SUMMARY

Particular flow conditions in concrete structures associated with wastewater treatment and reticulation can produce severe damage in very localised areas unless appropriate precautions are taken.

This paper demonstrates the sensitivity of concrete durability in the wastewater environment by presenting the findings of a walk through inspection of one wastewater treatment facility, highlighting why concrete is damaged in particular locations. It also suggests measures for preventing such damage in future structures.

1. INTRODUCTION

Effective design procedures for managing common concrete durability issues are well established. Poor abrasion resistance and cracking of concrete floors and reinforcement corrosion are the most commonly reported concrete defects in New Zealand. To reduce their incidence the industry has over the last few years promoted awareness of the issues involved at all levels of the supply chain. Although the defects may not have not been completely prevented, this effort has highlighted the issues involved so that they are less often considered to be a normal and acceptable part of concrete construction.

The durability of concrete in the wastewater environment is also worthy of consideration. We often see cases of rapid deterioration in concrete structures associated with the reticulation and treatment of wastewater. Such poor durability may result from the scope of the original design, the design itself, or subsequent modifications to the structure or system to improve the treatment process or capacity or to control odour. This paper uses the findings of a walk-through survey of a municipal wastewater treatment plant to demonstrate the sensitivity of concrete to small changes in exposure conditions in the wastewater environment.

Repairing concrete in the wastewater environment is expensive because of the logistics involved. The aim of this paper therefore is to draw the attention of designers, suppliers and contractors to the risks associated with this sensitivity, and to appropriate ways of dealing with it at the construction stage to minimise the need for future repair.

2. BACKGROUND – CONCRETE DETERIORATION IN SEWERS

The degradation of concrete in the wastewater environment as summarised here is a well known and well documented process (see for example reference [1] in the list of references at the end of this paper).

The chemical element sulphur is present in sewage in several forms, including sulphates, sulphites, organic sulphur compounds, elemental sulphur and sulphides. Sulphur is converted from one form to another by bacteria in the slime layer on the sewer walls. Some of these bacteria require oxygen to survive, i.e. are aerobic. They are also known as sulphur oxidising bacteria because they oxidise sulphides to sulphur, sulphites and sulphates. Other bacteria will only flourish where there is little or no oxygen, i.e. are anaerobic. These species are known as sulphur reducing bacteria because they reduce sulphur, sulphites and sulphates to sulphides.

Below the flow level, anaerobic bacteria metabolise sulphates and sulphates to sulphides. If the sewage stream contains sufficient oxygen, an overlying layer of aerobic bacteria at the surface of the slime will then convert most of the sulphides to sulphates, otherwise the sulphides will diffuse into the stream where they exist as hydrogen sulphide and hydrosulphide ion. This does not harm the concrete and consequently structures that operate full are not at risk.
Problems start when turbulence releases the hydrogen sulphide into an air space above the sewage stream. Here it dissolves in moisture on the concrete surface, where it reacts with oxygen to form elemental sulphur. Sulphur oxidising bacteria may then convert the sulphur to sulphuric acid.

The sulphuric acid thus created attacks the concrete above the flow level, softening the cement paste so that it can be easily eroded. The aggregate particles that are not acid resistant will disintegrate along with the cement paste. In a pipe system, deterioration is fastest at the crown, where hydrogen sulphide is concentrated by rising air currents, and at the waterline, where softened material is washed away.

To reduce the risk of this type of attack for a given sewage composition and temperature the hydrogen sulphide levels in the headspace in pipes, channels and chambers must be minimised by:

• Maintaining a relatively high flow rate to minimise sulphide generation;
• Minimising turbulence and changes in flow rate and chemistry to limit the amount of hydrogen sulphide released into the air space; and
• Ventilating air spaces to remove hydrogen sulphide before it condenses on the concrete.

For sewage flows of constant composition and temperature this type of concrete deterioration is usually related to turbulence at junctions and where the velocity or direction of flow change, e.g. with a change in diameter, surface profile or slope, particularly where the head space is poorly ventilated. This is demonstrated in the following case study.

3. CASE STUDY: MUNICIPAL WASTEWATER TREATMENT PLANT

The case study presented here is a wastewater treatment facility serving a population of about 50,000 and several industries that process primary produce. The domestic sewage is between 2 and 6 hours old (occasionally more than 8 hours) when it reaches the site. Our experience and anecdotal evidence from others familiar with wastewater structures suggests that the deterioration exhibited at this site is common to many such facilities. To focus on the generic issues involved rather than drawing attention to specific site design we have not identified the site in this paper.

3.1 Plant History

The facility was developed in stages.

The original facility was constructed in 1981. Concrete structures from the original facility that were incorporated into the current design include:

• An open grit chamber, where reduction in flow velocity allows mineral solids to settle out and be removed from the liquid flow;
• An enclosed flume, which controls the rate of flow from the grit chamber into the wet well;
• An enclosed wet well, from which the effluent is pumped to a marine outfall;
• An open channel bypassing the grit chamber;
• Enclosed channels connecting comminuters (no longer in use), grit chamber and control flume channel, with open junction chambers where the bypass channel joins the grit chamber inlet and outlet channels.

Turbulence in the grit chamber and adjacent inlet and outlet junction chambers releases hydrogen sulphide, which was considered to pose a potential odour nuisance to a nearby settlement. To control the odour, fibreglass covers were installed over the grit chamber and associated inlet and outlet chambers in about 1993 (see figure 1).

![Figure 1. Covers over grit chamber and adjacent inlet chamber.](image-url)
• Enclosed channels exiting and bypassing the milliscreen chambers;
• Enclosed channels connecting the milliscreen outflow channel to the grit chamber inlet channel.

### 3.2 Concrete and Durability Design Features

We do not know the strength of the 1981 concrete but it was reported to be very hard to cut during the 1994 modifications. Design concrete cover depths were 65mm for in situ concrete, 50mm for precast elements and 28 mm for prestressed elements.

A maximum water to cement ratio of 0.35, minimum cement content of 350kg/m$^3$ and minimum cover depths of 35mm (slabs and walls) and 40mm (beams and columns) were specified for concrete in contact with sewage in the 1994 structures.

The pipe connecting the junction chamber and the milliscreen inlet chamber was Class Y reinforced rubber ring jointed concrete pipe.

No extra surface protection was applied to the 1981 concrete.

The roof soffits of the junction chamber and the milliscreen outlet channel were lined with a heavy plastic sheet of unknown composition cast integrally with the concrete.

The walls of the junction chamber, milliscreen inlet and outlet channels and milliscreen chambers were coated with an epoxy. This was not part of the original design but was done to protect surfaces affected by construction defects. The epoxy formulation and original coating thickness are not known.

Forced air ventilation systems operate within the milliscreen building and in the wet well.

The milliscreen ventilation system was designed largely for health and safety purposes rather than specifically to protect the materials in the structure itself. It draws air from downstream of the milliscreen chambers. Air curtains were installed where the flow enters and leaves the milliscreen building to prevent hydrogen sulphide laden air being drawn into the ventilated area from the channels upstream and downstream from the building.

The wet well ventilation system draws air out of the chamber through a single intake protruding from the top of the wall in one corner. In 1999 the door at the entrance was repaired to prevent odours escaping and a new fan and new fan intake were installed.

### 3.3 Observations

The site was inspected in 2004 from the flow measurement chamber to the wet well, excluding pipework between the flow measurement chamber and the junction chamber. Observations are presented in order of flow from upstream end to downstream end of the site.

#### Flow measurement structure (1994)

On the walls of the flow measurement structure above the flow level the concrete had softened and was partly eroded to a depth of about 20mm as a result of poor ventilation in the chamber above the level of the inlet and outlet (figure 2).

#### Junction structure (1994)

In the junction structure, concrete on the walls above the flow level had softened to a depth of around 20mm. Remnants of an epoxy coating were visible on the surface. The plastic lining on the soffit was intact, with no evidence of the underlying concrete deteriorating. The deterioration on the walls results from poor ventilation of an area where hydrogen sulphide is released from the stream by the turbulence created where the three flows combine.

On the upper half of the pipe connecting the junction chamber and the milliscreen inlet chamber concrete had softened to a depth of 10 to 15mm throughout the 7.5m length. This is a result of hydrogen sulphide laden air being drawn through the pipe from the junction structure.

#### Milliscreen inlet channel, chambers and outlet channel (1994)

The condition of the concrete in the milliscreen inlet channel varied from excellent to poor:

- The walls within about 1m of the air curtain on the upstream wall of the chamber show the worst deterioration, with concrete...
softened or eroded to between 50mm and 70mm. The deterioration was mostly more than 1m above the channel floor but extended to within 300mm of the floor close to the air curtain. On one wall within this affected area a horizontal reinforcing bar (with an original concrete cover of 40mm) was exposed and corroding but had only minor section loss. No remnants of the epoxy wall coating were visible in this area.

- Walls in the remainder of the upstream half of the inlet channel were softened to a depth of about 30mm from heights more than 1m above the floor. Remnants of the epoxy coating were visible.
- In the downstream half of the channel some of the walls were in good condition. In other areas the epoxy coating had deteriorated and concrete softened to a depth of 10mm to 15mm. All deterioration occurs more than 1m above the channel floor.

The walls of the milliscreen chambers were generally in good condition except for the following areas:

- Upstream of milliscreens 1 and 3 the coating had intermittent round holes through the coating and into the concrete, with diameter up to 30mm and underlying concrete softened up to 15mm deep. In milliscreen chamber 2 this damage was more extensive, with concrete more 1m above the floor being eroded to about 15mm deep (figure 3). In all three chambers damage was greatest on the east wall.
- Downstream of milliscreen 1 an area of coating approximately 800mm x 200mm had been removed and the concrete eroded to a depth of approximately 15mm.

The only deterioration in the milliscreen outlet channel was at the downstream end of the soffit, where the plastic lining had partly disbonded and the concrete softened slightly up to 50mm in from the lining edge. The lining and the epoxy wall coating were in good condition.

The deterioration in the inlet channel and milliscreen chambers suggests that the ventilation system was not providing sufficient air circulation to remove hydrogen sulphide from these areas, particularly from the upstream wall of the inlet channel where hydrogen sulphide laden air is drawn in through the air curtain.

The damage to the coating and underlying concrete in the milliscreen inlet channels and chambers indicates that although the coating performed satisfactorily in the outlet channels it was inadequate for the higher hydrogen sulphide concentrations in the milliscreen chambers and upstream from them. Its application may also have been substandard, with pinholes providing a means of ingress for the hydrogen sulphide laden air.

**Grit chamber and associated channels (1981)**

In the enclosed inlet and outlet channels associated with the grit chamber, concrete on the lower 1.2m of the walls (below the approximate flow level) has eroded to a depth of about 10mm. On the walls above the flow level the concrete is softened to a depth of 5mm to 10mm but in isolated areas the depth of deterioration may be as high as 15mm. On the channel soffits the depth of deterioration is a maximum of about 2mm. The deterioration above the waterline is thought to be related to hydrogen sulphide being released at changes in profile at the chambers where the channels intersect the bypass channel and accumulating in the poorly ventilated head space under the cover.

In the grit chamber, concrete on all walls above the flow level was softened. On three of the walls the depth of softening was about 50mm deep in a 500mm wide band above the flow level and 30-40mm deep above this (figure 4). On the fourth wall the concrete was softened up to 20mm deep. This deterioration developed since the grit chamber was covered in 1993 and is attributed to hydrogen sulphide being released by the turbulence in the chamber and lack of ventilation allowing it to build up in high concentrations. The fourth wall may have been less affected because it is the furthest from the inlet, where most of the hydrogen sulphide is released.

Figure 3. Damage to coating and underlying concrete on milliscreen chamber wall.
Control flume channel (1981)
In the control flume channel the walls were softened and eroded 5-40mm deep in a band representing the flow level 300-600mm above the floor. The depth of erosion increases going downstream. Deterioration above the flow level on the walls and soffits is generally less than 5mm deep, except for discrete areas with softening and erosion 20-60mm deep. These areas are related to local areas of poor ventilation at the upstream end, at a manhole, at a site stormwater outlet and at the downstream end. The worst area is at the downstream end, where the airflow meets the top of the downstream wall (figure 5).

Wet well (1981)
In the wet well concrete condition varied considerably:
- The soffits of the precast prestressed floor slabs forming the roof (which also serves as the floor of the pumphouse above) were in good condition except in the corner near the fan intake for the ventilation system, where the surface was eroded to about 10mm deep.
- The two precast beams supporting the floor slabs were generally in good condition, with surface softening up to 1mm over most of their length. The beam near the door, however, had deteriorated to 20-30mm deep at each end. At one end the damage was associated with the outlet from a sump in the pump room above, which appeared to collect and concentrate gases (figure 6). At the other end the damage was an extension of damage to the walls around the entrance, where air flow is restricted.
- The walls are generally in good condition with less than 2mm depth of deterioration. The exceptions are the walls behind the fan intake and around the entrance, where poor air circulation has led to deterioration up to 30mm deep (figure 7), mostly since 1999.
- The top of the cantilevered walkway around two walls was in good condition. The underside was coated in a layer of fat, but no concrete appeared to have been lost from the surface.
Damage in the wet well is associated with hydrogen sulphide released by turbulence at the inlet (and augmented by gas in the natural airflow from the flume channel) being concentrated at localised poorly ventilated areas associated with a sump outlet, the shadow of the fan uptake and in the recessed entranceway. Damage to the roof near the fan intake is associated with elevated concentrations of hydrogen sulphide drawn from throughout the chamber.

3.4 Summary

Significant damage at the site can be related to localised areas where hydrogen sulphide is concentrated by poor ventilation or by forced air flow. The damage is greatest where poor ventilation is combined with the release of hydrogen sulphide from the sewage stream at a point where turbulence is generated by a change in flow direction or velocity. The damage in the upstream milliscreen channels and chambers and in the wet well demonstrates that coatings and ventilation systems will not protect the concrete in the most aggressive environments unless they are specifically designed for that purpose.

4. SIGNIFICANCE OF DAMAGE

4.1 Effect on Performance and Service Life of Structure

Although the surface erosion may affect flow rates and itself generate a small amount of turbulence and grit, the main effect on the structure itself is the loss of concrete cover over the reinforcement. Once reinforcing steel is exposed to the acidic environment it will corrode and the structure may no longer be considered serviceable. The time at which concrete deterioration is predicted to reach the steel was therefore considered to represent a practical definition of the end of service life.

Above the maximum flow level the rate of deterioration may slow with time as a build up of reaction products provides a barrier to ingress of the aggressive agents. Below the maximum flow level the reaction products are eroded and deterioration rates may be close to linear. An indication of the minimum remaining service life of each structure inspected was therefore calculated from the designed cover depths assuming a linear rate of deterioration.

The minimum remaining service life thus calculated was zero years (total service life 10 years) for the pipe connecting the junction chamber and milliscreen building and for the milliscreen inlet channel. The maximum remaining life was 45 years (total service life 68 years) for the prestressed floor slabs forming the wet well roof/pumphouse floor. The remaining lives of most of the 1994 structures were less than 15 years, with corresponding total service lives of less than 25 years. The exception was the walls of the milliscreen outlet channel, which had an indefinite remaining life.

Some municipal wastewater treatment facilities may be designed for shorter service lives than the 50 years used for many concrete structures. This is because the facility design may be obsolete well within 50 years owing to insufficient flow capacity, changes in sewage composition and more stringent requirements for discharged effluent quality. Nevertheless, sewerage reticulation facilities upstream of the treatment facility may be expected to last somewhat longer (see for example ref [2]), despite being exposed to similar conditions in places.

Even if the intended service life was 25 years, we believe that the degree of deterioration observed at this site is undesirable because it leaves little room for error and reduces options for continued use or adaptation of the facility after 25 years.

4.2 Repair Options and Costs

Repair options include:
- do nothing;
- modify the process;
- reinstate and protect the concrete.

“Do nothing” is only appropriate for structures with little or very slow deterioration or those that will soon be obsolete. At this site the milliscreen outlet channel was the only structure inspected that was considered not to need any remedial treatment.

Improvements to the ventilation in the milliscreen building and in the wet well were recommended as an immediate priority, to be carried out within 5 years. These involved consideration of the source from which fresh air is taken so that sulphide laden air is not drawn through the concrete structures, sealing air gaps within the ventilated area, and ensuring that biofilters are accessible for maintenance and of appropriate size and location. The rough order contract cost for the proposed work was $200,000.

Options for reinstating the concrete in the wastewater environment are often limited to treatments that can be applied and put into full service within the lowest flow periods each day, during seasonal low flow periods if applicable. Fortunately, many of the repair sites at this particular facility can be isolated from the flow, except for the structures upstream from the milliscreen chambers, the control flume channel and the wet well.
Suitable repair materials for this environment are proprietary rapid setting, acid resistant mortars and concretes based on silicate cements or calcium aluminate cements, or Portland cement based materials overcoated with a protective epoxy coating of appropriate formulation. A calcium aluminate repair system was recommended for this facility because of its versatility, ease of application and rapid setting time.

Rough order contract costs for the repair and protection of concrete totalled $220,000, including reinstatement of approximately 400m$^2$ of concrete to a depth of 20-60mm of concrete, recoating parts of the milliscreen inlet chamber and replacing some joint sealants. Most of this work was deemed to be needed within 5 years to prevent the onset of reinforcement corrosion. Contractor mobilisation and site establishment costs would increase the total cost if less urgent repairs were to be carried out later as a separate contract.

The rehabilitation cost at the site, including ventilation improvements, could therefore be in the order of $420,000 excluding inspection, design and contract management costs, costs of diverting the flow and other operational costs incurred by the client.

### 4.3 Preventive Treatment

Could these repair costs have been avoided? We believe that design and construction should take a more cautious approach than may have been done in the past.

As an absolute minimum level of protection, concrete mix designs for all structures exposed to wastewater or the air above it should have water to cement ratio of 0.40 or less, a minimum cementitious binder content of 400 kg/m$^3$ and incorporate appropriate quantities of a suitable supplementary cementitious material (SCM) that has been shown to improve sulphuric acid resistance in the wastewater environment. (These limits are proposed in the revised draft of NZS 3101 for concrete exposed to highly aggressive soil and groundwater, not for exposure to the higher acidities that may be found in wastewater structures.). Construction schedules may need special provisions to allow for adequate curing and possibly strength development to ensure that such concrete achieves its optimum properties.

Whatever its composition and quality, Portland cement concrete cannot withstand prolonged exposure to sulphuric acid. For example, modelling for a particular sewer main subject to highly aggressive flow conditions predicted a 7 year service life for standard concrete pipe, increasing to 30 years for pipe made from an SCM concrete with 20mm sacrificial cover [2]. Laboratory tests have shown that SCM can increase service life of pipe exposed to sulphuric acid by 30-50% [3]. In addition, ventilation systems installed for the purposes of health and safety and/or odour control will not necessarily be sufficient to protect the structure. Therefore all concrete surfaces above flow level that could potentially be exposed to hydrogen sulphide should be protected with an appropriate surface coating or lining applied in accordance with the supplier’s recommendations.

Surface protection ideally should be applied to all surfaces within the facility to at least 1m below the minimum flow level because of the difficulty of accurately predicting the areas that will be affected. Often, however, the owner may prefer only to protect high risk areas, and this is where special care is needed. In these cases ventilation and surface protection should extend beyond areas immediately at risk to include those that that would be at risk should the process not operate exactly as anticipated. A risk assessment with a sensitivity analysis considering all such eventualities must be applied to the design to establish the appropriate limits for protection.

Extra protection above the minimum is often considered an unnecessary expense, possibly because the designer or the client does not fully appreciate the consequences of inadequate protection and particularly the rate at which concrete can deteriorate. Designers may need to show their clients examples of the damage that can occur (e.g. this paper or references such as [4] and [5]) so that they can establish an acceptable level of risk. Budgets can then be set for a suitable level of concrete protection, including quality control during construction.

### 5. CONCLUSIONS

The exposure environment within wastewater treatment and reticulation facilities varies from benign to highly aggressive with features that result in the production, release and concentration of hydrogen sulphide gas. In aggressive situations concrete deterioration can be rapid, several centimetres of concrete turning to mush within 10 years. Very short distances can separate benign and highly aggressive environments.

Because of the sensitivity of the concrete to changes in exposure conditions, it is recommended that designers provide extra levels of protection by extending ventilation and surface protection beyond the areas at immediate risk,
and providing an improved background level of protection by incorporating SCM in the concrete mix design.

Designers should encourage their clients to provide sufficient amounts in their budgets for concrete protection. Showing examples of the damage that can occur may help to establish appropriate levels of risk.

ACKNOWLEDGEMENTS

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REFERENCES


3. Hume Industries Ltd, B. Veljanovski, pers. comm..
