Concrete Pipe Association of Australasia Technical Paper

Durability of reinforced concrete pipe – the hard facts!

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ABSTRACT

Cracking of steel reinforced concrete pipe, according to Australian Standards, following American practices, allows for a limiting crack width for the pipe under a specified proof load as a criterion of performance in a non- destructive, quality control test. In America, and subsequently in Australia, the crack widths are set arbitrarily for the purposes of testing and do not represent limits, either from the aspect of structural adequacy or protection of the steel reinforcement.

When design or installation requirements have not been met on a particular project, cracks wider than those empirical limits may appear inside the pipeline. It then becomes necessary to consider:

- Is the cracking acceptable?
- Will the life of the asset be compromised?
- Are repairs required?
- If so, what form should they take?

Such considerations depend on the pipeline application, the consequences and risk of failure, and the effect on pipeline services life. The occurrence, function and significance of cracks in reinforced concrete pipe is often misunderstood leading to unnecessary concern by specifiers and designers.

The purpose of this paper is to emphasise the reasons why cracks occur, and to define the importance of the crack to long term durability of reinforced concrete pipe.

INTRODUCTION

Pipelines are vital to the health and functioning of our communities. A pipeline that is out of service, even for a short period of time, can cause extreme inconveniences and result in expensive consequences. As a result, the design, selection, manufacture and installation of reinforced concrete pipe is an extremely complex mechanism to ensure that the system performs in accordance to its importance.

Along with structural and hydraulic capacity, durability of reinforced concrete pipe is an important aspect to consider during the design stage. The principal stakeholders in the drainage infrastructure industry – designers, developers, consultants, manufacturers & installers, together with asset owners & managers, are all responsible for ensuring that reinforced concrete pipe durability is carefully considered with any project.

However, the durability of a concrete pipe cannot always be predicted with the same degree of precision as structural and hydraulic performance, as there are a number of factors outside the control of the designer that can affect the long-term performance of the asset. It is often thought that cracking in concrete pipe is the cause of poor durability, however this is not often the case.

DURABILITY PROPERTIES OF CONCRETE PIPE

The essential elements in the manufacture of durable concrete include:

- Sound and durable aggregates that are properly selected, tested and stored.
- Proper application of mix design principles.
- An effective water/cement ratio concrete.

- Efficient compaction, particularly in low workability mixes.
- Appropriate concrete cover, consistent with the size of the reinforcement bar or wire.
- Effective curing systems.
- Accredited quality assurance systems (manufacture and installation).

Reinforced concrete pipe in Australia is characterised by quality controlled manufacturers, who are capable of making a product that has low water/cement content with excellent compaction despite the low workability of the mix. The methods range from centrifugal roller compaction and heavy vibratory methods using dry mixes, to centrifugal spinning with slightly wetter mixes in which the water/cement ratio of concrete is reduced. The water/cement ratio of pipe concrete is always less than 0.4 (usually in the range of 0.3 and 0.35). The combination of high compaction levels and the low water/cement ratio means compressive strengths greater than 60 MPa are achieved. Thus the pipe is produced using a concrete mix that is highly impermeable to water and exhibits a level of durability unmatched by concrete elements produced in the casting process.

To demonstrate this using a typical example of how concrete passivity can be broken down, Beckett and Snow present the effect on durability that a low water/cement ratio can have. The relationship between rates of carbonation and water/cement ratio can be translated to corresponding strength grades. From these relationships, depths of carbonation for concrete exposed to the atmosphere (which is more severe than other conditions of exposure) are related to strength grade as shown in Table 1:

TABLE 1. DEPTH OF CARBONATION

Compressive Strength	**(MPa)**	32	40	50	**60**
	w/c	0.63	0.52	0.43	**0.37**
Carbonation Depth (mm)	after 50 yrs	29.3	17.7	6.2	**1.9**
	after 100 yrs	41.5	25.0	8.8	**2.7**

Carbonation depth for 50 MPa concrete is about one third of the depth at the same age for 40 MPa concrete. For 100 year design life, characteristic strength at least 50 MPa and any reasonable depth of cover, carbonation is not even a relevant mechanism. Nevertheless in environments where there is no other recognisable mechanism of deterioration AS 5100 allows only 5 mm reduction in cover for 50 MPa compared with 40 MPa concrete, and minimum cover at least 15 mm for 50 MPa. (Further effects are explained in this paper under "Cracks and the Corrosion Process").

IMPERMEABILITY

The low permeability of pipe concrete is important to its ability to resist reinforcement corrosion. Some aggressive agents weaken and degrade the concrete progressively from the surface, others penetrate into the concrete without necessarily reducing its strength but eventually neutralise the ability of the concrete to protect the reinforcement. Impermeable concrete also tends to retain moisture, which assists in continuing hydration, and is not affected by wetting and drying cycles.

An arbitrary acceptable limit of permeability for good concrete is 1.5×10^{-11} m/sec. Concrete pipe in Australia generally has a permeability of 1 to 10×10^{-14} m/sec. This is more than 10,000 times more impermeable than normal insitu concrete.

Strong and durable concrete is characterised by minimal void space created by the excess water – hence water absorption provides an index of the quality of concrete, related to both these properties. Permeability is particularly difficult to measure in dense, low water/cement ratio concrete, and so absorption is used for the purpose of quality control.

Australian Standards for concrete pipes use water absorption as the index of concrete quality, currently allowing a maximum of 8% for drainage pipe in non-aggressive environments and 6.5% for sewerage and pressure pipe, considered more demanding applications. These limits ensure high quality pipe concrete is achieved.

ALKALINITY AND AUTOGENOUS HEALING

Water in the pores of hydrated cement is highly alkaline, with a pH range of 12 to 13. The alkalinity of the pore water in concrete provides a double effect of providing a protective passivating layer around the steel reinforcement preventing corrosion, and creating a process known as "autogenous healing". In this process, water passing through the concrete section becomes saturated with calcium hydroxide. When exposed to carbon dioxide from the air, on the surface of cracks or voids, the calcium hydroxide is converted to the less soluble calcium carbonate. This substance precipitates out on to the crack surface and the slow deposition process eventually fills the crack or void in the concrete, effectively "healing" them!

Autogenous healing is common in buried reinforced concrete pipe due to the presence of moisture, either on the soil side or inside the pipe itself. These non-moving cracks, when healed autogenously, are impermeable and can yield a structure stronger than the original. One of the reasons is that the concrete pipe seals the crack with calcium-carbonate crystals formed when the carbon dioxide in the surrounding soil, air and water carbonates the free calcium oxide in the cement and the calcium hydroxide liberated by the hydration of the tricalcium silicate of the cement. The formula for this reaction is: $Ca(OH)_2 + CO_2 = CaCO_3 + H_20$

THE FACTS ABOUT THE CRACKS!

Steel reinforced concrete flexural members are typically designed on the basis of cracking in the concrete tensile zone, enabling the reinforcing steel to carry the tensile stress. With steel reinforced concrete pipe, flexural stresses are developed at the top and bottom inside surfaces and on the outside surface at the sides as a result of external vertical earth loads. In the load tests described in the Australian concrete pipe standards AS 4058, the cracking characteristic is used as a criterion for non-destructive quality control testing. Pipes are designed to withstand the specified proof load without developing a crack wider than a specified figure - most commonly 0.15 mm for 10 mm cover to steel.

The proof load test adopts procedures from previous Australian Standards for concrete pipe, which in turn follow American (ASTM) practice for a limiting crack width of 0.01 inch (0.25 mm) with 1 inch (25 mm) of concrete cover.

The design crack width of 0.15 mm in Australian Standards is set for the purpose of industry standardisation, and experience has shown that such cracks have no significant effect on the performance of an installed pipeline. Any steel corrosion at the tip of a crack this size seals the small void, thus stifling further corrosion.

However, where cracking occurs to an extent that was not envisaged in the design, it becomes necessary to consider whether repairs to cracks are required and, if so, what form they should take. Such considerations can often be complex, depending on the type of pipeline application (whether drainage, sewerage or pressure) and the consequence on serviceability of the pipeline as opposed to the mere visible presence of the cracks, which in themselves may be not harmful. For example, any crack passing through the pipe wall will be a concern with pressure or sewer pipe, on account of leakage, but not necessarily with a drainage line. In a moist environment fine cracks will heal, and where the pipeline must eventually be watertight it may be desirable to allow a period for this to take place, rather than embark immediately on replacement or repairs.

Apart from hydraulic considerations the basis for concern can generally be divided into two categories — structural overload due to the excessive loads acting on the pipe from the surrounding soil, and the possibility of gradual strength loss due to corrosion of the reinforcement.

STRUCTURAL ASSESSMENT

In a cracked pipe, the steel reinforcement confers flexibility on the pipe and allows a redistribution of stress both inside the pipe wall and to the surrounding earth.

The following points serve as a guide for structural assessment:

1. Multiple longitudinal cracks, particularly in the top quarter of the pipe, indicate effective transfer of stress from the concrete to the steel and so are of less concern than a single, wide longitudinal crack.
2. Visible longitudinal cracking will be more severe at the top and invert inside the pipe than on the outside. The appearance inside gives the worst indication of the condition of pipe cracking.
3. The most serious condition likely to be encountered is indicated by wide longitudinal cracks at the invert, perhaps with a step at the cracked concrete surface of the pipe resulting from mid-wall delamination or shear failure. This condition is due to hard and/or irregular bedding underneath the pipe.
4. Circumferential cracks can occur from loads imposed during installation, uneven bedding, or connection of the pipe to another structure followed by relative movement due to settlement. Unless closely spaced, circumferential cracks will have little if any effect on the ability of the pipe to carry external loads.

Table 2 signifies the typical pipeline crack assessment proposed by the Concrete Pipe Association of Australasia and offers a typical solution to the situation.

TABLE 2. PIPELINE ASSESSMENT

Defect	Description	Magnitude	Cause	Solution
Type 1	Circumferential crack Longitudinal crack	Width < 0.15mm Width < 0.15mm	Point loading during handling or installation Pipe uniformly loaded below allowable load	Accept installation Accept installation
Type 2	Circumferential crack Longitudinal crack	0.15mm < Width < 0.5mm Width > 0.15mm	Uneven bedding Excessive construction loading for overlay cover Inadequate bedding Excessive live loading Excessive soil dead load Inadequate pipe class for loads and bedding	Accept installation Accept installation Assess design Assess design Assess design Assess design
Type 3	Circumferential crack Longitudinal crack	Width > 0.5mm Width > 0.15mm	Uneven bedding Excessive construction loading for overlay cover As per type 2	Assess implication of ingress Assess implication of ingress As per type 2
Type 4	Chip or spall	Depth < 0.25 x cover	Handling during installation	Accept installation
Type 5 & 6	Chip or spall	Depth > 0.25 x cover	Handling during installation	Assess implication of ingress Repair

In a typical installation, soil loads will continue to consolidate and stabilise over about three months. If significant cracks are discovered during this time, the correct decision will often be to wait until the installation has stabilised before making a final assessment. In some areas the ground/soil condition is altered by seasonal changes affecting the water table level and a longer period of stabilisation (eg a year) may have to be anticipated. Obviously commissioning of the pipeline could not be deferred for this length of time, and a prediction of performance may need to be made at an early stage when unexpected cracking has been recorded.

CRACKS AND THE CORROSION PROCESS

A steel reinforcing bar or wire surrounded by concrete is normally protected from corrosion by the alkalinity of the concrete. In an alkaline environment, a very thin, coherent layer of oxide, which prevents corrosion, is formed on the surface of the steel. In this state the steel is described as being passivated. Only if this passivity is broken down will corrosion commence. Two states by which the passivity can be destroyed are (1) by carbonation of the concrete surrounding the bar, which reduces the alkalinity, or (2) by ingress of chloride ions, which appear to break down the passive layer at the steel surface. Carbonation is the result of the reaction between the hardened cement paste and carbon dioxide in the atmosphere or pipeline environment. Chloride ions are present in seawater and in saline ground water.

A crack in the concrete permits easier access of either chloride or carbon dioxide into the concrete, which may lead to depassivation of a small area of bar in the region of the crack. In the electrolytic process necessary for corrosion, the depassivated area becomes the anode, while portions of the bar still protected by sound alkaline concrete become the cathode. At the anode, metal ions are released. At the cathode, oxygen combines with water to form hydroxyl ions, which flow through the electrolyte to the anode, where they combine with the metal ions to form iron hydroxide. As a secondary reaction, this hydroxide combines with further oxygen to form rust.

The rate at which corrosion can progress depends on the electrical resistance of the path external to the bar between anode and cathode. This path passes through boundary layers at the steel surface, and the surrounding concrete. The rate also depends on availability of oxygen at the cathode, which is situated in sound concrete — see Figs. 1 and 2. Thus the role of the crack is to allow the process to be initiated by local loss of passivity but the rate of corrosion depends on the properties of the sound concrete.

Where the sound concrete is highly impermeable, as in concrete pipes made to Australian Standards, diffusion of oxygen to the cathode is so slow that the corrosion rate is negligible.

On this basis, flexural cracks up to 0.5 mm wide in pipes having correctly specified cover are not considered to be a threat to the long term load bearing capability of the pipe.

Rust formed from corrosion of reinforcement occupies a larger volume than the original steel from which it is formed. In some circumstances this increase in material volume can lead to progressive damage of the surrounding concrete through spalling. The circumstances favourable to this process are:

- Large bar diameter relative to cover thickness (eg the cover is less than the bar diameter).Weak, permeable cover concrete, which allows corrosion to occur in places even where the reinforcement is beneath a substantial layer of concrete, and which can exert little pressure on the corrosion products to stifle the corrosion process.

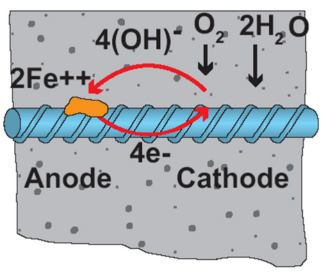

Figure 1. Simplified model of corrosion process

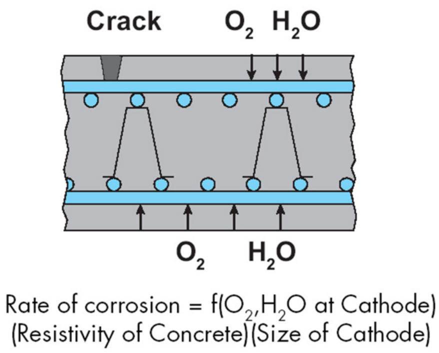

Figure 2. Factors affecting the rate of corrosion

In spun concrete pipe, the conditions are unfavourable to this process. Reinforcement consists of small diameter wire and the concrete is very strong and highly impermeable.

Concrete pipe may be found in service with steel exposed due to:

- Use of mild steel wire for reinforcement spacers.
- Cover removed by chemical attack (eg H_2S).
- A hole broken through the pipe wall, eg for field connection of a branch pipe or site-made lifting hole.

Where these situations have been observed, surrounding concrete has not been damaged as a result of steel corrosion. This is in contrast to common observations of aboveground structures. Thus with concrete pipe in typical conditions of service for drainage, sewerage or water reticulation, there will not be any accelerated deterioration due to disruption of cover by corroding steel, even if there are localised areas where a steel surface is exposed.

CONCLUSIONS

The service history of concrete pipes in Australia strongly supports the expectation that reinforced concrete pipe will achieve greater than 100 year design life when made in accordance with current and previous Australian Standards. Like most reinforced concrete elements used in infrastructure, the service life is often ended because of changes in use and to the environment, not because of deterioration.

Like ALL other reinforced concrete structures, steel reinforced concrete pipes made to AS 4058 are designed to crack, enabling the circumferential reinforcing steel to carry the imposed tensile stress. Hence it is important reiterate that:

- Circumferential cracks do not affect the load-bearing capability of the pipe.
- Circumferential cracks will not affect the long term durability of the pipe.

It should also be remembered that localised exposure of steel at the concrete surface does not lead to accelerated deterioration of concrete pipe. As with any concrete element, a reinforced concrete pipe should be checked and diagnosed before deciding upon the course of action to take.

With this in mind, in situ tests are often difficult to conduct due to the size of the pipe diameter and the underground placement of most conduits. Recent technology such as CCTV can use robotic camera inspections to distinguish between hairline cracks, corresponding to widths specified for proof load testing of the pipes, and cracks wider than 0.5 mm, which may represent a corrosion risk to the steel reinforcement. However, viewing a videotape of the inside of the pipe gives little or no information regarding concrete cover over the steel, strength, corrosion resistance, or life expectancy of the pipe. Pipe inspectors must be aware of the attributes of the pipe material, and cores must be taken to understand fully what they are seeing on tape. Specifiers and pipeline designers must be aware of the performance and durability of reinforced concrete pipe to match service life of products and materials with the design life of projects.

This shift towards better asset management techniques will have a dramatic affect on how pipe specifiers and owners look at the design life criteria of reinforced concrete pipeline, increasing the expectations of the 100-year life span the industry has come to desire.

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