WSP Research & Innovation Centre
33 The Esplanade, Petone
PO Box 30 845, Lower Hutt 5040
New Zealand

+64 4 587 0600
www.wsp.com/nz

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s7(2)(a)
Senior Project Manager

RCP
Level 4
40 Johnston Street
Wellington Central
Wellington 6011

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Durability Assessment of Waterloo Station Subway Cores

Dear s7(2)(a)

This letter provides the results of a durability assessment undertaken on two recently-received concrete core samples, reportedly extracted from the pedestrian subway at Waterloo Railway Station.[1]

It is understood that this structure was built in the late 1980s and, as part of a wider options report being completed for the station, testing was desired to ascertain whether there was any durability threat present that might compromise the foreseeable residual life of the structure.

Analyses were completed to measure carbonation depth and the extent of concrete contamination present; development of widespread reinforcement corrosion due to these deterioration mechanisms is considered to be the most probable limitation on the potential longevity of a reinforced concrete structure under New Zealand conditions according to NZS 3101: 2006 'Concrete Structures'.[2] At the request of Dunning Thornton,[1] risk analysis was primarily completed with respect to the exterior face of the concrete, which was unambiguously discernible by the remnants of a Bituthene® or similar asphaltic waterproofing membrane adhered to one end of each core.

1 Methodology

1.1 Carbonation

The cores were initially sectioned longitudinally with a water-cooled diamond saw to expose a fresh concrete surface suitable for carbonation testing that had not previously been directly exposed to the atmosphere. These cut surfaces were permitted to briefly air dry before being sprayed with a 1% w/v solution of phenolphthalein reagent.[3] Functioning as an acid-base indicator, phenolphthalein solutions are colourless below a pH of 8.5 but develop an intense pink to magenta colour where the pH is greater than ca. 9. The depth of concrete beneath the surface that is not stained by the application of the phenolphthalein solution is considered to be carbonated, i.e. depleted in alkalinity due to the complete consumption of calcium hydroxide within the cementitious matrix through reaction with atmospheric CO_2. Any mild steel reinforcement lying within this carbonated zone is no longer passivated by a highly-alkaline surrounding environment and hence becomes potentially susceptible to carbonation.

1.2 Chloride Contamination

Following completion of the carbonation testing, the split cores were then sub-sectioned transversely into four nominal 15 mm deep slices, representing depth increments from 0 – 20 mm, 20 – 40 mm, 40 – 60 mm & 60 – 80 mm through the cover region of the concrete, beneath the externally-exposed surface.

[1] Nicki Vance (Dunning Thornton), *personal communication*.

[2] Standards New Zealand. NZS 3101:2006. *Concrete Structures Standard. Part 1: The Design of Concrete Structures & Part 2: Commentary*. Wellington, New Zealand.

[3] RILEM Recommendation CPC-18. 1998. 'Measurement of hardened concrete carbonation depth'. *Materials & Structures* 21 no 6, pp 453 – 455, November 1998.

The concrete slices were dried, crushed to a fine powder and analysed by XRF (x-ray fluorescence spectroscopy) to determine the total chlorine content as a percentage of the dry mass of concrete (%w/w). Use of XRF by a suitably experienced IANZ-accredited laboratory is a permitted method of chloride analysis for determining risk of reinforcement corrosion under NZS 3101.

Chloride ions in sufficient concentration are unique and specific agents for the corrosion of mild steel reinforcement; they destroy the protective surface oxide layer that ordinarily develops on steel surrounded by alkaline concrete, a process known as 'depassivation'. It is generally accepted that corrosion will only occur once the chlorides accumulate beyond a critical concentration in the concrete surrounding the reinforcement. Consequently it is important to understand the intensity and distribution of any chloride contamination present. Chloride ions can be introduced either through progressive infiltration by environmental sources or cast-in contamination that typically arises from incorporation of poorly-washed marine aggregate or calcium chloride based set accelerating admixtures in the original mix design.

In practice, because of the wide variety of possible concreting materials and exposure conditions, there is no unique concentration of chloride ions that invariably cause reinforcement depassivation.[4] Current thinking identifies a range of probabilistic risk levels for corrosion with particular concentrations, as shown in Figure 1;[5] the broad diffuse nature of the plot emphasises the range of uncertainty associated with these assertions. For simplicity, this report considers two discrete thresholds for corrosion suggested by the UK Concrete Society: Chloride ion concentrations above 0.05% by mass by mass of concrete at the depth of the reinforcement can be thought of as sufficient to present '*some risk*' of depassivation with subsequent corrosion developing, whereas concentrations above 0.15% indicate a '*high risk*'.[6]

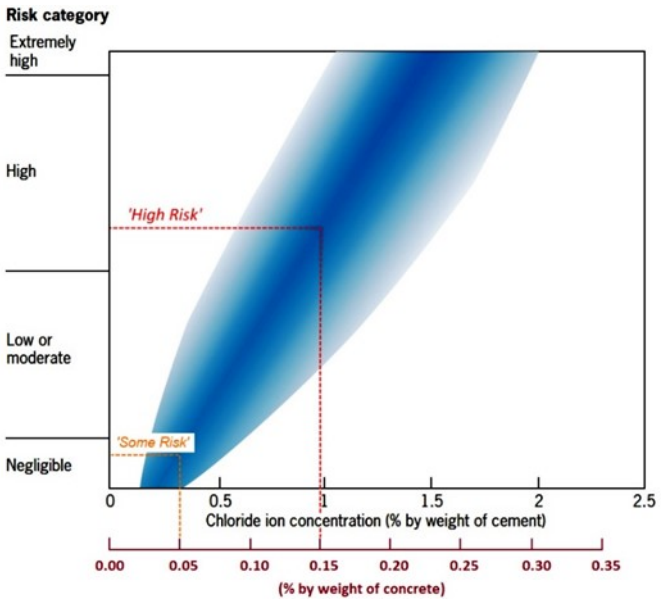

Figure 1. Estimated risk of steel reinforcement corrosion associated with ingress chlorides (adapted from BRE Digest 444 Part 2 to account for chloride analyses determined on percent concrete rather than cement).

[4] Glass, G. K. & Buenfeld, N. R. 1995. 'Chloride threshold levels for corrosion-induced deterioration of steel in concrete'. RILEM International Workshop on Chloride Penetration in Concrete, St-Remy-Les-Chevreuse, France, pp 429 – 440.

[5] BRE. 2000. Digest 444 Part 2. *Corrosion of Steel in Concrete: Investigation and Assessment*. Watford, United Kingdom.

[6] UK Concrete Society. 1984. *Technical Report 26 Repair of Concrete Damaged by Reinforcement Corrosion*. Camberley, United Kingdom.

2 Results

Table 1 summarises the results obtained from measurement of the carbonation depth and extent of chloride contamination in the cores.

To aid interpretation of this numerical data, the results for the individual cores are also depicted graphically as Figure 2. In these corrosion risk plots, the chloride profiles (i.e. the measured concentration vs. the midpoint of the sampling depth increment) are plotted in blue and the orange and red dashed horizontal lines indicate the UK Concrete Society's chloride concentration thresholds for various probabilities of the onset of corrosion. Chloride contamination levels that lie above the risk threshold at, or beyond, the depth of the concrete cover over the reinforcement indicates a potential threat of reinforcement corrosion.

The maximum depth of the carbonation front beneath the exterior surface of the concrete is illustrated by the position of the solid green vertical bar annotated with the label 'C.F.'. Where the carbonation front has progressed as far as, or beyond, the depth of the reinforcement, these bars lie in alkali-depleted concrete and are consequently also potentially vulnerable to corrosion.

Table 1. Summary of durability analysis of supplied cores.

Core Identifier	Reinforcement Cover (mm)	Maximum Carbonation Depth (mm)	Chloride Analysis	
			Depth Increment (mm)	Concentration (%w/w on concrete)
1	45 mm	5 mm *from exterior (membrane coated) face*	0 – 20	0.010
			20 – 40	0.013
			40 – 60	0.010
			60 – 80	0.013
2	45 mm	4 mm *from exterior (membrane coated) face* 13 mm *From interior face* *Patchy carbonation visible along margin of apparent construction joint extending full length of core*	0 – 20	0.042
			20 – 40	0.014
			40 – 60	0.036
			60 – 80	0.036

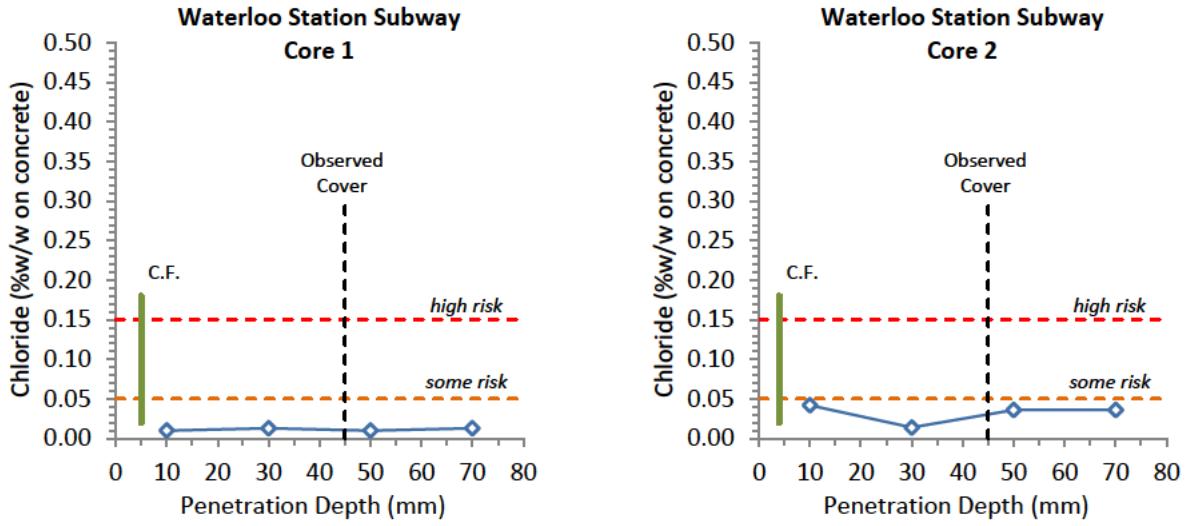

Figure 2. Chloride contamination profiles and position of the carbonation front (from the external concrete face) measured on the provided core specimens for evaluation of the current and future reinforcement corrosion risk.

Illustrative photographs of the longitudinal slices cut through the cores to determine carbonation depth recorded following application of the phenolphthalein indicator solution are reproduced as Figure 3. The coarse aggregate is a quite heavily-weathered alluvial greywacke with a maximum particle diameter of 13 mm. Core 2 has intersected a prominent construction joint extending the full length of the specimen. The reinforcement intersected in both cores is 20 mm diameter deformed bars with a measured cover of 45 mm from the exterior surface. The original interior face of Core 1 is not preserved with the sample delivered displaying a cut surface.

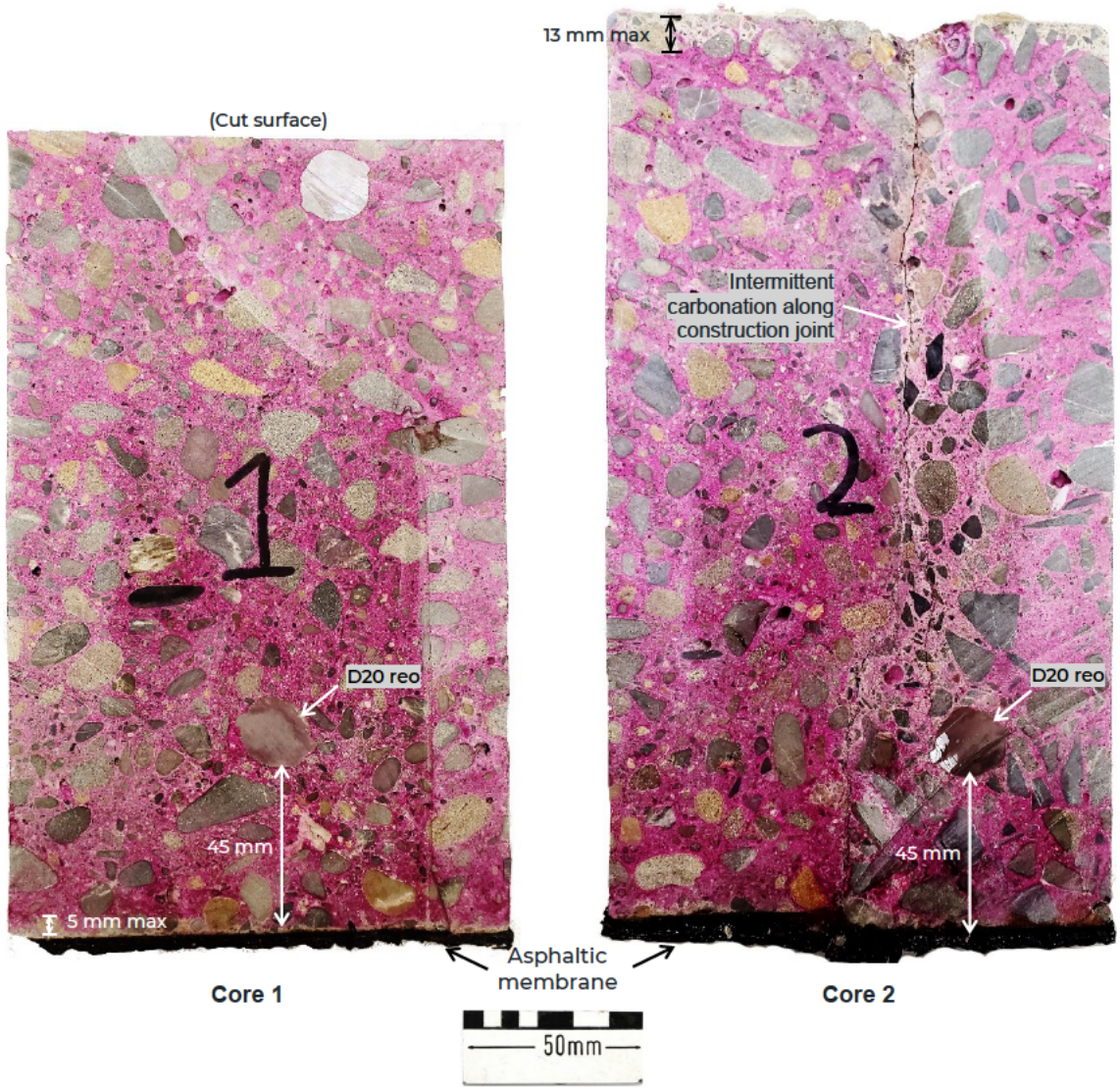

Figure 3. Longitudinal slices through cores photographed after application of phenolphthalein indicator to ascertain carbonation depth; the exterior face of the core is at the bottom. Any regions of the concrete that remains colourless – rather than being stained a magenta colour – is effectively carbonated.

3 Interpretation

It can be seen that:

i. Carbonation of the concrete is minimal with no appreciable loss of alkalinity from either the exterior or interior faces of the cores that would threaten the embedded reinforcement at the observed cover depth.

ii. There is no obvious chloride concentration profile through the cover concrete that would suggest permeation from an external environmental source that will accumulate further in the future. The background concentration in Core 2 is typically somewhat more elevated than would be expected from the normal contribution of routinely used Wellington ready-mix concrete constituents but at an observed maximum of 0.042% w/w is not sufficiently high as to pose a realistic risk for initiation of

reinforcement corrosion providing the bars are thoroughly encapsulated within well-consolidated concrete. This appears to be the case, with no appreciable excessive voidage or gross compaction defects noted to affect the supplied cores.

iii. Consistent with these findings, there is no evidence for active corrosion initiation on any of the reinforcing bars intersected by the cores.

Based on the durability analyses completed, there is no evidence for the presence of a systemic durability threat that would compromise the foreseeable future serviceability of the subway structure from which the cores were extracted. This statement is contingent upon the following caveats:

- WSP was not involved in the selection of the core locations and has no knowledge of how representative the particular specimens supplied for testing may be of the durability performance or exposure environment of the subway in its entirety.
- It is assumed that the environment to which the concrete has historically been exposed remain comparable in the future.

I trust this information is helpful. Please contact us if you have any queries regarding the contents of this report.

Prepared by:

s7(2)(a)

Senior Concrete Technologist

Reviewed by:

s7(2)(a)

Laboratory Technician