DEVELOPING A CORROSION STRATEGY TO PROTECT NEW ZEALAND'S LARGEST WASTEWATER ASSET

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ABSTRACT (500 WORDS MAXIMUM)

The Central Interceptor is a new deep tunnel sewer that will provide additional capacity in the network to meet planned population growth and development in Auckland, provide a more resilient wastewater system, and mitigate wet weather overflows in central Auckland. The tunnel is to be built between Western Springs and the Mangere Wastewater Treatment Plant (WWTP) over the next six years. The main tunnel will be approximately 13 kilometres long and up to 110 metres below the ground surface. It will cross under the Manukau Harbour approximately 15 metres below the seabed. The main tunnel will be excavated by tunnel boring machine and will have an internal diameter of 4.5 metres. In addition, two separate link sewer tunnels of 2.4 and 2.1 metres internal diameter and 1.1 and 3.2 kilometres in length respectively will be constructed by pipe jack methods. The pipe jacking drive lengths range from 300 to 960 metres between shafts.

Nine drop shafts will be constructed along the Main Tunnel alignment to provide flows to the tunnel. With a spacing of up to 4 kilometres between shafts, future access for maintenance is a recognised challenge for the project. The main tunnel and shafts are required to have a 100-year design life and therefore must be made of durable materials with an extremely low level of maintenance. To achieve this design life, a number of strategies are being employed including environmental controls, material selection, and hydraulic design.

Watercare has undertaken multiple sampling campaigns to determine the corrosion potential of the wastewater to be conveyed in the system. This has consisted of sewage sampling as well as advanced computer modelling to predict corrosion rates. Over the last two years Watercare has undertaken extensive laboratory testing of corrosion resistant materials for the highest risk elements. Concurrently, samples of these corrosion resistant materials have been exposed to the existing sewer network to replicate the in-service conditions that the Central Interceptor tunnel and shafts will experience throughout the asset's life. Additionally, design elements such as concrete cover, embedded polyethylene liners, and the overall hydraulic performance have been considered in determining the optimum strategy. A risk assessment further assisted in defining what strategy should be applied in specific elements of the scheme.

This paper will describe the overarching strategy, field investigations, modelling, lab testing process, and results of the testing programme. With construction works to commence in 2019 on this flagship project, Watercare can proceed with confidence that the design objectives can be achieved.

KEYWORDS

Central Interceptor, sewer, tunnel lining, drop shaft, corrosion, materials

PRESENTER PROFILE

Stephen has worked in the NZ water industry in a range of roles for 30 years at Watercare. He is Watercare's Engineering Manager for the CI project, and has been on the project since 2014.

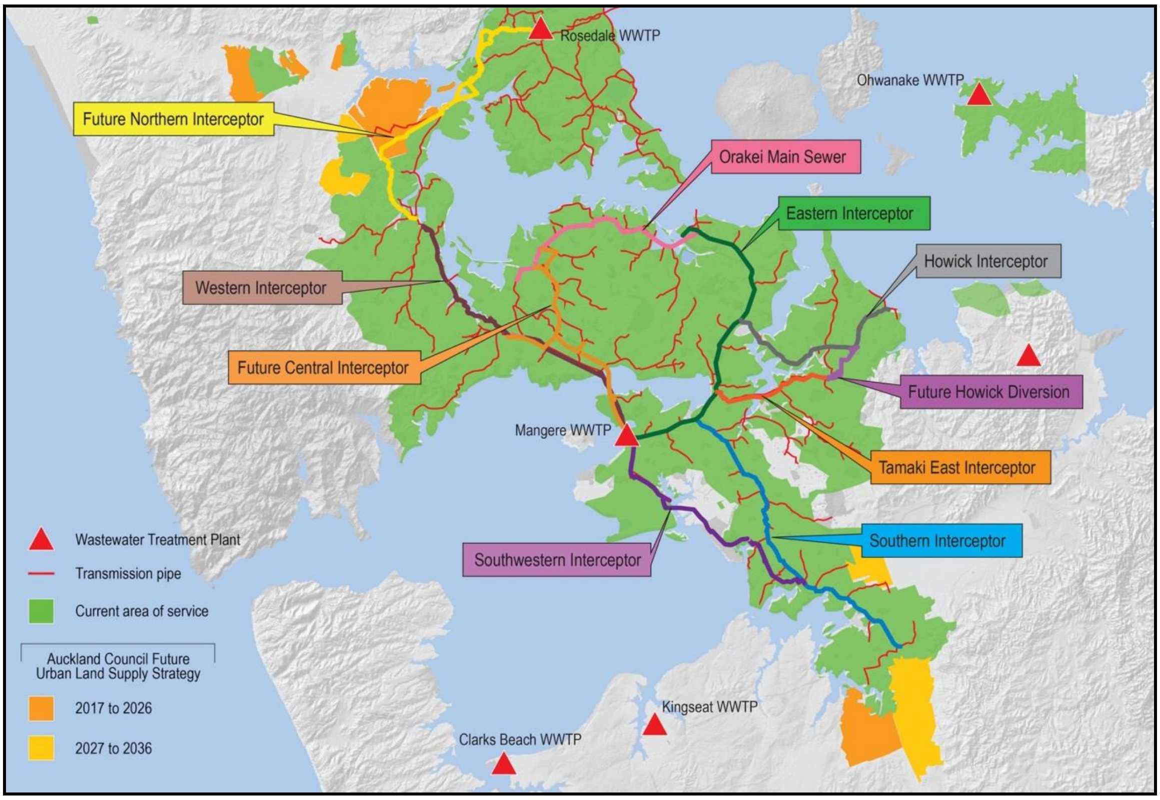
Shannon Goff is an Associate with McMillen Jacobs Associates with over 12 years of experience in the design and construction of tunnels in the water and wastewater industries. She was the lead tunnel designer for the CI detailed design team responsible for the segmental lining specimen design issued for tender.

Nigel is a Senior Principal with Jacobs New Zealand, as well as having led the consultant team of Jacobs NZ, AECOM and McMillen Jacobs through the CI detailed design and tender process. Nigel has over 40 years' experience working on infrastructure projects including the Sydney Desalination Plant and a number of upgrades of the Rosedale Wastewater Treatment Plant.

1 INTRODUCTION

The Central Interceptor is a new deep tunnel sewer that will provide additional capacity in the network to meet planned population growth and development in Auckland, provide a more resilient wastewater system, and mitigate wet weather overflows in central Auckland. The project is an integral part of Watercare's long-term strategy to effectively manage wastewater within the Auckland region, to protect public health and the environment, and to provide for growth. In the older parts of central Auckland, wastewater and stormwater currently flow into a combined network of pipes. When it rains, the stormwater can overwhelm these pipes and dilute wastewater flows into Auckland's waterways. The main project component is a 13-kilometre-long tunnel between Western Springs and the Mangere Wastewater Treatment Plant for collecting and transferring wastewater for treatment and safe disposal. The tunnel will provide 200,000 m3 of capacity to temporarily store wastewater thereby controlling the flow into the treatment plant.

Figure 1: Watercare's Wastewater Network with Central Interceptor (orange line)



2 PROJECT OVERVIEW

The tunnel will have an internal diameter of 4.5 metres. There are nine drop shafts to be constructed along the length of the tunnel to provide flows to the tunnel ranging in diameter from 3 metres to 10.8 metres. Shaft diameters are determined by both hydraulic and construction requirements. The two large diameter shafts utilise vortex drops. The other shafts utilise cascade drops. Additionally, there are two link sewer tunnels (Link Sewers B and C) to be constructed by pipe jacking methods. The link sewer tunnels are 2.4 and 2.1 metres internal diameter and 1.1 and 3.2 kilometres in length respectively. The pipe jacking drive lengths range from 300 to 960 metres between the shafts. There are an additional seven temporary or permanent shafts associated with the link sewer tunnels. The main tunnel has a constant grade of 1:1000.

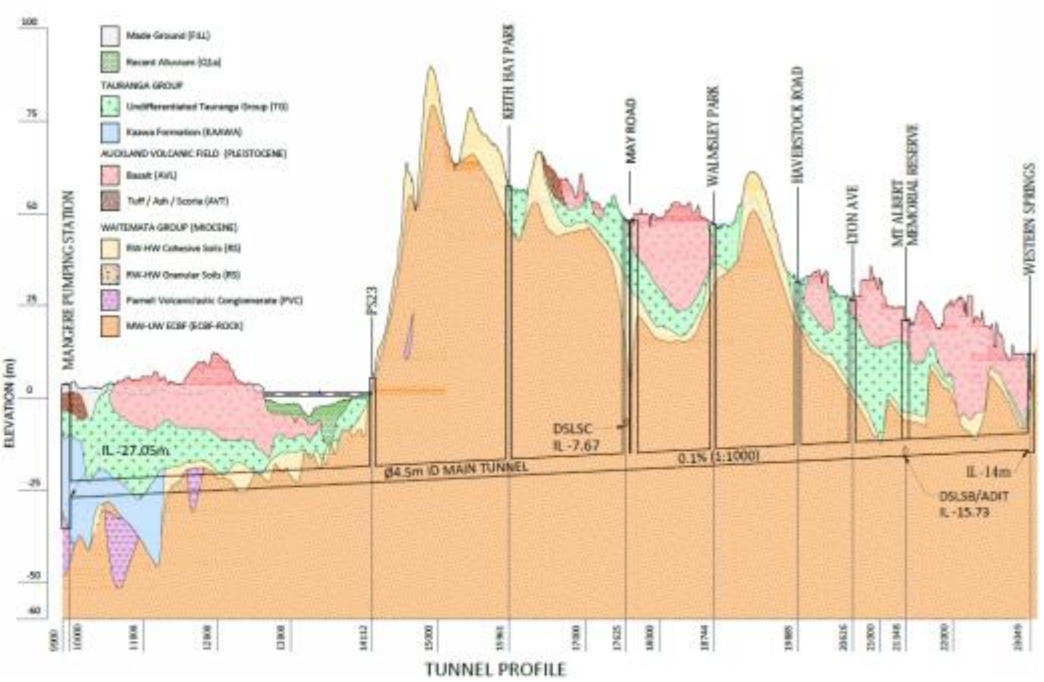
The project elements are shown in Figure 2. Construction will commence in mid-2019 with project completion by 2025.

Figure 2: Central Interceptor Project Overview

The tunnel will be constructed with a tunnel boring machine utilizing precast concrete segments installed behind the machine for ground support. The depth of tunnel ranges from 15 metres (below the Manukau Harbour seabed) to 110 metres below the ground surface. The tunnel lining will be subject to groundwater pressures up to 8.7 bar. It will be driven predominantly through weak sandstones and mudstones/siltstones of the Waitemata Group rocks, in particular the East Coast Bays Formation (ECBF), alluvium and marine sediments, with limited risk of striking harder basalt.

The sewer flows enter the tunnel at the drop shafts and traverse the length of the tunnel to the Mangere Wastewater Treatment Plant (MWWTP) where a terminal pump station will lift the flow into the MWWTP headworks. The pump station is designed to transfer up to 6 m^3/s of storm flow to the plant.

Figure 3: Central Interceptor Geotechnical Longitudinal Section



3 ANTICIPATED CORROSION

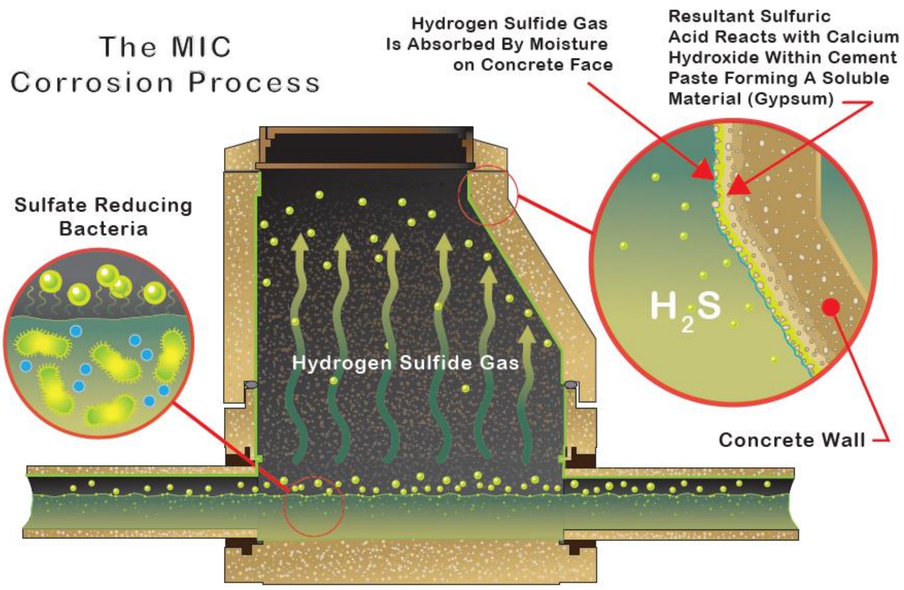
The Central Interceptor tunnel is designed to have a 100-year asset life and a design horizon of 50 years. This means that the physical asset is designed to achieve a 100-year life whilst the design flows are projected out to 50 years from the consent award date (to 2062). Despite the tunnel being principally for wastewater, the northern catchments that the tunnel serves include large areas of combined sewer networks, so the wet weather contribution is significant and large storms can dominate capacity requirements.

However the catchments to the west and north of Auckland (currently served by the Western Interceptor) carry predominantly sanitary sewage which will be highly corrosive given the long transit times from the network extremities. It is this sanitary sewage flow that affects the corrosion rates, particularly on Link Sewer C and the Main Tunnel south of the May Rd shaft.

3.1 MICROBIALLY INDUCED CORROSION

Microbially induced corrosion (MIC) is a bacterially mediated process of forming hydrogen sulphide (H_2S) gas and the subsequent conversion to sulphuric acid that attacks concrete within wastewater environments. The hydrogen sulphide gas is biochemically oxidized in the presence of moisture to form sulphuric acid. The effect of sulphuric acid on concrete surfaces exposed to severe wastewater environments can be devastating.

Figure 4: Microbially Induced Corrosion



The rate of corrosion of a concrete sewer is influenced by:

- the extent of dissolved sulphide generation in the sewage;
- the sewage pH (which establishes the distribution between sulphide in ionic form and in molecular form as H_2S in the sewage);
- the extent to which H_2S is desorbed from the sewage;
- the sewer gas space H_2S concentration;
- the sewage and sewer gas space temperatures; and
- relative humidity in the sewer gas space.

The extent of dissolved sulphide generation in the sewage and the sewer gas space H_2S concentration are in turn dependent on many factors including but not limited to sewer slope, sewage velocity, air flow velocity, dissolved sulphide and sulphate concentrations in the sewage, sewer surface roughness, and aggregate sewage detention times in the network. These factors are accounted for in the sulphide generation modelling completed for this project discussed in the next section.

3.2 MODELLING AND SAMPLING

As part of the Central Interceptor (CI) project Detailed Design, assessments were undertaken on the H_2S and corrosion potential for the proposed CI system. Sulphide generation and corrosion models were developed to estimate the rates of corrosion of the CI system under both natural ventilation conditions (i.e. there is no mechanical air induction into or extraction from the CI system) and forced ventilation conditions, utilising extraction fans.

The purpose of the sulphide and corrosion models is to provide an estimate of potential dissolved sulphide concentrations in the sewage, H_2S in the sewer gas space and corrosion rates assuming sewer is constructed of corrodible material (i.e., concrete). The sulphide and corrosion model utilised a 2030 average dry weather flow (ADWF) scenario. The model incorporated the physical details of the CI design, hydraulic characteristics consistent with the hydraulic design, sewage and sewer air characteristics consistent with anticipated in-service conditions. Five design parameters were varied in the modelling to bound the results for the overall corrosion estimates. These were sewage characteristics, method of analysis, seasonal effect, ventilation efficiency, and the factor of safety.

Sampling was initially completed in two phases (March 2015, November 2015) and results in the sewage characterisation nominated as ‘As Sampled.’ However as there were some concerns about the accuracy of the sampled values resulting in the generation of ‘Normal’ sewage characterisation, a third round of sampling was carried out in March 2016 to confirm the data.

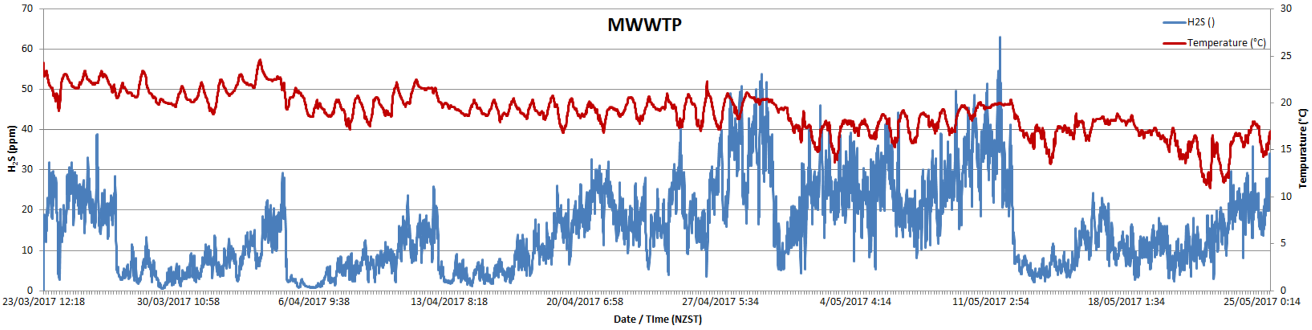
The sampling included a wide range of parameters that were collected and analysed by Watercare’s laboratories, and a lab in Sydney, Australia. The typical range of sampled parameters is in Table 1.

Table 1: Parameters Measured for Sewage Sampling Campaigns

	Unit	**Parameter**	**Maximum**	**Minimum**	**Average**
Liquid Phase	mg/L	Dissolved Sulphide	18	1.0	8.1
	mV	Oxidation-Reduction Potential	74.1	-255.5	-130.2
	mg/L	Dissolved Oxygen	6.0	0.1	1.0
	mg/L	TBOD5	800	170	392
	mg/L	COD (as O2)	5900	370	1011
	mg/L	Dissolved CBOD5 (1.2 μm Filtered)	7971	78	194
	pH unit	pH by electrode	8.5	5.1	7.1
	◦C	Temperature	25.1	21.9	23.7
	uS/cm	Conductivity	3969	48	1078
Gas phase	OU	Odour	166250	250	18289
	ppm	H2S	175	0.0	10.2
	ppm	Mercaptans	2.8	0.0	0.4
	ppb	Hydrogen sulphide	25600	0.1	1145.5
	Ppb	Carbon disulphide	133	5.3	20.6
	Ppb	Methyl mercaptan	2137.0	0.2	276.7
	ppb	Dimethyl sulphide	28400	5.0	758.2
	m/s	Airflow	Only measured at Pump station wet wells with fan on Max 4.9 Min 0.1		
	Pa	Pressure	143	-344	-2

Additionally, Odalog H_2S meters were installed in parts of the network to gauge the ambient H_2S levels (not grab samples). Temperature and humidity were also measured to assist in the analysis.

Figure 5: Environmental Monitoring of In-Sewer Conditions



Modelling was completed using both gas and liquid phase characterisations with their results presented separately. Ultimately, the more conservative ‘As Sampled’ results were utilised for design. The method of analysis relates to assumptions on how to estimate the “approach to equilibrium” factor for determining H_2S concentrations in the sewer gas space based on the relative “free air flow space” for the CI compared with an equivalent sewer transporting the same ADWF flows and with lower peak flow containment (to dry weather flow) ratios. Two methods (the USEPA “Hydrogen Sulphide Control Manual” method and the University of Queensland “SCORe” method) were considered reasonable and a weighted average of the two results was used.

The individual "summer" and "winter" corrosion rate results have been averaged to obtain a "year" round rate (noting that "winter" results are based on dilution by factor of 0.8 and a lower temperature compared with summer).

Ventilation efficiency assumes that the benefits of forced ventilation in reducing corrosion rates is realised. It is prudent to assume at this stage that the ventilation system will not be 100% effective at all parts of the CI.

Therefore, an allowance was made for times when the ventilation system is shut down and for reduced ventilation efficiency at points more distant from the extraction point. The factor of safety utilised for each CI section considers the relative "criticality" of each section as well as climate change and the uncertainty around relative humidity. Overall corrosion results were presented as estimated annual corrosion rate for Ordinary Portland Cement (OPC) concrete.

3.3 PREDICTED CORROSION RATES

The combined networks dominate the central areas of Auckland and were built from the early 20th century whereas the separated systems were built after the 1950s in the outer suburbs. This means that the tunnel south of the May Road shaft (which is the connection point for the Western Interceptor flows) will see the more corrosive sewage from the outer suburbs to the north-west which have been rapidly growing since the 1980s. Some of the northern most catchments have pressurized sewer networks with longer residence times that add to the corrosion potential of the sewage. Watercare's proactive management of trade waste means that the proportion of corrosive industrial wastewater is relatively minor.

Forced ventilation of the main tunnel and link sewers is proposed to reduce H_2S gas concentration and reduce the rate of corrosion. Forced ventilation refers to the exhausting and treatment of air from the sewer air space, which fluctuates as the tunnel fills and drains of sewage. This has a dual benefit of controlling odours by only exhausting at shafts with air treatment facilities.

After taking ventilation into account, the depth of corrosion in OPC concrete during a 100 year design life is predicted to range from 42 mm to 156 mm generally, and 50 mm to 268 mm at hot spots (areas of localised turbulence). The estimated aggregate systemic corrosion for the northern and southern tunnel sections, based on OPC concrete, were 88 and 156 mm respectively (assuming a 100-year asset life). At these rates a sacrificial concrete system for the segmental lining was considered difficult to construct; the segments would have been over 400mm thick and a challenge to erect in a 4.5m diameter tunnel.

4 CORROSION PROTECTION STRATEGY

Corrosion protection of the CI tunnel will be achieved through a multi-prong approach. The hydraulic and ventilation designs contribute, as does the selection of appropriate construction materials. The selection of materials considers the corrosion risk to the various project assets. For the tunnel, which is a considerable length and will be the most difficult to access to complete inspections and repairs, a more traditional corrosion protection strategy was selected referencing similar international projects (discussed below). For the shafts, an investigation into alternative materials was undertaken.

4.1 HYDRAULIC DESIGN

Extensive hydraulic analysis has been undertaken using Infoworks CS models that have considered numerous storm events and periods of low flow to develop a picture of how the tunnel will perform once it is commissioned in 2024. Flows to the pump station range from 0.2 to 6 m^3/s (maximum pump station capacity). This large range of flows demonstrates how variable the flow regime is with the combined sewer contribution. The tunnel must be designed to cope with these extremes. The hydraulic performance was used in the corrosion modelling to gauge the velocity of the flow (affecting siltation and viscous drag) as well as air space areas during dry weather flow.

Inflow is controlled by real time control gates that close when the tunnel is full. The tunnel must not fill as it will behave erratically under surge events that have been modelled to determine a venting strategy under extreme conditions. These gates operate rarely (2-6 times per year) to limit flow into the tunnel which has a finite capacity. Pump out rates need to be matched to the WWTP capacity and the flows from other interceptor sewers that feed the plant.

The drop shafts are designed for the maximum likely hydraulic inflow while minimising the entrainment of air into the flow. The tunnel and link sewer gradients are designed to be self-cleansing under peak flow in dry weather conditions, in accordance with usual design practice.

4.2 VENTILATION DESIGN

Management of H_2S corrosion of sewers constructed of corrodible material such as concrete can be achieved by a number of means including:

- control of precursors (e.g. trade waste controls);
- chemical dosing (for pH control or precipitation of dissolved sulphide); and
- forced ventilation.

For the CI system, forced ventilation is the preferred means of managing both corrosion and odour issues as trade waste controls require constant surveillance and chemical dosing is costly. The CI sulphide and corrosion model results concluded that the CI system would suffer from unacceptably high corrosion rates under conditions of natural ventilation.

A sewer system which is force ventilated will have air flow rates higher than if it was only naturally ventilated and will result in a lowering of H_2S concentrations in the sewer gas space. The air flow rates through the system will be influenced by a number of factors including:

- Forced air extraction requirements from the system (i.e. via extraction fans);
- Need for a dedicated air induction point(s) to the system;
- Area for air flow through the system (through the sewers themselves and via drop shafts); and
- Size and location of any other air vents (including potentially to some extent those on tributary sewers to be intercepted).

4.3 ODOUR MANAGEMENT

Building a sewer tunnel of this scale in an urban environment means particular attention must be paid to the management of odorous air and control of tunnel pneumatics. The project’s resource consents require that no objectionable fugitive emissions reach the boundary of each of the shaft sites. To achieve this objective the tunnel will be operated under negative pressure ventilation, with air drawn to the Mangere Pump Station where it will be treated in a bark bioflter. The fans at the biofilter will draw up to 16 m^3/s of air from the entire 13 km length of the tunnel. The biofilter will be 1600 m^2 area, with a media depth of 1.2 m and a loading rate of 50 $m^3/h/m^2$.

In addition to the tunnel air treatment at the Mangere Pump Station, a second air treatment facility (ATF) will be located midway along the main tunnel at the May Rd shaft location. The primary purpose of this facility is to treat air from Link Sewer C, but when the tunnel is full at the downstream end (thus sealing the air outlet at tunnel crown) the air will be drawn from the main tunnel as well as Link Sewer C. The operating range for the May Rd ATF is 2.5 to 7.5 m^3/s. The May Road ATF will be a compact biotrickling filter design with activated carbon polishing to achieve high reliability of odour treatment in this mixed residential/industrial location.

The design also recognizes the potential for corrosion hotspots that will occur in turbulent zones of the tunnel. The drop-shafts along the tunnel range from 10m to 80m deep and the associated turbulence will release the corrosive gases into the shaft and tunnel environment in the vicinity of drop-shaft.

4.4 MATERIAL SELECTION

Forced ventilation reduces but does not eliminate the potential for microbially induced corrosion of shaft and tunnel linings and therefore the linings must also be designed to provide adequate corrosion resistance.

4.4.1 TUNNEL LINING

The Main Tunnel lining system will comprise a one-pass, gasketed precast concrete segmental lining system designed to handle the maximum anticipated loading conditions along the length of the Main Tunnel. Both short term (during construction) and long-term loading conditions are considered in the design of the segments. Two types of reinforcement are utilised in this design (steel fibres and steel bar reinforcement) as appropriate for the varying structural design actions along the alignment. Construction of the Main Tunnel will utilise a single tunnel boring machine (TBM) and a single set of segment moulds, so the segment thickness is the same throughout the project regardless of the type of reinforcement. In this regard, the durability design must consider the critical case of conventional steel bar reinforcement and its protection.

Photograph 1: Single pass concrete lining used on the Project Hobson Tunnel (Watercare, 2010)

The tunnel lining system has a design life of 100 years. Deep tunnels such as CI are difficult to inspect using conventional technologies due to the depth, distance, and flow regimes; so achieving the design life becomes even more critical. The long-term durability of the tunnel lining must accommodate the corrosive acid environment prevalent within the sewer as a consequence of microbial activity on the lining surface in the presence of hydrogen sulphide gases.

The binder in typical concrete used for a segmental tunnel lining is Ordinary Portland Cement (OPC), which is susceptible to acid attack by the dissolution of the calcium compounds present in the concrete. Several tunnel lining systems were considered during preliminary design including both one-pass (single lining) and two-pass (primary and secondary lining) options.

For one-pass lining systems, the single lining provides the structural support as well as the durability for the design life of the project. For the corrosive environment in question, one-pass systems considered for this project include:

- an OPC segmental lining with additional thickness of concrete (referred to as sacrificial concrete);
- segmental lining made of materials more resistant to corrosion, such as polymer concrete or acid resistant concrete; and
- and segmental linings with a cast-in plastic lining.

Two-pass systems considered during preliminary design phase included an initial lining of an OPC segmental lining with a secondary lining of OPC concrete (sacrificial), GRP pipe, or spray-on epoxy coating.

The two-pass tunnel lining systems were generally considered by the design team to be undesirable due to cost and programme considerations; and were not adopted by the tenderers despite the specifications allowing for this option.

For the one-pass systems, the simplest solution of an OPC segmental lining with sacrificial concrete presented constructability and cost challenges due to the amount of sacrificial thickness predicted by the corrosion modelling, which left only two options to consider. Of these two options (corrosion-resistant materials or cast-in plastic lining), only one (cast-in plastic lining) had previous project examples for tunnel linings to verify its performance and provide guidance in the design and construction. Project examples include the North West Interceptor Sewer in Sacramento, California, the Strategic Tunnel Enhancement Programme (STEP) in Abu Dhabi, the Doha South Sewer Infrastructure Project in Doha, Qatar and the Deep Tunnel Sewer System (DTSS) in Singapore.

During the design phase, Watercare's designers produced a specimen design for the tunnel lining for a one-pass system with cast-in PE membrane (plastic lining) on the intrados (inside) surface of the segments. For this design, the PE membrane is cast into the segments during manufacture and the membrane joints between segments are welded in situ during lining installation. The contractor (Ghella Abergeldie Joint Venture) is responsible for the final design of this system due to the need to adapt this design to suit the specific tunnel boring equipment to be used on the project. The basis of the design is that the PE membrane provides the specified 100-year maintenance free design life. However, to allow for potential in-service damage to the PE membrane, the design also provides additional sacrificial concrete thickness based on the estimated corrosion over a 50-year period; on the assumption that localised damage to the PE membrane and associated loss of segment concrete section could be identified and repaired within that timeframe. The segment thickness is governed by the higher corrosion rates in the southern section of tunnel resulting in an overall concrete cover to reinforcement of 100 mm, including a sacrificial concrete layer of 80 mm.

The specimen design included specifications for the concrete, the tunnel segmental lining, and the PE membrane corrosion protection liner (CPL). All specifications included both material and construction requirements, with the methodology for installing the CPL being based on experience gained on previous sewer tunnel projects. The segment hardware (dowels on the circumferential joints and guiding rods on the radial joints in lieu of bolts) was selected to eliminate the need to backfill bolt pockets on the intrados of the segments. With the use of a PE membrane CPL, the selected hardware also minimizes welding requirements without the need to patch the CPL at bolt pocket locations. For the specimen design, a lifting socket is specified in lieu of vacuum lift to avoid any potential damage to the PE membrane. However, the contractor is reviewing appropriate handling methods.

From a design perspective, the critical aspect for this solution is the hydrostatic pressure. The maximum hydrostatic pressure along the alignment is estimated at 8.7 bar, which by far exceeds the undrained capacity of a cast-in PE membrane. Theoretically though, given a drainage pathway, the hydrostatic pressure should drain from behind the PE membrane without otherwise damaging the lining. The drainage pathway is provided via un-welded joints below the dry-weather flow level (i.e., in the invert of the tunnel). The contractor will be testing the assumed drainage relief behaviour using full-scale testing prior to tunnel construction, which will include pull-off tests and back pressure tests.

One option considered for the tunnel lining system was Combisegments, a proprietary product manufactured by Herrenknecht Formwork for plastic-lined tunnel segments. A benefit to Combisegments is that in-situ joint welding is not required due to the plastic lining wrapping around segment joints. However, this results in fully sealed (undrained) membrane joints requiring consideration of other drainage options. To date, this system has not been utilised in such high hydrostatic pressure conditions.

Photograph 2: Combisegment cast in lining

From the construction perspective, the critical aspects for this solution are the quality of the precast lining system and the quality of the in-situ welded joints. Quality of the lining system (i.e. concrete segmental lining and CPL) will be achieved through pre-production and production testing. Welding of the joints is a significant task with an estimated joint length of 80 km in the 13 km long tunnel. The contractor will determine how best to complete the welding adapting some lessons learned from previous projects.

Photograph 3: Example of Plastic-Lined Segmental Linings from Doha

Photograph 4: Radial Joint Welds on Plastic-Lined Segmental Linings from Doha

4.4.2 SHAFT LINING

There are a total of 17 shafts (including Mangere Pump Station) across the project (for the main tunnel and link sewers) that would typically be constructed of OPC concrete. However, due to the predicted corrosion rates, similar options to the tunnel lining were considered for the shaft linings on a case-by-case basis. For the two small shafts (3m internal diameter), a solution utilising a GRP pipe liner in a drilled shaft was adopted. For shafts larger than 3m diameter where drilling a bentonite-filled shaft is impractical, the selected solution depended on the predicted corrosion rate at the specific shaft. Where predicted corrosion rates were sufficiently low, the solution of OPC concrete with sacrificial concrete thickness was adopted. However, where predicted corrosion rates exceeded practical limits for this solution, an alternative solution was needed.

Based on the complex geometry of the cascade drop shafts and the confined space nature of these shafts, the assessment of the lining options resulted in a different solution. Eight of the shafts together with the Mangere Pump Station wet well lining are to be constructed using Acid Resistant Concrete (ARC). The basis for the use of ARC is a three year comprehensive investigation into using ARC materials undertaken by Watercare. This investigation included the following activities over the course of the investigation:

- a desktop study of potential suppliers of ARC material;
- material coupon exposure to the in-situ environment (i.e. "field testing" of several suppliers);
- Request for Information (RFI) for the supply of ARC for linings;
- independent laboratory testing study on pre-qualified suppliers from the RFI; and
- an assessment of approved suppliers based on results of independent testing study.

DESKTOP STUDY

Watercare and the design team explored the use of ARC as a corrosion mitigation strategy as a desktop study in the early design stages of the project. The binder for ARC should be inherently more corrosion resistant than OPC concrete therefore reducing the corrosion rate and consequently reducing the required sacrificial section. The study included initial discussions with Wagners (Earth Friendly Concrete suppliers) and Sydney Water who were in the process of developing a specification for 'Corrosion Protection of Sewers using Geopolymer Concrete' (SS 212). Additionally, this included discussion with an in-house concrete specialist. The results of the desktop study indicated that the use of acid resistant concrete would be feasible to provide a reduced corrosion rate relative to OPC concrete.

Based on product supplier information and relevant literature at the time, it was anticipated that ARC concrete would provide corrosion rates that were 20% of the estimated OPC corrosion rates. The subsequent investigation was targeted at validating this reduction.

COUPON TESTING

In the early stages of investigating ARC materials, several potential suppliers were offered the opportunity to submit 200mm (length) x 100mm (diameter) coupons to be placed into a live sewer environment similar to the environment that the new CI construction works will be exposed to. The following suppliers provided coupons for this portion of the investigation:

- Wagner Concrete – Earth Friendly Concrete (EFC),
- Geopolymer Solutions – Cold Fusion Concrete,
- bannahUK – bannahCEM,
- Hynds / Holcim – B2 and XA3 concrete with Bicrete, and
- Holcim – control OPC concrete samples.

Two coupons from each supplier were placed in three separate locations in the Watercare sewer system: MH07 and MH12 on the Western Interceptor and MH01C of the South Western Interceptor (inside MWWTP). These coupons were marked for identification and placed within existing manholes on 10 February 2017. Additional samples, not exposed to the sewerage system environment, were kept as a reference to determine if a reduction in strength is apparent.

These coupons have been subject to inspection by WSL every 6 months including calculation of mass and dimension loss. The location of the coupons has been monitored for H2S concentration, humidity and temperature. As one of the originally selected locations (MH7 on the Western Interceptor) has demonstrated a lower corrosive environment than predicted, this set of coupons was moved to PS43 (Highbrook) in August 2018 – a location known as a very corrosive site in East Auckland.

Additionally, Kerneos Calcoat RG samples were added much later to MH12 on the Western Interceptor and MH01C of the South Western Interceptor in August 2018. The Kerneos samples are slightly different than other coupons in that they are 150mm diameter permeability samples. At the time of writing, the original coupons had been tested at 6, 12, 18, and 24 months. The Kerneos samples have been tested at 6 months. There has been no appreciable change in mass or dimension although the samples are showing some visual evidence of corrosion, particularly at the MWWTP site. The pH readings had high variability from the initial readings and pH readings have since ceased. Destructive testing for compressive strength is proposed at a future date.

RFI TO SUPPLY ARC

On 24 February 2017, an RFI was presented to the market by Watercare, detailing the CI project and seeking information from suppliers for ARC products, specifically for resistance against microbially induced corrosion (MIC), suitable for precast and cast in-situ concrete applications. The RFI document noted that the information supplied would form the basis of selection for a testing program conducted by Watercare. There were 11 respondents to the RFI and, from this pool of potential suppliers, four products qualified to be included in the independent test programme. This qualification process involved assessment of the following:

- adequacy of information received;
- appropriateness of acid resistant testing;
- ability to supply to NZ;
- suitability for use with NZ-based aggregates;
- quality system accreditation;
- significant health and safety concerns;
- suitability of mix design and composition elements (proven track records and commercially available);
- case history (examples of proven quantitative reduction in corrosion rate for material proposed); and
- supplier ability to supply bulk materials to NZ.

After an initial screening process using these criteria four ARC suppliers were selected to proceed into the testing programme. They were:

- Wagners – Earth Friendly Concrete (EFC), referred to as “W”, a geopolymer concrete
- Kerneous (Imerys) - Calcoat RG, referred to as “K”, a calcium aluminate concrete
- Hynds / Holcim Ultracem concrete with Bicrete, referred to as “ARCB”, a Pulverised Fly Ash (PFA) OPC with titanium dioxide biocide
- Holcim – Ultracem, referred to as “ARC,” a PFA OPC concrete without Bicrete and
- Holcim – control OPC concrete samples. Referred to as “B2.”

LABORATORY TESTING

During the detailed design of CI, the design team continued to investigate ARC materials and relevant industry standards. It was determined that the German DIN 19573 standard for testing the resistance of concrete materials to biogenic sulphuric acid attack was more applicable than the testing procedure from Sydney Water (SS212), as it provided performance requirements for suitable materials. Additionally, testing in a biogenic corrosion chamber was identified to be the best representation of MIC resistance. However, due to the duration of the MIC chamber testing, both acid bath (accelerated method) and corrosion chamber testing were utilised to confirm the resistance properties of the concrete materials.

The independent testing programme funded by Watercare evolved significantly over the course of its development. The final programme involved the samples being prepared by an independent laboratory, WSP Opus International Consultants, with the majority of the relevant testing procedures being carried out by either WSP Opus in New Zealand, or alternatively sent to a suitable independent testing laboratory in Australia.

The suppliers provided binder samples and mix designs for the testing and witnessed the batching of the concrete. Fine and coarse aggregates were provided by Stevensons and Atlas Quarries in Auckland, and shipped to the WSP Opus lab in Petone, Wellington. WSP Opus tested the physical properties of the selected ARC materials through a range of test procedures that assessed the materials suitability for producing concrete to the required standards for use on the CI project. These procedures are described in the following table.

State	Property	Test Method
Fresh Concrete	Slump – initial and after 90 minutes	NZS 3112:Part 1
	Temperature	NZS 3112:Part 1
	Fresh Density	NZS 3112:Part 1
	Air content	NZS 3112:Part 1
	Bleed volume & %	NZS 3112:Part 1
	Setting time – initial, final	AS/NZS 2350.4
	Soundness	AS/NZS 2350.5
	Heat of Reaction	AS 2350.7
Hardened Concrete	Compressive strength @ 24 hrs., 7, 14, 28 and 56 days	NZS 3112: Part 2
	Cured at 50 degrees C 3, 7 and 14 days	NZS 3112: Part 2
	Concrete density at 28 days	NZS 3112: Part 2
	Sulphate content	BS EN 196-2
	Sorptivity	RMS (NSW) T362
	Drying shrinkage	AS 1012.13
	Dimensional change before drying and at 56 days	
	Water permeability (for CAC post conversion)	BS EN 12390-8
	Absorption	AS 1012.21
	Chloride ion migration	NT Build 492
	Chloride ion diffusion	NT Build 443

Table 2: ARC Physical Property Testing

Acid immersion testing per German DIN 19573 standard, to test the products' resistance to biogenic sulphuric acid attack, was undertaken by the University of Sydney. Test samples prepared by WSP Opus were provided to the University of Sydney and immersed after 29 days of curing. The 40mm cubed samples were immersed in baths of sulphuric acid (at pH = 0 and 1) that sat on a shaker table to keep the acid concentration homogenous, with additional samples in a separate tank of tap water as a control.

Sixty samples were tested in this facility with the samples being crushed after the test period (which was 14 days at pH = 0 and 70 days for pH = 1). The test rig and results after immersion are shown in figures below.

Photograph 5: Acid Bath Immersion Test Rig at the University of Sydney

Figure 6: Results of Acid Bath Immersion Testing by the University of Sydney

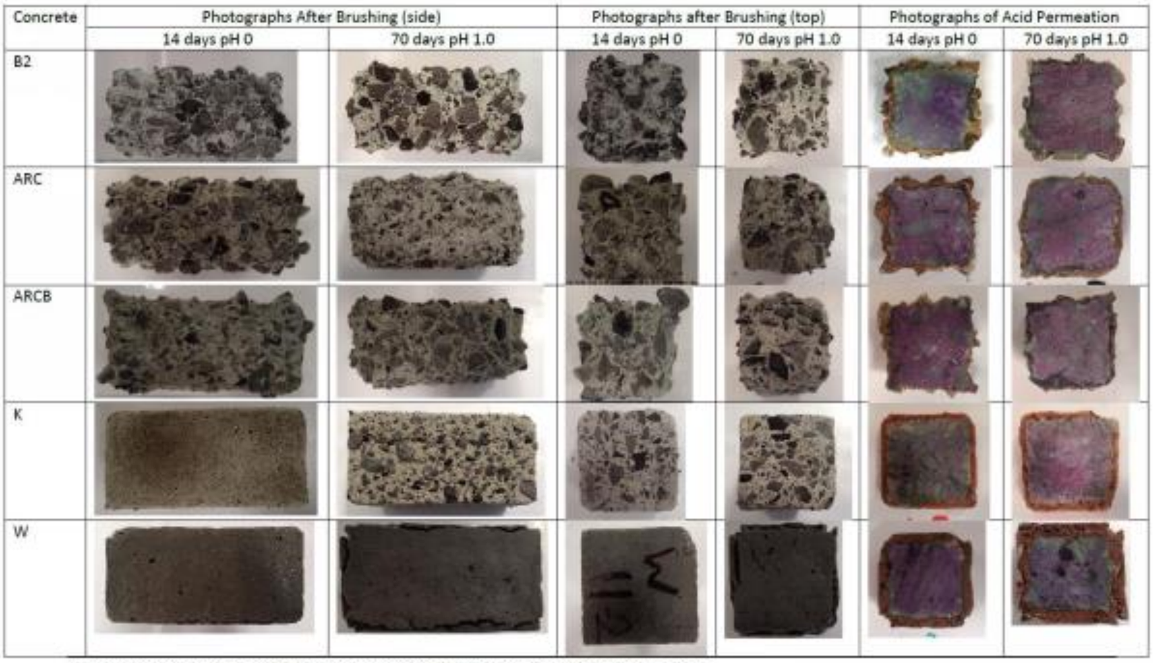
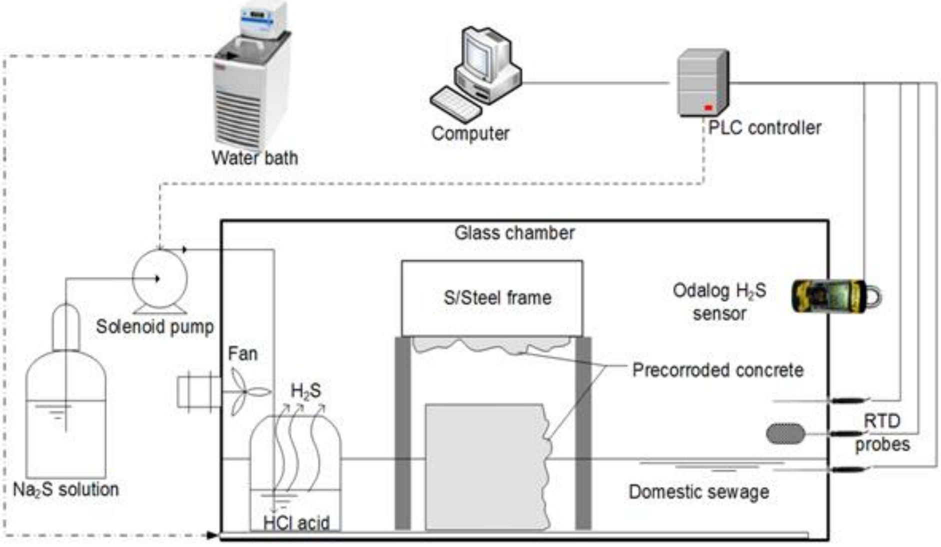


Figure 1 Summary of Example Photographs of Corroded Concretes and Acid Permeation

Testing of the samples within a biogenic corrosion chamber (simulating the sewer environment) was undertaken by the University of Queensland. The corrosion chamber tested the four different types of ARC, together with the OPC concrete control sample for microbial induced corrosion and durability properties. The procedure tested the corrosion development over a period of 12 months. The coupons were pre-treated in acid to reduce the surface pH and facilitate the growth of acidophilic microorganisms and then placed in the corrosion chamber. The samples were inoculated with real wastewater to induce active microbial corrosion. The corrosion chamber is constructed to achieve a relative humidity of 100% and average H_2S gas concentration of 50 ppm. Refer to Figure 7 and Photograph 6 for the test chamber setup.

The purpose of operating the corrosion chamber under these conditions is to achieve accelerated corrosion rates (greater than would be experienced in the CI sewage network) to establish the corrosion resistance of the selected materials. This had to be completed in an acceptable timeframe for confirmation of the most appropriate material of construction for the CI. The test programme was concluded prior to contract award.

Figure 7: Biogenic Corrosion Chamber setup at the University of Queensland



Photograph 6: Reactor Chamber and On-line Monitoring of ARC samples at the University of Queensland

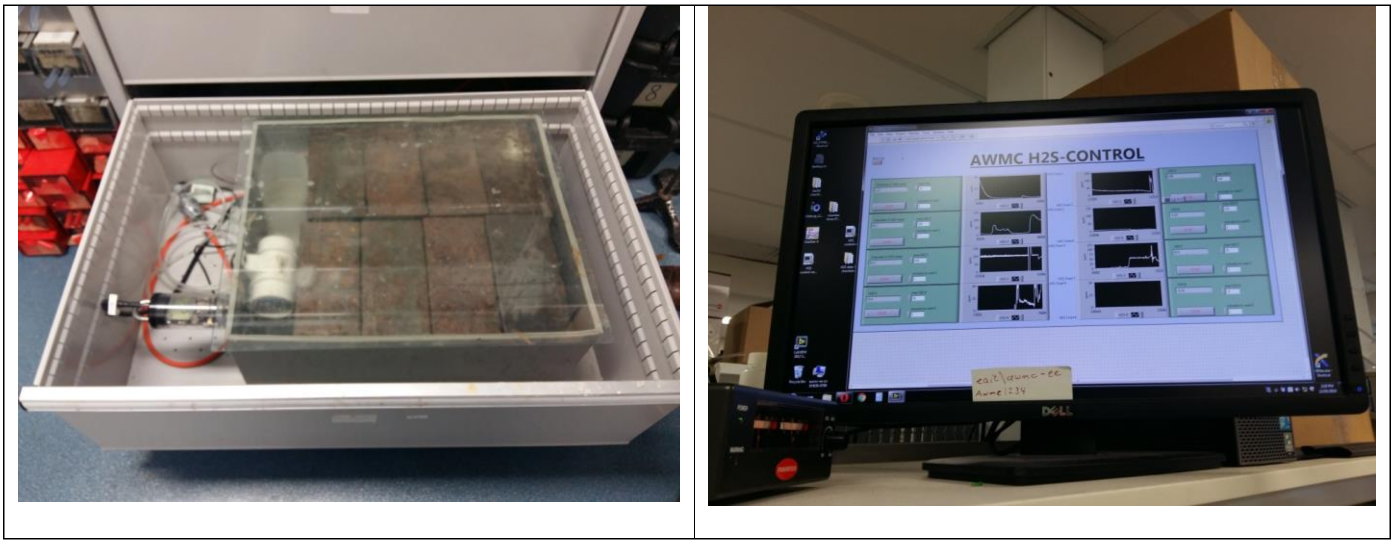
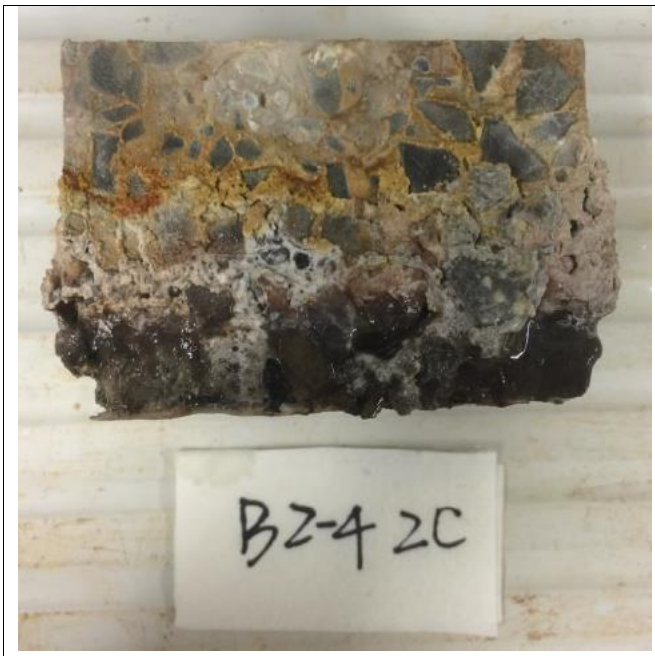
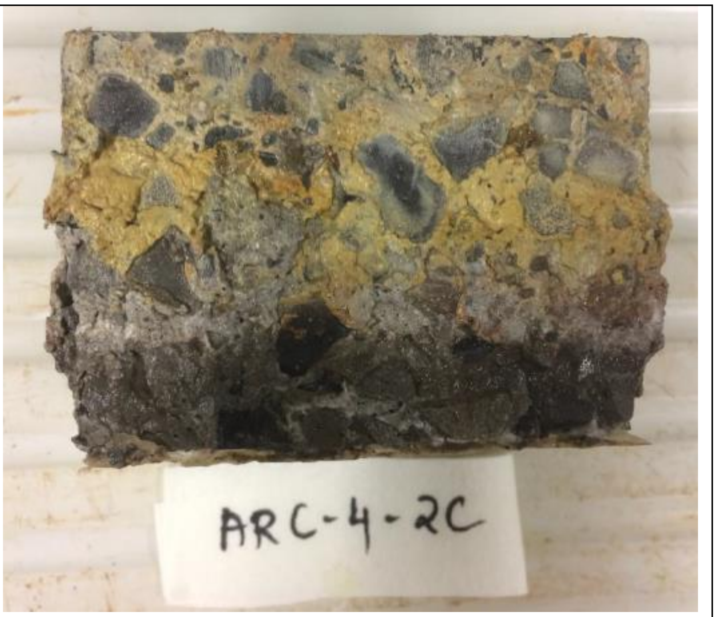


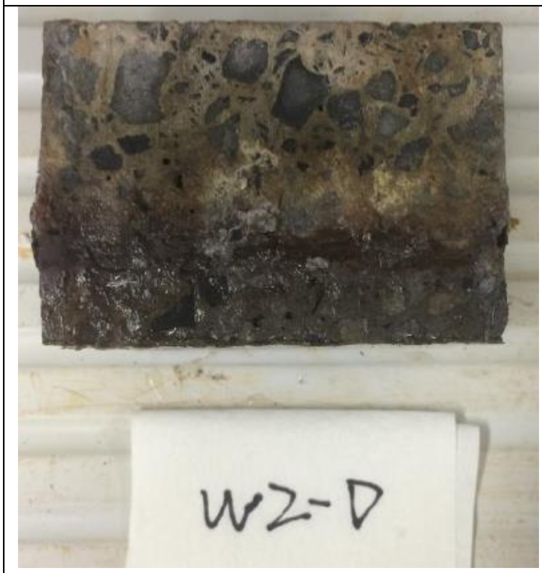
Figure 8 below shows the ARC samples after exposure in the biogenic chamber for 12 months. The B2 (OPC), ARC and ARC-B samples all show advanced corrosion. The K sample is not as severe (an aggregate chunk has fallen out on the right-hand side making it look worse than it actually is) whilst the W sample is the most intact. On conclusion of the exposure testing all but one of the remaining samples were crushed in an unconfined compression strength test rig to confirm the residual strength of the remnant.

Following the biogenic chamber testing the remaining K, W and B2 samples were sent to the USA for petrographic examination and analysis by scanning electro microscopy (SEM) and x-ray diffraction (XRD). The findings from the petrographic examination show evidence of chemical and mineralogical alteration of the binders that is typical of sulphuric acid attack associated with microbial activity. The three samples showed significant variability in capillary porosity with the W sample the lowest and K the highest. The deterioration mechanisms involved microcracking filled with gypsum, pervasive replacement of the paste by gypsum, and leaching and increased porosity. The W sample was the only sample to exhibit microcracking in the gas phase.

Figure 8: Biogenic Corrosion Chamber Samples After 12 Months







Average residual strength after 12 months exposure in the biogenic corrosion chamber:

Sample	**Residual**	**Original**	**% change**
B2	77.8 MPa	87.5 MPa	-11%
ARC	73.0 MPa	77.8 MPa	-6%
ARC-B	63.6 MPa	77.6 MPa	-18%
K	63.6 MPa	74.5 MPa	-15%
W	55.0 MPa	52.8 MPa	+4%

ASSESSMENT OF APPROVED SUPPLIERS

The results from the independent testing programme were intended to form a benchmark for the supply of ARC materials to the project, with further mix designs anticipated to be tested for optimisation during the post-tender and pre-production stages.

During the tender process, further testing of the products from the pre-qualified suppliers was conducted to prove the workability of the ARC materials. This testing included the following:

- demonstration of concrete batching, slumping, pouring into mould, and test sample casting of an EFC mix provided by Wagners on 27 July 2018 and
- demonstration of concrete batching, slumping, pouring into mould, and test sample casting of a Calcoat RG mix provided by Kerneos on 1 August 2018.

Following the receipt of the full suite of test results including the DIN 19573 acid bath testing (14- and 70-day immersion), the corrosion chamber testing (at 5 and 12 months), the physical property testing completed before and during the tender process, and the results of petrographic examination, Watercare confirmed their selection of the pre-qualified suppliers. These suppliers were Wagners – Earth Friendly Concrete (EFC, a geopolymer concrete product) and Kerneos Calcoat RG (a calcium aluminate concrete product, CAC). These ARC materials achieved the target corrosion rate of not more than 20% of the reference OPC sample results.

The intention of using both acid bath testing and corrosion chamber testing was to establish a correlation between these tests such that future acid bath testing, which is much quicker (70 days exposure), may provide indicative results of a material's MIC resistance. However, due to anomalies reported in the test results of the acid bath testing, this correlation cannot be established with the current test results. As agreed by the durability experts engaged on the project, the corrosion chamber results should provide a better reflection of the service conditions, as opposed to the acid immersion testing, and therefore a greater reliance is be placed on these results for this project.

4.4.3 OTHER ELEMENTS

In addition to selected drop shaft linings, ARC is being utilised for the construction of the Mangere Pumping Station wet well lining, for MWWTP confluence chamber, and the roof slabs of two additional shafts.

For two of the small (3m) diameter shafts, the selected solution is a single pass lining system provided by glass-fibre reinforced polymer (GRP) pipes. GRP pipes have been utilised for sewer linings in both tunnels and shafts worldwide. GRP is an inherently corrosion resistant material. The critical aspects for the design of such a system are related to the connection details to ensure continuous corrosion protection and groundwater control.

The link sewers to be constructed by pipe jacking methods will utilise OPC concrete jacking pipes with a corrosion protection liner and redundant sacrificial concrete section similar to the main tunnel segmental lining.

4.5 QUALITY, MONITORING, AND MAINTENANCE

For the tunnel lining system, the contract specifications require a robust testing and inspection scheme for the OPC concrete, tunnel segments, and CPL. This scheme is targeted at ensuring that appropriate materials are selected for the concrete and CPL and that the construction methodologies do not damage these materials in such a way that might affect their long-term performance. The tunnel will be difficult to access for future inspection and maintenance, so the contractor is currently reviewing options for incorporating monitoring into the design.

Some examples utilised on other projects include a clear PE membrane that allows for easier identification of issues in the tunnel segments, a PE membrane that includes a warning layer (i.e. a different colour that indicates where the membrane is scratched or damaged during installation), and potentially the use of fibre optics to measure deflection of the lining systems.

Similarly, for the shaft linings, the contractor is reviewing options for incorporating monitoring into the design. Current options in discussion include the use of lining deterioration pins that can monitor the loss of concrete over time. This will allow Watercare to validate performance against design assumptions.

In addition to standard concrete production tests, additional biogenic corrosion chamber testing (12-month duration) will be conducted in parallel with the CI construction for samples of the specific mixes being utilised for construction. Acid bath testing may also be conducted by Watercare to review correlation. Standard production testing for physical properties such as strength, permeability, and chloride diffusion will be utilised throughout the project to confirm consistency of the mix.

5 KEY LESSONS

The Central Interceptor project is a significant investment in wastewater infrastructure that ranks on a global scale. The size of Watercare's investment warranted a rigorous examination of the in service environment and system performance during the design phase. The investigations have spanned three years of research into the anticipated operational regime and the available materials to ensure that the proposed 100 year asset life was achievable.

The field and laboratory testing has endeavoured to mimic the accelerated corrosion that is anticipated throughout the asset's life in a relatively short time. Durability standards and test methods are still being developed and correlated against the actual performance of materials in the field. The laboratory work done to date has confirmed the performance of these materials in a corrosive sewer environment.

The pool of suppliers willing to participate in such a programme was limited due to the type of application and the scale of investment. The RFI process yielded a small group of products that were selected on track record and ability to supply into New Zealand, but there were a number of promising suppliers who could also have participated if they had the resources and willingness to join the test programme.

Such research requires considerable resource and time when also trying to meet the procurement schedule. Watercare took the decision in 2016 to undertake the research ahead of market engagement, as there would have been insufficient time during the tender process to obtain the required evidence to select an appropriate system.

6 CONCLUSIONS

The corrosion protection strategy for the CI project was determined through a programme of analysis and testing of the real life in-sewer environment, computer modelling, laboratory testing and risk assessment, with guidance from international expertise. The corrosion protection of this critical asset will be achieved through a multi-prong approach. The hydraulic and ventilation designs contribute as does the selection of appropriate construction materials. When completed the CI tunnel will be the longest tunnel in New Zealand and will be difficult to access to complete inspections and repairs, so a more traditional corrosion protection strategy was selected such as that utilised on the STEP and IDRIS projects. For the shafts and other project elements, an investigation into alternative acid-resistant materials was undertaken and completed in time for the tender process.

ACKNOWLEDGEMENTS

This paper is based on the work of a wide team of advisers including:

- Watercare – Stephen Grace, Bojan Jovanovic
- Jacobs – Nigel Kay, David Lynch, Don Wimpenny, Jon Sickling
- AECOM – Tony Margevicius, James Aldred, Martin Evans, Peter Stacey
- McMillan Jacobs Associates – Victor Romero, Shannon Goff, David Kubik

The authors also wish to acknowledge Ashghal (the Doha Public Works Authority) for use of the photos from the Doha South Sewer Infrastructure Project, and Anna Olliver of Jacobs for arranging this permission.

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