experienced at which point cavitation can occur, unless the surface is smooth and internal offsets at joints are closely controlled. Velocity and bed loads combined can have an abrasion impact if not engineered correctly.

Lining and Coatings
Linings and coating can be used where there is severe exposure to an acidic environment or elevated chlorides. Some alleviation of exposure to elevated levels of acids or chlorides can be completed through engineering of the system to minimize acid generation or limit exposure to corrosive environments.

Thin coatings that are generally brushed on are typically epoxies and bituminous (i.e. coal tar & asphalt) materials. Bituminous materials can be useful for exterior surface sealing against chlorides intrusion.

Thick linings and coatings will generally provide better long term protection. The two types of basic materials used are epoxy resin mortars (generally mechanically applied) and polyvinyl chloride sheets (placed around the inner pipe form prior to placement of the concrete).

Alkali Silica Reaction (ASR)
ASR occurs when aggregates used in concrete contain silica that reacts with the alkalis in the cement. The reaction of the silica and alkalis produces a silica gel that forms around the aggregates. The gel reaction product will absorb available water and will expand or swell, causing expansive pressures in the concrete. The expansive pressure can lead to cracking and ultimately deterioration of the concrete.

Methods for Controlling or Minimizing ASR:

- Entrained air in the concrete can aid in preventing ASR
No potential for ASR if concrete is dry – Low W/C Ratio will reduce permeability and reduce movement of moisture and alkalis within concrete

- Use of non-reactive aggregates
- Use of Low alkali cements (<0.6%)
- Additives (Lithium Compound)

**Delayed Ettringite Formation (DEF)**
DEF occurs when concrete is cured at extremely high temperatures (such as 190° F) and is exposed to wetting/drying conditions. Water that has penetrated the concrete reacts with the existing sulfurs to create a crystalline structure that will expand, causing cracking and ultimately deterioration of the concrete.

Methods for Controlling or Minimizing DEF:
- Entrained air in the concrete can aid in preventing DEF
- Curing concrete at 140°F (60°C) or lower have a low probability of DEF deterioration (The maximum curing temperature recommended by ACI is 160° F)

Cracks caused by ASR usually “radiate” outwards from the aggregate, and frequently result in a crack running right through the aggregate. The cracking of the aggregates is what differentiates ASR cracking from DEF cracking.

**Significance of Cracking**
Reinforced concrete pipe, like other reinforced concrete structures, is designed to crack. Reinforced concrete pipe is very strong in compression, but lacks any real tensile strength. Reinforced concrete pipe design accommodates the high compressive strength of concrete and the high tensile strength of steel. As load on the pipe increases and the tensile strength of the concrete is exceeded, cracks will form as the tensile load is transferred to the steel. For nearly 70 years the 0.01-inch crack has been used as a service load design criteria. The presence of a 0.01-inch crack does not represent failure, but rather an indication that the concrete and reinforcement are working together, as intended. The 0.01-inch crack width has absolutely no relation to the size of a crack that should be considered a structural failure of an installed concrete pipe.

RCP also possesses the ability to perform “self-healing” and seal small cracks. *Autogenous healing*, is quite simply the ability of the reinforced concrete pipe to heal itself. Autogenous healing occurs when there is moisture present either on the inside of the pipe or the soil side of the pipe. The concrete extrudes calcium hydroxide, and when exposed to the atmosphere is then converted to calcium carbonate (limestone) and acts to seal the crack. The resulting self-healing process creates a calcium carbonate monolithic structure in place of the crack.

**Least Cost Analysis (LCA)**
Material selection and development of appropriate design criteria are essential to stretching construction budgets while still creating a project that will last past it design service life. When looking at a project’s materials, an engineer should consider the *durability and economics* of the materials used. The least cost of a project is the lowest lump sum of money that would have to be set aside at the start of a project to cover all expenditures during the entire life cycle of the project. The amount set aside is affected by both interest and inflation and must be analyzed to calculate the least cost. The following factors should be considered during a Least Cost Analysis:

- Project Design Life
- Material Service Life
• First Cost
• Interest (Discount) Rate
• Inflation Rate
• Maintenance Cost
• Rehabilitation Cost
• Replacement Cost (Direct & Indirect)
• Residual Value

Least Cost Analysis is necessary when considering and comparing alternative materials that have different service lives, maintenance costs and replacement costs for capital projects. Pipeline, culverts and related drainage material are essential components of our infrastructure and material selection should be made after considering the durability and economics of a material through a Least Cost Analysis and not on a material’s initial cost.