Geopolymer “Green" Concrete – Reducing the Carbon Footprint – The VicRoads Experience

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Abstract Geopolymer concrete consists of the normal components of fine and coarse aggregate, any required admixtures and aluminosilicate based industry by-products such as fly ash and ground granulated blast furnace slag which can be activated with a concentrated solution of alkali-based chemicals such as sodium hydroxide and sodium silicate in water to form the binder (glue) in this new material. Geopolymer concrete was developed in the old Soviet Union in the 1950’s and used in the form of soil cement, alkali activated cement and acid cement. The name geopolymer was first applied to these materials by Joseph Davidovits in France in the 1970s. Over the past 10 to 15 years, significant amounts of research on geopolymer concrete has also been undertaken at a number of Australian universities particularly in Victoria and Western Australia mainly under laboratory controlled conditions without any significant on-site field work. In more recent times, the need to reduce the carbon foot print in the construction sector is helping with the marketing, manufacture and supply of geopolymer concrete in some parts of Australia, particularly for low risk general paving works.In an effort to obtain a greater understanding of the practical potential of geopolymer concrete VicRoads has over the past two years undertaken a small number of trials which include the in-situ construction of landscape retaining walls at a bridge site, precast footway panels on a bridge and construction of a significant length of footpath. These trials form part of a strategy to generate a greater understanding on long term performance particularly with respect to higher risk structural applications, which includes visual inspection, sampling and testing and monitoring of embedded probes. At this stage VicRoads has gained sufficient confidence with regards to low risk general paving works (i.e. footpaths, driveways, kerb & channel and other concrete surfacings) and has incorporated geopolymer binder concrete into its general concrete paving specification Section 703 as an equivalent product to Portland cement concrete.

This paper presents the VicRoads experience with regards to use, testing and ongoing monitoring of geopolymer concrete and further discusses the various parameters incorporated into the VicRoads specification for general paving works with regard to geopolymer concrete.Geopolymer concrete has the potential to be used in structural applications for both in-situ and precast construction provided various current impediments 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.

Introduction

Geopolymer concrete was developed in the old Soviet Union in the 1950's and used in the form of soil cement, alkali activated cement and acid cement. The name geopolymer was first applied to these materials by Joseph Davidovits in France in the 1970s. Over the past 10 to 15 years, significant amounts of research on geopolymer concrete has also been undertaken at a number of Australian universities particularly in Victoria and Western Australia mainly under laboratory controlled conditions without any significant on-site field work. In more recent times, the need to reduce the carbon foot print in the construction sector is helping with the marketing, manufacture and supply of geopolymer concrete in some parts of Australia, particularly for low risk general paving works.

In an effort to obtain a greater understanding of the practical potential of geopolymer concrete VicRoads has over the past two years undertaken a small number of trials which include the in-situ construction of landscape retaining walls at a bridge site precast footway panels on a bridge and construction of a significant length of footpath. These trials form part of a strategy to generate a greater understanding on long term performance particularly with respect to higher risk structural applications, which includes visual inspection, sampling and testing and monitoring of embedded probes. At this stage VicRoads has gained sufficient confidence with regards to low risk general paving works (i.e. footpaths, driveways, kerb & channel and the like) and has incorporated geopolymer binder concrete into its general concrete paving specification Section 703 as an equivalent product to Portland cement concrete. This paper presents the VicRoads experience with regards to the use, testing and ongoing monitoring of geopolymer concrete and further discusses the various parameters incorporated into the VicRoads specification for general paving works with regard to geopolymer concrete.

Geopolymer Concrete

Geopolymer concrete consists of the normal components of fine and coarse aggregate, any required admixtures and aluminosilicate based industry by-products such as fly ash and ground granulated blast furnace slag which can be activated with a concentrated solution of alkali-based chemicals such as sodium hydroxide and sodium silicate in water to form the geopolymer paste that binds the loose coarse and fine aggregates, and other un-reacted materials together. This can take place at temperatures ranging from ambient to as high as 200 ^{o}C. Coarse and fine aggregates occupy about 75 to 80% of the mass of geopolymer concrete, similar to Portland cement concrete.

The alkaline component consists of combinations of alkali and alkali earth containing salts, minerals and glasses, with most research and commercial supply to date focusing on combinations of sodium hydroxide and sodium silicate. The alkaline component dosage rates can be manipulated to achieve the desired strength and various other plastic and hardened properties. Although geopolymer concrete is not meant "to contain" any Portland cement up to 10% may still be used to enhance the chemical reaction. Geopolymer concrete can be formed in one of two ways, namely,

- Reactive aluminosilicates (i.e. Fly ash or Slag) + alkali silicate solution as a 2-part mix; or
- Reactive aluminosilicates (i.e. Fly ash or Slag) + reactive solids (Highly soluble alkali and silicate "activator") 1-part mix, with water added in the dry materials. The 1-part mix is considered more practical to apply and this is the method used in the VicRoads work.

The major difference between cement based concrete and geopolymer binder based concrete is that cement based concrete is characterised by the formation of calcium silicate hydrates (CHS), whereas geopolymer binder concrete is characterised by an amorphous (non-crystalline) microstructure, where the polymerisation process involves the formation a three-dimensional polymeric chain and ring structure consisting of aluminosilicates (Si-O-Al-O).

Environmental Issues

Cement manufacture is considered to be the fourth largest global carbon emission activity following the oil, gas and coal industries. It is estimated that the cement industry is responsible for between 5% and 10% of all CO_2 emissions primarily due to the production of one tonne of Portland cement emitting approximately one tonne of CO_2 into the atmosphere, mostly from the process step of high-temperature calcination of limestone (i.e. limestone ($CaCO_3$) → $CaO + CO_2$ ↑). The cement content of concrete is of the order of 10 to 15 percent, the balance consisting of fine and coarse aggregates which have their own emissions contribution from quarry and transport operations.

One of the primary advantages of geopolymer concretes over traditional Portland cement concretes is largely associated with the much lower CO_2 emissions. This is mainly due to the absence of the high-temperature calcination step in the process of geopolymer synthesis. The activators used in geopolymers do reintroduce some CO_2 emissions, and the by-product binders provide a use for an otherwise waste product. Overall, the CO_2 saving due to the use of geopolymer concrete can be as much as 80% when compared with Portland cement concrete. Fine and coarse aggregates still have their own emissions contribution from quarry and transport operations, similar for both concretes.

It should be emphasised that VicRoads has been utilising supplementary cementitious materials (SCMs)(i.e. fly ash, slag and silica fume) in the construction of its bridges and as specified in its structural concrete specification Section 610 for more than 20 years in order to improve the qualities and long term performance of the in-situ concretes. This of course has consistently contributed over this period reduction in CO_2 emissions of the order of 20% - 40% per cubic metre of concrete used. Examples of VicRoads structures constructed with significant amounts of cement replacement materials (i.e. SCMs) includes the Jacana Tunnel (18% fly ash replacement of cement of the main RC portal frames and other components) and the E.J. Whitten Bridge (Western Ring Road)(30% to 40% replacement of cement of all components)(Fig. 1).

Fig. 1. Jacana Tunnel and Whitten Bridge (Western Ring Road) constructed with significant amounts of SCMs

Use of Geopolymer Concrete in VicRoads

In order to obtain a greater understanding of the practical potential of geopolymer concrete VicRoads has over the past two years undertaken a small number of trials which include the in-situ construction of two landscape retaining walls at a bridge over the Yarra River and precast footway panels on a bridge over a freeway and construction of a significant length of footpath (Fig. 2).

The key requirement with these trials was the need to ensure compliance with the requirements of Section 610 for both the in-situ and precast structural concrete components and Section 703 for the footpath work. As such the mix designs used were based on comparable minimum strength and minimum cementitious content to cement based mixes as allowed in the VicRoads specification Section 610. The in-situ landscape retaining walls were characterised by a mix with 40 MPa and minimum cementitious content of 400 kg and the precast footway panels with 55 MPa and minimum cementitious content of 470 kg.

Fig. 2. Geopolymer concrete, retaining wall (L), footway panels (C) and footpath (R)

Geopolymer Precast Footway Panels

The choice of a minimum strength of 55 MPa for the precast footway panels was to compensate for lack of sufficient cover to the underside of the units. This was supplemented with galvanised steel reinforcement. A single test unit was manufactured prior to full production in order to facilitate a better understanding of handling, placing, compacting, finishing, curing and sampling and testing of this type of concrete. The unit was manufactured successfully with only some minor finishing problems which were subsequently improved. The full scale production and installation of some 180 units was completed within an 8 week period which is very comparable with conventional type concrete (Table 1). All units were manufactured within a 5 week period.

Table I. Manufacturing schedule of precast geopolymer footway panels

Cast No.	Date	GCT Cert. No.	Units Cast
1	1/06/09	50791	Single Test Unit
2	16/06/09	51036	8

3	18/06/09	50993	8
4	23/06/09	51189	20
5	25/06/09	51144	20
6	30/06/09	51239	30
7	2/07/09	51348	30
8	6/07/09	51417	32
9	8/07/09	51440	32
Total			180

The stacking, storage and curing of units is shown in Fig. 3. The minimum required lifting strength for the units was readily achieved and the units were cured using polyethylene sheeting. The dark green colour which is a characteristic of the use of slag was retained, thus indicating the integrity of the polyethylene curing.

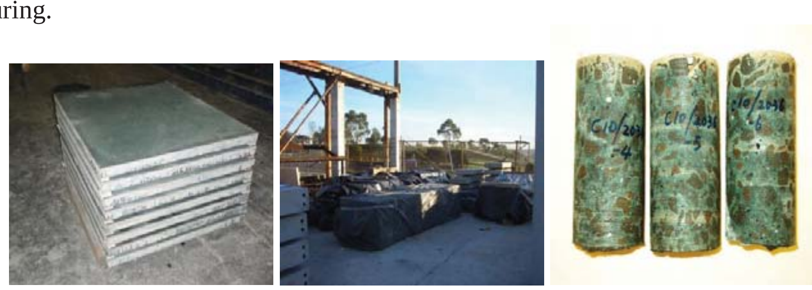

Fig. 3. Storage/ curing of precast geopolymer footway panels and geopolymer concrete cores with distinctive green colour

Tables 2, 3 and 4 show the test results for compressive strength, drying shrinkage and volume of permeable void (VPV/permeability) respectively. Table 2 shows that on the average with the exception of the initial test panel the minimum required 28 day compressive strength of 55 MPa was on the borderline of acceptability. Although it is considered that with more experience, further refinement of the mix design and manipulation of the alkaline activator dosage rates the strengths should be readily achieved on a consistent basis. The results in Table 3 indicate that the maximum limitations of drying shrinkage of 750 microstrain can be achieved.

Table II. Compressive Strength of panels (Min. required @ 28 days 55 MPa)

	Date	**GCT Cert. No.**	**1 Day**	**2 Days**	**7 Days**	**28 Days**	**28 Days**	**56 Days**
1	1/06/09	50791	24.0		40.5	44.0	45.5	45.0
2	16/06/09	51036	24.5	36.5	48.5	60.5	59.0	
3	18/06/09	50993	14.5	29.0	48.0	56.0	56.0	
4	23/06/09	51189	23.0	36.5	43.0	50.5		
5	25/06/09	51144	21.0	32.0	46.0	49.0		
6	30/06/09	51239	24.5	35.0	50.5	59.5	59.5	
7	2/07/09	51348	21.0	44.0	42.5	52.5	54.0	
8	6/07/09	51417	21.5	32.5	45.5	54.5		
9	8/07/09	51440	22.0	34.0	45.5	53.0	52.5	
Average			21.5	34.9	46.2	54.4	56.2	

Table III. Drying Shrinkage of panels (Max. Limit at 56 days- 750 micro strain)

Cast Num	Date	GCT Cert Num	Cast	7 Days	14 Days	21 Days	28 Days	56 Days
1	1/06/2009	Zeobond	0	-118	32	179	382	550
2	16/06/2009	54424(CRL)	0	191	311	413	501	710
2	16/06/2009	Zeobond	0	-75	154	364	246	375
3	18/06/2009	Zeobond	0	111	343	543	554	714
4	23/06/2009	Zeobond	0	-39	236	161	282	589
5	25/06/2009	Zeobond	0	186	361	375	475	614
6	30/06/2009	Zeobond	0	168	357	489	546	729
7	2/07/2009	Zeobond	0	18	396	518	607	614
8	6/07/2009	Zeobond	0	-179	21	179	204	582
9	8/07/2009	Zeobond	0	68	393	450	546	729
			Average	33	260	367	434	620

Table 4 however, indicates that the geopolymer concrete used in the precast footway panels was not able to achieve the VPV requirements of Section 610 for an equivalent 55 MPa concrete. The table indicates that the VPV results ranged between 19.5% and 21.7% for both cylinders and concrete cores far exceeding the maximum allowable limits of 12% for rodded cylinders and 14% for concrete cores for an equivalent concrete grade of VR470/55 as specified in Section 610.

Geopolymer Precast Footway Panels - Observations

The general observations relating to the geopolymer footway panels trial can be summarized as follows:

As indicated in Table 2 strength development was initially an issue and as such acceleration of strength development was required due to the geopolymer mix design used and the urgency with which the mix design was developed at the time.

- The casting bed was heated to a temperature range of 18°C to 35°C with an even heat distribution following some initial problems. It was considered that the requirement for bed heating may be eliminated with improvements in raw materials and the geopolymer mix design.
- The overall slump retention, discharge, kibble transfer and placement and consolidation under vibration were considered satisfactory.
- Finishing was found to be somewhat difficult with coarse aggregate difficult to get down from the surface and paste was brought to the surface using an expanded mesh roller which was also forcing down the coarse aggregate. The mix was found to be stickier than conventional concrete and as such water spray was applied on the surface to facilitate finishing due to stiffness of the mix. Generally longer setting times were indicative of higher water content. Optimal finishing includes screeding then waiting as long as possible before final finish. Stipple finish was found to work better than broomed and was selected for finish of the panels.
- With respect to curing the precast practice to cover in polyethylene plastic was found to be sufficient.

The units stripped well and lifting was facilitated within normal times of 16-20 hours, with lifting strengths in the order of 15-20 MPa.

Table IV. VPV % for Footway Panels, Max Limits at 28 days - rodded cylinders – 12%, - cores – 14% (VR470/55)

Cast No	Date	GCT Cert No	GCT Cert No	Slice A	Slice B	Slic e `C	Slic e D	Ave @ 28d	
4	23/06/0 9	Zeobond	51189	21.8	22.3	21. 9	20. 8	21.7	
7	2/07/09	Zeobond	51348	20.1	21.2	21. 2	21. 3	20.9	
8	6/07/09	Zeobond	51417	20.7	21.3	21. 4	20. 6	21.0	
9	8/07/09	Zeobond	51440	19.5	20.6	20. 7	21. 4	20.6	
9	8/07/09	CRL Ltd	51440	20.8	20.9	20. 7	19. 6	20.5	Cyl1 (63d)
9	8/07/09	CRL Ltd	51440	20.8	20.7	20. 2	19. 5	20.3	Cyl2 (63d)
P2	10/06/0 9	CRL Ltd	51440	19.6	19.6	19. 7	19. 6	19.6	Cyl1 (86d)
P2	10/06/0 9	CRL Ltd	51440	19.4	19.7	20. 1	20. 3	19.9	Cyl2 (86d)
P2 Core1	10/06/0 9	CRL Ltd	51440	21.2	21.2			21.2	Cor (86d)
P2 Core2	10/06/0 9	CRL Ltd	51440	21.3	20.9			21.1	Cor (86d)
Average				20.5	20.8	20. 7	20. 3	20.7	

In-situ Geopolymer Concrete Landscape Retaining Walls

Construction of the in-situ geopolymer concrete landscape retaining walls was undertaken utilising conventional techniques for formwork construction, concrete placement by pumping, compaction with a poker vibrator, finishing and curing with polyethylene plastic (Fig. 4).

Fig. 4. Construction of geopolymer concrete retaining walls using conventional techniques

The quality of the landscape retaining walls ranged form a good surface finish to a significant proportion of the walls to areas with sizeable surface blowholes and to some areas with significant honeycombing due to lack of flowability and effective compaction which necessitated conventional patch repairs (Fig. 5).

In order to monitor the long term performance of the geopolymer concrete and enable monitoring of the corrosion state of the reinforcing steel, three MnO_2 half-cell reference electrodes were also installed at the centre of the in-situ walls and attached to the steel reinforcement at three different levels along the height of the wall (Fig. 6).

Fig. 5. Surface finish of geopolymer concrete retaining walls

Fig. 6. Finished painted wall and installed reference electrodes

Tables 5, 6 and 7 show the test results for compressive strength, drying shrinkage and VPV (permeability), rapid chloride permeability and chloride diffusion determination respectively. Tables 5 and 6 show that the concrete achieved the compressive strength and drying shrinkage requirements. Cylinders were also cured at $60^{O}C$ to demonstrate the consistency of the strength development of the geopolymer concrete. However, as indicated in Table 7 and consistent with the precast footway panels the geopolymer concrete was unable to comply with the maximum VPV requirements.

Geopolymer Concrete Landscape Retaining Walls - Observations

The general observations relating to the geopolymer retaining walls trial can be summarized as follows:

Concreters had problems to adequately consolidate the material into the vertical wall sections and as such they were unhappy with performance and results of pours. The general observation was that the mix was too sticky, was difficult to flow and took longer to vibrate. This resulted in some poorly consolidated areas characterised by honeycombing and surface blowholes.

- It was considered that the likely causes were due to the alkaline activator holding the materials together and the lack of superplasticiser in the geopolymer mix which was identified as a major issue. The variable clay content on the aggregates was also considered an issue.
- With respect to safety concreters complained of redness/itchiness/burning sensation on hands that had contacted material most likely due to the effects of the alkaline activator. However, no major incidents were reported. As such it was considered essential to enforce (despite complaints) the use of safety equipment for handling the geopolymer material in the same way as it is required for conventional concrete applications. It was considered that a solution to this problem was to reduce the alkaline activator content required (by improving raw materials as well) which would obviously result in overall water reduction and therefore overall improvement to the performance of the