geopolymer concrete as well. Reduction in the alkaline activator content also has the potential of reducing the overall cost of the geopolymer concrete.

Table V. In-situ Geopolymer Concrete Landscape Retaining Walls Cylinder Compressive Strengths

Cast No	Date	Zeobond B No.	1 Day	3 Days	7 Days	14 Days	28 Days	7 Days @60^{O} C
1	15/07/2009	233	-	9.7	33.3	-	44.3	45.8
2	11/08/2009	271	15.0	23.7	33.4	-	48.5	47.3
3	14/08/2009	276	14.5	25.3	33.3	37.9	42.5	48.9
4	14/08/2009	277	8.4	20.9	28.7	34.1	40.4	44.3
5	16/09/2009	308	3.7	30.1	36.0	41.2	-	49.7
6	17/09/2009	309	11.3	26.6	34.9	38.6	-	50.0
7	23/09/2009	312	18.0	22.2	34.2	45.2	-	-
8	23/09/2009	313	11.4	26.3	36.6	44.6	-	53.0
Average			11.8	23.1	33.8	40.3	43.9	48.4
In-situ core strength D/S Wall			Average Strength – 50.9 MPa (Core)(After 7 months)					
In-situ core strength U/S Wall			Average Strength – 44.3 MPa (Core) (After 7 months)					

Overall Observations and Learnings from both Trials

A major observation of both the precast and on-site geopolymer trials was the need to significantly improve and optimize geopolymer mix designs in order:
to facilitate workability, flowability, compactability and finishability;

- to significantly minimise the amount of water used and W/C ratio;
- to significantly reduce the VPV (reduce permeability); and
- to consistently satisfy the compressive strength requirements

The amount of total water used in the geopolymer concrete is significantly higher (by some 50 to 80 litres compared to conventional structural concretes of 150 – 180 litres per cubic metre. In general discharge times can be managed similar to conventional concrete (up to 90 – 120 minutes).

Table VI. Drying Shrinkage Retaining Walls (Max. Limit at 56days-750micro strain)

Cast Num	Date	Zeobond B No.	Cast	7 Day	14 Days	21 Days	28 Days	56 Days
1	15/07/2009	233	0	25	250	343	368	432
2	11/08/2009	271	0	107	282	361	582	618
3	14/08/2009	276	0	121	321	489	486	-
4	14/08/2009	277	0	36	218	396	579	-
5	16/09/2009	308	0	39	286	389	-	-
6	17/09/2009	309	0	-29	146	-	-	-
7	23/09/2009	312	0	36	36	-	-	-
8	23/09/2009	313	0	79	118	-	-	-
Average				-	-	-	-	-

Table VII. VPV % for Retaining Walls, Max Limits at 28 days - rodded cylinders – 14%, - cores – 16% (VR400/40)

Cast Num	Date	Zeobond B No.	Slice A	Slice B	Slice C	Slice D	Ave @28Days
3	14/08/2009	276	22	22	22	-	22
4	14/08/2009	277	21	21	20	-	20.7
Average			21.5	21.5	21	-	21.4
In-situ VPV D/S Wall			VPV – 18% (Core)(After 7 months)				
In-situ VPV U/S Wall			VPV – 19% (Core)(After 7 months)				
In-situ core strength D/S Wall			Average Strength – 50.9 MPa (Core)(After 7 months)				
In-situ core strength U/S Wall			Average Strength – 44.3 MPa (Core) (After 7 months)				

In-Situ Testing of Geopolymer Concrete Retaining Walls

This site and laboratory investigation was aimed at giving a general assessment of the geopolymer concrete properties. Three cores were drilled from each of the two retaining walls, and tested for compressive strength, VPV and resistance to chloride penetration. The microstructure of the concrete was observed using the petrographic microscope and SEM/EDX (scanning electron microscope/energy-dispersive X-ray spectroscopy). The half-cell potentials were also measured to assess the corrosion state of the reinforcing steels.

On-site measurement results of the half-cell potential indicated that the steel is still passive, and corrosion activity is unlikely at present. However, the potentials are different in the different positions in each wall, and there is a significant difference between the two walls.

The two retaining walls contain somewhat different concrete mixes; that in the downstream wall having higher quality, indicted by higher strength and lower VPV. The denser downstream concrete had strength of 50.9 MPa and a VPV of 18%, whereas the less dense upstream concrete had strength of 44.3 MPa and a VPV of 19%. Petrographic examination showed that the concrete in both walls contained basalt as coarse aggregate, but the cementitious matrix showed much more micro-cracking in the upstream wall than the downstream wall.

The resistance to chloride penetration was tested only in one core from the downstream wall and was found to be very low which would be attributed to the high content of slag in the mix. The upstream wall may have a lower resistance to chloride penetration, due to the larger extent of microcracking.

Site Work and Tests Arrangement

Six cores were drilled from the retaining walls, including one 94 mm diameter and five 76 mm diameter x about 150 mm long cores. Table 8 presents details of the cores drilled and their allocation to various tests.

Table VIII. Details of Cores **Error! Reference source not found.**

Wall	Core ID	Diameter (mm)	Length (mm)	Tests
Downstream	C10/2036-1	94.2	154 – 162	ASTM C1202, NT Build443
	C10/2036-2	76.5	160 – 165	VPV, petrographic examination
	C10/2036-3	76.5	150 – 160	Compressive strength
Upstream	C10/2036-4	76.5	151 – 155	Compressive strength
	C10/2036-5	76.5	155 – 156	VPV, petrographic examination
	C10/2036-6	76.5	154 - 156	Compressive strength

The reference electrodes lead to two "reference electrode monitoring boxes", one on the top of each retaining wall, and each containing three pairs of wires labelled Top, Mid and Bottom to indicate the locations of the electrodes in the retaining wall. The wire to the reinforcing steel is white and that to the Mn/MnO2 reference electrode is blue. The half-cell potentials between reinforcing steel and reference electrode were measured at the different locations using a multimeter (internal impedance > 10 mm).

Drilling of Core 3 resulted in cutting the wire to the reference electrode at the mid location of north retaining wall.

It was observed that the concrete binder contains blast furnace slag which gave the newly exposed concrete a typical dark greenish colour in the interior and a light colour in the surface zone, due to oxidation in air (Fig. 2).

Results and Discussion

Half-Cell Potentials of Reinforcing Steel Bars

The reference electrodes were a manganese dioxide electrode in alkaline gel (Fig. 5), which was installed adjacent to steel bars at nominated locations. The potential of each electrode was measured against saturated calomel electrode (SCE) by the manufacture as calibration value. The calibration data were used for converting the measured values to CSE potentials. To compare the half-cell potentials with conventionally used criterion for steel corrosion, i.e. -350 mV copper-saturated copper sulphate electrode potential (CSE), the SCE values were converted to CSE.

The initial half-cell potentials readings after the hardening of the backfill in Sep–Oct' 09 were very negative; the direct reading being -600 to -800 mV for upstream wall and about -1000 mV for the downstream wall. The half-cell potential of the steel in concrete appeared to be stabilising over the following six months after construction with the potentials having shifted to more positive values by about 200 mV, as shown by the results of the monitoring system incorporated in the walls (Table 9).

Table IX. Half-Cell Potentials of Reinforcing Steel Bars (4)

Retaining Wall	Location of Electrodes	Potential as measured (mV)	SCE (mV)	CSE (mV)
Upstream	Top: Steel- Mn/MnO_2	- 393.0	- 201	- 301
	Mid: Steel- Mn/MnO_2	- 441.0	- 236	- 336
	Bottom: Steel- Mn/MnO_2	- 516.7	- 333	- 433
Downstream	Top: Steel- Mn/MnO_2	- 754.3	- 567	- 667
	Mid*: Steel- Mn/MnO_2	- 173.6	-	-
	Bottom: Steel- Mn/MnO_2	- 782.0	- 591	- 691

* According to CRC Handbook of Chemistry and Physics, the standard potential of calomel electrode in saturated KCl is 0.2412 V The standard electrochemical potential at 25°C is 0.3412 V SHE for reaction Cu2+ + 2e- R Cu.

At present, the steel bars in the downstream wall appear to be still in an oxygen deficient condition, which resulted in the very negative potential readings. The potential of steel in the upstream wall appear to be in the range which would indicate likelihood of corrosion initiation. The potentials are more negative towards the lower part of the wall. However, the potentials may still be on the way to shift to more positive direction in the future, and no conclusion can be made at this stage.

Compressive Strength of Concrete

The compressive strength tested on cores are shown in Table 5. The concrete of the downstream wall has a higher strength than that of the upstream wall. The more negative potentials for the downstream wall probably arise because the concrete is denser and slower to dry out.

VPV of Concrete

The VPV tested on cores is shown in Table 7. The VPV of downstream wall is better than that of upstream wall. Note that 1% VPV separates two grades of concrete, e.g. minimum VPV is 16% for VR400/40 and 15% for VR450/50 (tested by cores). However, the VPV is too high considering the strength values obtained. This could have arisen due to the nature of the geopolymeric binder. The VPV requirements for different grades of structural concrete, stated in VicRoads specification section 610, are yet to be validated with this type of binder.

Resistance to Chloride Penetration

As it was originally expected that the two retaining walls would have the same concrete only one core from the downstream wall was tested for chloride penetrability. Two test methods were used to assess the chloride penetrability, i.e. ASTM C1202 (Electrical Indication of Concrete Ability to Resist Chloride Ion Penetration), and NT Build 443 Method. The results are presented in Table 10 and Table 11, respectively.

The ASTM C1202 method ranks the concrete as having very low chloride penetrability. This may have resulted from the high slag content of the concrete, which would reduce the amount of ionic charges in the pore solution of the concrete, rather than from low porosity of concrete. As shown in Table 11, the

NT Build 443 test method resulted in a very low chloride diffusion coefficient (D= 1.58 x10^{-13} m^2/s). This result confirms the conclusion of ASTM C1202 test. The NT Build 443 test results and theoretical curve calculated using the diffusion parameters in Table 11 are presented in Fig. 7.

Table X. Downstream Retaining Wall - ASTM C1202 test results (Chloride Resistance) (Core testing after 7 months) (4)

Voltage (V)	Initial Current (mA)	Total Charge after 6 hours (C)	Penetrability
60	31.7	648	Very low

Table XI. Downstream Retaining Wall - NT Build 443 test results (Chloride Diffusion) (Core testing after 7 months)(4)

Duration of immersion (days)	Initial Chloride Content (%)	Chloride content at the boundary, Cs (%)	Diffusion Coefficient (m2/s)
35	0.01	1.15	1.58 × 10^{-13}

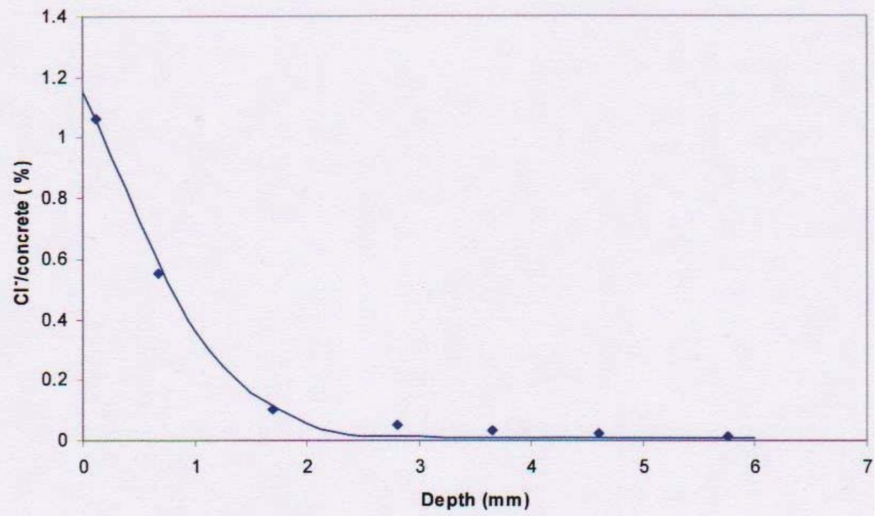

Fig. 7. Chloride profile of the NT Build 443 Test and theoretical curve based on diffusion parameters given in Table 11

Petrographic examination of cores

Core 2036-2 (downstream retaining wall)

In addition to the information relating to the various aggregates the petrographic examination found that the cementitious matrix appears to be very compact and includes numerous angular grains, typical of slag cement. The cementitious matrix exhibits isotropic features under cross-polarised light and is well bonded to the aggregate particles. Some areas of the matrix include a considerable number of round air bubbles, typically 0.3 - 0.5mm in diameter. Some areas of the matrix show a few fine microcracks which run between fine aggregate particles and sometimes join microcracks at the periphery of coarse aggregate pieces. The presence of microcracks may indicate reduced strength and increased VPV of the concrete, although the microcracking is not significant.

Core 2036-5 (upstream retaining wall)

In addition to the information relating to the various aggregates the petrographic examination found that the cementitious matrix is compact and isotropic under cross-polarised light, but contains fewer slag grains than the matrix in Core 2036-2, which could indicate better hydration. Numerous microcracks run throughout the entire cementitious matrix in different directions and some of the cracks traverse a portion of the coarse aggregate boundaries. It would be expected that the strength reduction and increased VPV would be more serious in this concrete than that represented by Core 2036-2.

SEM/EDX Examination

The SEM/EDX microstructural examination of the geopolymer concrete further compliments the observations from the petrographic examination and shows that the paste is very different from the paste of Portland cement concrete (Core C10/2036-3 from downstream wall which corresponds to Core C10/2036-2). Figure 8 shows a view of the geopolymer concrete paste and its composition. The paste is compact and rich in Na, Al and Si, with moderate amounts of Ca. Small amounts of Mg are also present. This composition arises from the use of Slag and Na-silicate as the main components of the concrete mix. This composition is very different from the composition of the Portland cement paste, which is dominated by Ca, with much smaller amounts of Si and Al, and only trace amounts of alkali. The high Al content helps in reducing the rate of chloride ion ingress into concrete, as indicated by the low diffusion coefficient (1.58 x 10-13 m2/s) obtained in the earlier study.

Crystalline phases were found in the paste which appear to be related to the monosulfate phase of Ca-sulfoaluminates (the larger crystals), and probably incorporates Si in its composition. The sulfate originates from the Portland cement. The finer granular crystals contain large amounts of Mg, which originates from the slag. In one core (Core C10/ 2036-3 from downstream wall) distinct alkali aggregate reaction (AAR) products have been identified which can be attributed to the enhanced reactivity of the aggregate, caused by addition of large amounts of Na-silicate. However, this may not be significant as alkali solutions are used up for the initial reactions and therefore they will not be replenished at a later age. In addition, it should be noted that some aggregate reaction would result in chemical bonds which develop between the cement matrix and the aggregate particles, thereby enhancing the hardened concrete tensile strength. Nevertheless, any potential AAR should be monitored into the future.

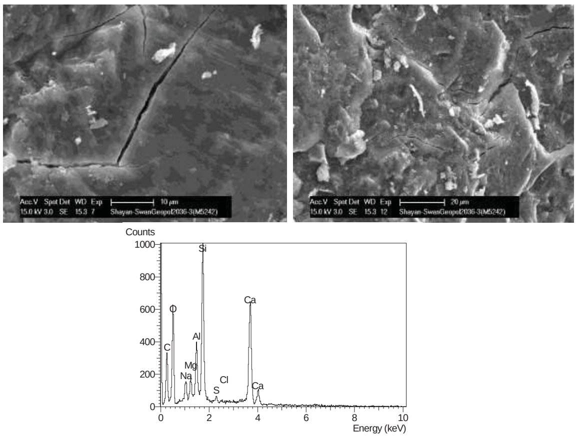

Fig. 8. SEM Views of geopolymer paste and EDX composition **Error! Reference source not found.**

Introduction of Geopolymer Concrete in Section 703 (General Concrete Paving)

Geopolymer concrete has been specifically defined and incorporated into the November 2010 version of Section 703 for the construction of lower risk general paving works such as traffic islands, median slabs, bicycle paths, edgings, footpaths, shared paths, vehicle and pram crossings and other similar slabs or pathways on prepared bedding, as a direct equivalent product to Portland cement concrete.

It is required to comply with the minimum 28 day compressive strength requirements for each strength grade ranging from 20 MPa to 32 MPa. Various requirements dealing with the constituent materials, manufacture, delivery, placement, compaction, finishing and curing of geopolymer concrete have been addressed.

Summary

The use of geopolymer concrete in major structural applications for items such as bridge beams, precast parapet barriers, piles, columns, crossheads, abutments and bridge decks to VicRoads Standard Specification Section 610 "Structural Concrete" needs to be investigated further and monitored carefully prior to venturing into full scale production and construction. It is important that performance, durability and batching control issues are resolved. The major impediments include:

- Geopolymer mix designs specifically for the higher strength and durability applications to demonstrate compliance with Section 610 requirements;
- The confidentiality of the alkaline solution recipes (dosage rates);
- The susceptibility of the alkaline solution dosage rates to variation in production batching and subsequent hardened concrete property implications;
- The need to demonstrate unquestionable protection of the steel reinforcement and prestressing tendons against corrosion and other forms of potential deterioration;
- The need to establish the permeability performance of geopolymer concrete in terms of VPV.

In addition, it is very important that much improved practices and procedures, better trained workforce and quality control measures must be utilised in concrete batching plants to ensure the ongoing consistency of production and quality performance of geopolymer concrete. Geopolymer concrete can have a significant susceptibility to uncontrolled water additions at various stages, and excess water additions can have pronounced effects on both the plastic and hardened properties compared to conventional concrete.

Lower risk components such as kerbs, edge strips, vehicle and pedestrian crossings, footpaths, median and other concrete surfacings applications which require relatively low strengths of 20 to 32 MPa may eventually become a regular market for geopolymer concrete.

Finally, geopolymer concrete has the potential to be used in structural applications for both in-situ and precast construction provided the various impediments mentioned above are satisfactorily resolved, although at this stage it may be more suitable for precasting operations where accelerated curing is available, strength development can be assured and only acceptable components may be delivered. As a way forward the use of geopolymer concrete in lower risk structural applications may be considered on a job by job basis.

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