

Precast Concrete Pipe Durability

Design methods for buried pipe are fairly well established, but durability, historically, has not been given proper consideration. Determining a project design life and the durability, or service life, of a pipe are considerations as significant as its hydraulic and structural functions. The definition of a durable pipe contains three variables that must be evaluated; required performance, pipe properties, and service conditions.

This C.P. Information reviews the significance of various physical and chemical factors which may be aggressive to concrete pipe; reviews the significance of pertinent service factors and concrete pipe properties, and durability design and performance of concrete pipe.

Introduction

Durability, or service life, of a pipe material is as equally important as its ability to perform intended structural and hydraulic functions. The capability of the pipe to continue to perform satisfactorily for an economically acceptable period is a fundamental engineering consideration. Unfortunately, predictions of durability cannot be made with the same degree of precision as can structural and hydraulic performance, consequently, durability is not accorded adequate consideration. Durability is concerned with life expectancy, or the endurance characteristics of a material or structure. Much research has been directed to the durability of some pipe ma-

terials, but the varying nature of climate, soils and geology, fluid impurities, construction materials, and the construction process itself have prevented the development of a systematic and practical theory for predicting performance.

The problem has been compounded by the assumed requirement that pipe must last almost indefinitely. The U.S. Bureau of Reclamation¹ defines a durable pipe as one that will withstand, to a satisfactory degree, the effects of service conditions to which it will be subjected. This definition contains three variables that must be evaluated; the pipe, the satisfactory degree of performance, and service conditions.

At the present time, there is no known material completely inert to chemical action and immune to physical deterioration. Concrete, under what might be considered normal exposure conditions, has a very long life.

Concrete pipelines have a history of excellent durability, and it is unlikely this record will change. Pipelines are beneath the ground where temperatures have very little variation, where atmospheric exposure is either not present or is greatly reduced, and where the materials in close proximity to the pipe may be nonaggressive. Laboratory test results, and damage records for cast-in-place concrete pavements and structures that have been exposed to atmospheric conditions, should not be related to buried precast concrete pipe unless it is determined that comparable conditions exist. Improper application of data could lead to overdesign and excessive cost.

Aggressive Factors And Significance

The specific physical and chemical factors which can be aggressive to concrete pipe and which collectively account for practically all perceived durability concerns that could be encountered in traditional applications of the product include freeze-thaw and weathering, abrasion, acids, sulfates and chlorides. Conditions severe enough to result in actual durability problems for concrete pipe are, however, quite rare, especially when compared to an estimated installation rate of 10,000 miles per year for the last four decades.

Freeze-Thaw/Weathering

Freeze-thaw damage is caused by water penetrating into the concrete and freezing, which generates expansion stresses and disrupts the concrete if it does not have sufficient strength to resist the expansion stresses. Severity of exposure is usually described by the frequency of freeze-thaw cycles. Atmospheric exposure usually accompanies freeze-thaw action, which complicates the situation. Thus, instead of a pure freeze-thaw situation, thermal stresses and evaporative surfaces with concentration effects and crystallization of various soluble salts in the pore structure could combine to provide an accelerated weathering effect.

Normally, concrete pipe is not exposed to this combined set of conditions. When it has been, however, its performance has been ex-

cellent, primarily due to the high density and quality of the concrete. If the pipe is not buried, weathering could be serious enough in some areas to warrant sealing the surface with a barrier coating.

The high strength, low water-cement ratio concrete of precast concrete pipe inherently has excellent resistance to freeze-thaw forces.

Abrasion

Effluent velocity, by itself, does not create problems for concrete pipe within the ranges normally encountered. Below velocities of 40 feet per second, the severity of velocity-abrasion effects depends upon the characteristics of the bed load and the frequency of flows capable of moving the bed load through the pipe at abrasive velocities. Above velocities of 40 feet per second, cavitation effects can occur unless the wetted surface is smooth. Bed loads are usually more of an engineering flow problem than a question of pipe abrasion, particularly in a sanitary or storm sewer system, and can be controlled by proper design. Increasing the compressive strength of the concrete, and the specific hardness of the aggregates, increases abrasion resistance.

Acids

Acids will attack most materials. Acid attack of concrete is a surface attack, in which the acid is neutralized by the concrete alkalinity, so that without acid replenishment, the reaction stops. Continuous replenishment of acid with a pH below 5.0 is considered aggressive and below 4.0 is highly aggressive to buried concrete pipe.

Exterior acid attack, although chemically the same as an interior attack, involves a completely different environment. When an acidic soil or groundwater is encountered, its effect on concrete is governed by pH, total acidity, groundwater conditions, and backfill material. Total acidity is the amount of acid available to attack the pipe. As an example, a total acidity of 25 milligrams per gram of soil equivalent with a pH of five would indicate a potentially aggressive situation, and a comprehensive analysis of the site and countermeasures should be required. Such aggressive situations occur very rarely naturally, and are generally manmade, such as sanitary landfills and industrial waste disposal areas.

In an installation with no movement or slow movement of groundwater, the acid in contact with the

concrete pipe will be neutralized and form a neutral zone which stops further corrosion. For installations with significant groundwater flow, limestone backfill has been successfully used as a neutralizing barrier to prevent corrosion of the concrete pipe; and, also, an impermeable backfill material, such as clay, has proven to be an economical and successful barrier which prevents flow from reaching the concrete pipe.

In the pipe interior, acid attack can occur from two sources. The first source is the hydrogen sulfide mechanism, which may occur in sanitary sewers. Under the right conditions, sewage can generate hydrogen sulfide gas which may be converted to sulfuric acid on the unsubmerged crown of the pipe. Several scientific breakthroughs now enable the generation of hydrogen sulfide to be controlled in existing sewers and predicted in new sewers; and, in new sewers, if the problem cannot be alleviated by proper system design, then the concrete pipe can be designed to be sufficiently resistant to acid attack so as to meet the required project service life^{2,3}. Acid attack resulting from sulfuric acid generated by hydrogen sulfide gas in sewers is limited to the unsubmerged interior of the pipe, and is affected by a number of factors, including effluent properties and velocity, and total alkalinity of the pipe^{2,3}.

Note: Confusion prevails regarding sulfates, sulfides and sulfuric acid. Potentially aggressive sulfates are the soil alkalies found in dry western areas. Sulfates must penetrate the concrete and be concentrated by evaporation to cause disruption. The use of Type II or Type V cement is recommended to make cast-in-place concrete more sulfate resistant. Sulfides in sewage do not attack concrete. Hydrogen sulfide gas does not attack concrete, but it does attack iron, steel and other metals, and is toxic and flammable. Under favorable conditions, hydrogen sulfide gas is converted to sulfuric acid on the crown of the sewer pipe. Sulfuric acid attacks the surface of concrete, iron, steel and other materials. Type II and Type V



cements do not make concrete more resistant to acid attack, although they are erroneously specified as such by some agencies and engineers.

The second source of interior acids is the effluent. Occasionally, an effluent can contain some acid. In culverts, mine acid drainage could be a problem; in sewers, acids can be dumped in from a variety of sources. An acidic effluent will attack most pipe materials, and the area of attack is limited to the

total alkalinity, increased concrete cover, a barrier coating or lining, or any combination of these. Additionally, for exterior exposure only, the backfill material can be either of low permeability, so as to inhibit acid replenishment, or calcareous aggregate, so as to neutralize the acid. Table 1 summarizes evaluation procedures and possible countermeasures for interior and exterior acids. Neither Type II nor Type V cement will increase the resistance of concrete to acids.

Table 1: Acid Exposure Evaluation and Countermeasures

Exposure Condition	Evaluation Procedures	Countermeasures
Interior	<ul style="list-style-type: none"> • For potential biochemical problems in sanitary sewers, determine rate of acid development, if any • For acidic effluents, determine pH, including cyclic variations, as well as continuous or intermittent flow characteristics • Accurately determine pH and total acidity 	<ul style="list-style-type: none"> • Increase total alkalinity by use of calcareous aggregates • Increase concrete cover as sacrificial concrete • Use barrier lining
Exterior	<ul style="list-style-type: none"> • Evaluate installation condition from the standpoint of the potential acid replenishment 	<ul style="list-style-type: none"> • Increase total alkalinity by use of calcareous aggregates • Increase concrete cover as sacrificial concrete • Use low permeability clay backfill • Use calcareous backfill • Use barrier coating

pipe invert, or the submerged portion. In any case, in the United States, it is illegal to dump acid in a sewer or stream. Pretreatment is required and has successfully alleviated corrosion problems. Acid attack by acidic effluents is limited to the wetted perimeter, and is affected by pH, total acidity, effluent velocity, and total alkalinity of the pipe.

If acids are encountered, and cannot be alleviated by other countermeasures, for either interior or exterior acids, a precast concrete pipe can be produced with a higher

Sulfates

Sulfate problems have been almost exclusively limited to exposed cast-in-place concrete structures located in arid areas of North America with alkali soils. The U.S. Bureau of Reclamation has wide experience in these areas, and has developed general criteria for evaluating sulfate environments. The Bureau states, however, it has not found any sulfate problems in buried precast concrete pipe¹. The resistance of precast concrete pipe to sulfate attack is easily under-

stood in view of the Bureau's guidelines for preventing sulfate attack in exposed cast-in-place concrete, and the mechanism of sulfate attack. Besides use of Type II or Type V cement, and fly ash, the Bureau indicates sulfate resistance is increased by accelerated curing, high cement content, and low absorption - exactly the characteristics of precast concrete pipe.

Sodium, magnesium, and calcium sulfates in soil, groundwater, or effluent may be aggressive to concrete, if absorbed and concentrated by an evaporative surface in sufficient quantities within the concrete. The reaction of sulfates with certain concrete constituents results in expansive products which may disrupt the concrete. With respect to buried precast concrete pipe, sulfate problems are inhibited by a lack of the proper mechanism to concentrate sulfates in the concrete, and further inhibited by the high strength, low absorption properties of precast concrete. Table 2 lists the relative severity of various sulfate soil and water conditions. Table 3 summarizes the exposure conditions which must be present for a sulfate problem to exist and some recommended countermeasures.

Chlorides

The most significant aggressive action of chlorides is corrosion of steel in reinforced concrete. Such problems are highly visible as damage to bridge decks resulting from use of de-icing chemicals. Maintenance problems have also been encountered with reinforced concrete seawater structures, such as pilings and piers, because of chloride-induced corrosion of the reinforcement in tidal zones. Portland cement concrete protects embedded steel against corrosion under conditions that would be highly corrosive to bare steel.

Chloride ions disrupt the passivating action of concrete, which may allow corrosion of the reinforcement steel if oxygen is present. Research has established there is a critical chloride concentration at the concrete-steel inter-

Table 2: Degree of Sulfate Attack

Relative Degree of Sulfate Attack	Percent Water-Soluble Sulfate in Soil Samples	PPM Sulfate in Water Samples
Negligible	0.00 to 0.10	0 to 150
Positive ¹	0.10 to 0.20	150 to 1,500
Severe ²	0.20 to 2.00	1,500 to 10,000
Very Severe ³	2.00 or more	10,000 or more

¹Use Type II cement.
²Use Type V cement, or approved portland-pozzolan cement providing comparable sulfate resistance when used in concrete.
³Use Type V cement plus approved pozzolan which has been determined by tests to improve sulfate resistance when used in concrete with Type V cement.

face required for corrosion to occur, and that oxygen must also be present to support corrosion. The factors needed to induce corrosion will more readily occur under the following conditions; low quality concrete of high permeability and porosity, cracks, and the inclusion of calcium chloride in the concrete mix.

A number of conditions can reduce the severity of chloride attack. Increased concrete cover will normally extend service life but will not prevent eventual corrosion under severe exposure conditions. High quality concrete with low permeability, and the absence of cracks and voids, will also extend the life of reinforced concrete under severe exposure conditions but will not prevent eventual corrosion if the mechanism of chloride build-up continues. Under extreme exposure conditions, the use of barrier type coatings is probably the most effective alternative.

Seawater has approximately 20,000 parts per million of chloride. Many concrete pipe installations are completely immersed in seawater and are performing satisfactorily after many years. This is primarily due to low oxygen solubility in high chloride waters plus the extremely low diffusion rate of oxygen through the saturated concrete cover.

As with sulfates, to cause corrosion, chlorides must be in solution, permeate the concrete, be concentrated, and, also, have a ready sup-

ply of oxygen. There are no reports nor evidence of any chloride induced corrosion problems with buried precast concrete pipe. Again, this absence of problems is attributed to a lack of the proper mechanism to concentrate chlorides in concrete, a lack of oxygen, and the high strength, low absorption properties of precast concrete pipe.

Service Factors And Significance

There are a number of purely physical characteristics of the installation which directly and significantly influence the severity of ex-

Table 3: Sulfate Exposure Conditions and Countermeasures

EXPOSURE CONDITIONS	
■	Sulfates must be in solution
■	Hydrostatic gradient exists
■	Evaporative surface to produce concentration effect exists
COUNTERMEASURES	
■	Reduce C3A content of cement
■	Use accelerated curing
■	Increase cement content
■	Use pozzolans
■	Decrease absorption

posure to potentially aggressive factors.

Hydrokinetics

With water at equal pressure on both sides of a pipe wall, the concrete eventually becomes saturated, stability is reached, and there is no water movement through the pipe wall. With a differential pressure, the hydraulic gradient causes movement of water through the wall, but direction of flow is highly significant. If the aggressive water were on the side of low pressure, the movement of non-aggressive water through the wall would tend to mitigate any aggressive attack. In any case, with no exposure to the atmosphere, there is no concentration effect. With an evaporative surface condition, water movement is due to either hydraulic gradient or capillary action, and there would be a concentration at or near the evaporative surface of whatever chemicals are in solution. These considerations are not relevant to acid environments, since acid attack is confined to the exposed surface. They are significant, however, in evaluating severity of sulfate or chloride exposures.

Full Atmospheric Exposure - Full atmospheric exposure of an installation can be a severe service condition for concrete pipe. Depending upon climate and location, the exterior of the pipe could be subjected to freeze-thaw cycles and thermal stresses, and chlorides in coastal tidewater areas.

Partial Burial - Partial burial can be a severe exposure condition. Only a partially evaporative surface is provided, but the concentration effect is more complex since the source of salts or sulfates may be either the effluent or moisture from the ground entering the pipe wall through capillary action and moving toward the evaporative surface.

Full Burial - Buried pipe usually is not exposed to freeze-thaw or thermal stresses, and concentration effects are negligible. When installed above the water table, the

hydraulic gradient within the pipe wall of a partially filled pipe is toward the outside, and directly opposite when below the water table. The former condition is more critical for high sulfate or chloride-containing effluents, while the latter is more critical for aggressive groundwater. If the pipe is located between the minimum and maximum groundwater elevations, the hydraulic gradients would reverse on a cyclical basis.

Replenishment

Certain installation characteristics have particular significance in relation to acidic groundwater exposure. The high alkalinity of concrete pipe will immediately neutralize acid that comes in contact with it, and the reaction will result in some loss of concrete surface. For this reaction to continue, there must be replenishment of the acid at the concrete surface. The rate of this replenishment at the external surface of the pipe depends upon the relative permeability of the backfill and bedding material in the pipe zone, the location of the pipe with respect to the water table, and to the fluctuation of the water table. These latter characteristics are categorized as essentially quiescent, moderately fluctuating, and grossly cyclic.

A tightly compacted clay around the pipe will create a relatively impermeable zone, minimizing the potential rate of replenishment. Conversely, a permeable zone around the pipe will not impede the free movement of groundwater and tends to maximize the replenishment potential. The least potential problem with either type of zone exists when the pipe is above the water table. The situation most conducive to replenishment is a permeable zone between the high and low water table, with grossly cyclic groundwater fluctuations, where both horizontal and vertical movement of groundwater can take place. A calcareous backfill, such as limestone, can provide a highly alkaline barrier around the pipe and neutralize the acid before it can contact the pipe wall.

Significance Of Concrete Pipe Properties

The properties of concrete pipe that may influence its durability are compressive strength, density, absorption, water-cementitious material ratio, cement content and type, aggregates, and total alkalinity. Reinforcement cover and admixtures, also, may influence the durability of concrete pipe.

Concrete Compressive Strength

Concrete compressive strengths are a function of available aggregates and cementitious material, mix design, inherent characteristics of the manufacturing process, and curing procedures. Higher strength usually means overall higher quality, i.e., greater abrasion resistance, lower permeability, and greater resistance to weathering and chemical attack. Minimum concrete compressive strengths of 4,000, 5,000, and 6,000 pounds per square inch are required by ASTM standards for precast concrete pipe. The strengths relate to structural, not durability, considerations and are required at time of delivery, usually a short period of time. The 28-day compressive strengths are much higher, often exceeding 8,000 pounds per square inch.

Density (unit weight)

Concrete density of pipe ranges from 135 to 165 pounds per cubic foot. The higher densities are achieved by greater consolidation of the concrete, higher specific gravity aggregates, or by a combination of the two. Higher densities attained exclusively through the use of aggregates with higher specific gravity are not necessarily indicative of an improved level of concrete durability.

Absorption

Absorption is an indicator of the concrete pore structure. The orig-

inal application of the absorption test was in the early 1900's and for agricultural concrete drain tile, which was experiencing leaching action through the thin wall of this small diameter product. The absorption test proved to be an effective method for ensuring quality tile. Over the years, the absorption test has come to be erroneously considered by some engineers as a durability measure for impervious, thick wall concrete pipe.

Absorption by the cured concrete is influenced significantly by the absorption characteristics of the aggregates and the inherent characteristics of the manufacturing process. Hydration of the cement, which continues under the normally favorable installed pipe environment, further reduces the initial low absorption values for precast concrete pipe.

Water-Cementitious Material Ratio

Precast concrete pipe is produced with low water-cementitious material ratio concrete. The water-cementitious material ratio is so low for machine-made pipe that the concrete is said to have a negative slump, which means that water would have to be added before reaching a zero slump. Cast-in-place concrete mixes are designed with much higher water-cementitious material ratios, and placed with slumps ranging from two inches up to the maximum limited by size of the aggregate, resulting in relatively low strength concrete with excessive voids.

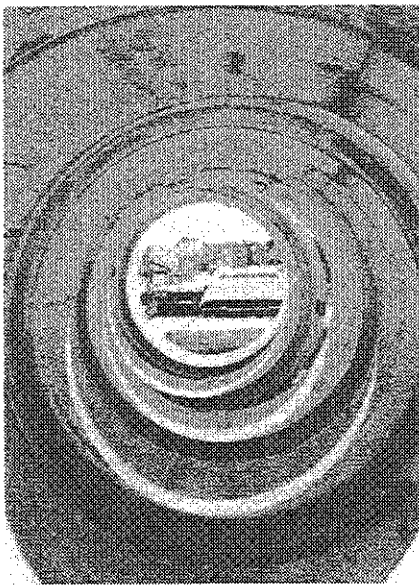
Cementitious Material

A high cementitious material content is normally used by precast concrete pipe manufacturers for a variety of reasons, but mainly because of manufacturing requirements. Other things being equal, increased cementitious material content leads to lower absorption, higher compressive strength and increased resistance to weathering, freeze-thaw, and certain chemical environments. Higher cemen-

titious material contents may also increase the probability of shrinkage cracking.

Cementitious Material Types

Both cement and fly ash are considered cementitious material. Combinations of cementitious materials used in the manufacture of concrete pipe may be portland cement only, portland pozzolan cement only, or a combination of portland cement and fly ash



wherein the proportion of fly ash is between 5 and 25 percent by weight of total cementitious material.

As specified in ASTM C150, Types I, II and V cements differ primarily in the allowable levels of tricalcium aluminate, C3A, content. C3A is the ingredient in cement which is principally involved in the disruptive expansion caused by sulfate reactions. Concrete made with lower C3A contents provides greater resistance to sulfate attack. Since cements are made from locally available materials, some Type I cements have less C3A than allowed by ASTM C 150 for Type V. Unless high sulfate resistance is required by the project specifications, or unless the type of cement is otherwise specified, concrete pipe is usually manufactured with

Type I cement. Type II and Type V cements, and low C3A contents, do not increase resistance of concrete to acid attack. Type II and Type V cements may not be readily available in all areas.

Portland blast-furnace slag cement or portland-pozzolan cement used in the manufacture of concrete pipe must meet the requirements of ASTM C595. If Type IP portland-pozzolan cement is used, the pozzolan constituent must be flyash, which cannot exceed 25 percent by weight of the total portland-pozzolan content.

Fly ash used in the manufacture of concrete pipe must conform to ASTM C618, Class C or Class F.

Aggregates

Aggregates used in concrete pipe must meet the requirements of ASTM C 33, except for gradation. Gradation is established by the pipe manufacturer to provide compatibility with a particular manufacturing process, to achieve optimum concrete strength, and to control permeability. Other things being equal, harder and denser aggregates produce concrete with greater abrasion resistance. Aggregates that react with cement are rarely, if ever, a problem with precast concrete pipe. Aggregate sources are carefully tested and selected by the individual pipe manufacturer, and any problems would be clearly evident in pipe stockpiles.

Alkalinity

Total alkalinity of concrete has a greater influence on the ability of concrete to resist acid environments than any other property. All portland cement concrete is alkaline and will react with acid. Total alkalinity is a measure of the total reactivity of any given mass of concrete. Concrete with a total alkalinity of 40 percent will react with and neutralize twice the volume of any specific acid as would the same mass of concrete with a total alkalinity of 20 percent. Concrete pipe made with an aggregate which in

nonreactive with acid, such as granite, will have a total alkalinity of 16 to 24 percent, depending upon cement content. Using calcareous aggregate, such as dolomite or limestone, can increase the total alkalinity to as much as 100 percent. Suitable sources of calcareous aggregates are not readily available in all geographical areas, and requiring their use could increase the cost of the pipe. All means of increasing durability for a specific aggressive environment should be evaluated by cost/benefit analyses.

Concrete Cover

Minimum concrete covers over the reinforcing steel are specified in ASTM standards. These minimum covers represent a balance between structural efficiency and durability. Assuming both structural adequacy and proper crack control, greater durability is provided against a variety of aggressive conditions by a thicker concrete cover. A modification of cover to increase durability, however, requires re-evaluation of the structural design of the pipe, and possible use of non-standard forms which could lead to increases in pipe costs.

Admixtures

Admixtures sometimes used by concrete pipe manufacturers include calcium chloride, air entraining agents and water reducing agents. Air entrainment agents, which are normally used only in wet-cast pipe, increase freeze-thaw and weathering resistance. Water reducing agents are used to provide adequate workability with drier mixes. With the same cement content, water reducing agents can reduce absorption and increase compressive strength. Calcium chloride, while accelerating setting time, tends to reduce resistance to sulfate attack. Chlorides are also related to potential reinforcement corrosion. The use of admixtures should be evaluated as to possible effects on durability performance.

research money is normally spent only on problems, 63 percent of the reports are concerned primarily with the deterioration and short service life of corrugated metal pipe; 28 percent of the reports cover multiple pipe materials; and five percent of the reports deal with only concrete. An updated bibliography of these reports is presented in Buried Fact No. 9, Bibliography - Pipe Material Durability.

In 1982, the Ohio Department of Transportation published a major report on the results of a ten-year study of more than 1,600 culverts in all areas of the state, which included 545 precast concrete pipe installations¹⁰. The environmental conditions in Ohio are relatively neutral, as are most areas of North America, and the soils and water do not possess any characteristics which would contribute to premature deterioration of pipe, except for a few areas with mine acid drainage problems. A look at the overall study indicates the excellent performance of concrete pipe. Of the 519 concrete culverts studied, only nine were rated in poor condition, 33 in fair condition and 477 in good to excellent condition. Of the nine in poor condition, one has been repaired, and repairs are contemplated for the other eight. An equation for predicting service life was developed for precast concrete pipe, which relates pH and

pipe slope to the number of years for the pipe to reach a poor condition. With the equation plotted graphically, Figure 1, it is readily apparent that a concrete pipe placed on an average slope of 1-1/2 percent, and installed in an environment with a pH of 7, will take about 1,000 years to reach a poor condition; and, in an aggressive environment with a pH of 4, the concrete pipe will last 100 years, which is generally longer than required currently for sewers and high type road facilities. As a comparative example, the Ohio report predicts that 16 gage corrugated steel pipe in an environment with a pH of 7 will last 20 years, and, in an aggressive environment with a pH of 4, 16 gage corrugated steel pipe is predicted to have a service life of only 3.5 years.

SUMMARY

Precast concrete pipe has served in an impressive fashion for well over 100 years, is being installed at a rate of about 1,000 miles a month in North America, and has experienced very few problems. These problems have been identified, related to very specific environments, and adequate countermeasures developed to alleviate the problems.

References

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