FINAL REPORT

S19 Geopolymer Concrete Performance Review

Project No: 010574

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AN INITIATIVE BY:

SUMMARY

Geopolymer concrete is an emerging and innovative material that has gained rapid attention in Australia in recent years. It incorporates the use of industrial or natural waste products (such as fly ash or blast furnace slag) as a majority cementitious replacement for traditional Ordinary Portland Cement (OPC) in concrete. The purported benefits of this product are predominantly environmental, with reductions in carbon dioxide emissions and energy requirements in its manufacture and production. Research to date also suggests that this product offers equal or superior strength and durability performance when compared to OPC concrete. Cost savings have also been identified for some products.

Research into geopolymer concrete has increased exponentially in the last decade, with product development and investigation strongly driven by various sectors (i.e. academic, jurisdictions, and industry). However, all geopolymer concrete products currently used in Australia are proprietary products and detailed information regarding the composition and mix design of this product have not been commercially disclosed. With an increasing focus on sustainable products and industrial emission reductions, geopolymer concrete is emerging as a potentially viable and alternative construction material. Subsequently the Queensland Department of Transport and Main Roads (TMR) will be increasingly required to evaluate this product for its use in long-term structural and non-structural applications.

No formal guidelines to specify and assess geopolymer concrete are available to assist TMR. Therefore, the current report provides TMR with a summary of current knowledge and uses relating to geopolymer concrete. In particular, it reviews the basics of the material, its perceived benefits, where it has been used for structural and non-structural applications nationally and internationally, how it has been specified and assessed for performance and durability, and identifies the remaining research gaps requiring further investigation.

Australia is currently at the forefront of geopolymer concrete research and development. There are several structural and non-structural geopolymer concrete applications that have been implemented nationally; however, the majority of these have been industry driven and little to no recent objective performance information was available for review. Current research appears to confirm the equivalent or superior strength and performance characteristics of geopolymer concrete in comparison to OPC concrete; however, the majority of research is relatively short term. In terms of long-term performance, a number of research gaps still exist, particularly in relation to durability in aggressive environments.

A number of Australian standards have been referred to for the specification of geopolymer concrete, in particular AS 3600, for items such as strength development and creep. However, there are concerns that not all requirements are applicable or sufficient, as the current guidelines are based on long-term empirical OPC data. At present, no jurisdiction has published a geopolymer concrete specification for structural applications; however, Roads Corporation Victoria (VicRoads) and Department of Planning, Transport and Infrastructure South Australia (DPTI) have permitted the use of this product for a select number of non-structural applications.

No mix design details are specified, with the specifications identifying key performance indicators such as strength and shrinkage. Durability performance requirements are currently not accounted for.

It is recommended that future field trials on structural and non-structural applications be conducted to assess performance criteria specific to TMR's requirements, including slip resistance and long-term durability data in aggressive environments.

It is noted that Austroads Project TS1835 *Specification and Use of Geopolymer Concrete in the Manufacture of Structural and Non-structural Components* and the Standards Australia geopolymer handbook are currently being finalised and developed respectively. The conclusions and recommendations from these publications will provide TMR with further guidance regarding geopolymer concrete.

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1 INTRODUCTION

1.1 Background

The use of innovative materials such as geopolymer concrete in road infrastructure is gaining momentum both nationally and internationally. Geopolymer concrete incorporates the use of industrial waste products (such as blast furnace slag or fly ash) in lieu of traditionally used Ordinary Portland Cement (OPC). These waste products have the potential to provide environmental and economic benefits, such as a reduction in the CO_2 footprint of anywhere from 17% (Provis & Van Deventer 2014) to 64% (McLellan et al. 2011) and/or cost savings of 10-30% (when using fly ash-based geopolymer cement as compared to OPC) (Lloyd & Rangan 2010). Research to date based on laboratory trials has also suggested that the performance of geopolymer concretes may be superior to those of OPC concrete in terms of strength and durability (Wallah et al. 2004).

Development of knowledge in the application of these materials is rapidly increasing through not only research and development (universities and Austroads), but also by an increasing number of applications developed by commercial companies and suppliers of concrete. There is a growing industry awareness of the potential benefits of geopolymer concrete and commercial opportunities.

The Queensland Department of Transport and Main Roads (TMR) will be required to evaluate the use of geopolymer concrete applications in structural and non-structural applications including reinforced and prestressed bridge components. However, improved understanding and information on key material and performance parameters such as strength, durability and the mixing/placement of geopolymer concrete is required. Unlike general purpose (GP) concrete, which uses OPC, detailed information regarding the composition of geopolymer concretes is not commercially disclosed/available as it is typically held as intellectual property by suppliers. This places TMR at risk when assessing geopolymer concretes for structural applications such as bridges, culverts and other structures. While geopolymer concrete has the potential to provide cost and environmental benefits to TMR, the unknown long-term performance of these products may result in increased maintenance costs.

TMR needs to increase its knowledge base regarding geopolymer concrete so that informed decisions regarding its applicability and use can be made. To this end, a literature review forms the basis of this project to provide TMR with an overview of the current understanding of geopolymer concrete, of known issues and concerns regarding performance, and identifying the need for further research that would improve TMR's confidence in these products.

This report presents the methodology in the literature selection and review (Section 2), a summary of the literature findings in relation to the specific project objectives outlined in Section 1.2 (Section 3), and the provision of recommendations and future actions (Section 4).

1.2 Objectives

The objectives of this project are to provide TMR with a summary of the current understanding and issues surrounding performance and specification of geopolymer concrete, addressing the following specific questions identified by TMR:

- What is known regarding the (long-term) durability performance of geopolymers, especially in typically aggressive scenarios, e.g. marine environment, reactive aggregates and acid-sulphate soils?
- What is the current extent of geopolymer use in transport and marine infrastructure?
- How is this use specified and regulated?
- What criteria are used to assess/specify geopolymer performance?

- What methods are used to measure these performance criteria?
- Can existing Australian Standards (e.g. AS 3600) be applied to geopolymers?

This is not an exhaustive review, but provides TMR with practical information and recommendations that can be used as an informal guide in the increasingly likely event that geopolymer concrete applications are presented for assessment.

1.3 Project Exclusions

The following exclusions apply to this review:

- History of geopolymer development
- Detailed review of geopolymer mechanisms, chemistry and materials
- Mix design recommendations
- Data review and analysis
- A detailed review of AS 3600 or other related material standards
- Material test review and recommendations
- Summary of suppliers and available geopolymer products
- Exhaustive list and critical review of geopolymer applications (in particular international applications)
- Review of industry-owned trial sites (and associated data).

1.4 Related Projects

There are a number of initiatives that are running concurrently with this project, most notably the following:

- Austroads Project TS1835 – Specification and Use of Geopolymer Concrete
  Currently in its final year, scheduled publication date 2017
    - Note that due to concurrent postgraduate work in conjunction with this project, interim results are unable to be published in this report at this time.
- Standards Australia – Geopolymer Handbook
  Currently in development, scheduled publication date unknown

2 METHODOLOGY

The literature review was conducted in three stages:

1. literature search
2. literature selection
3. literature review.

Initial stages of the project required the sourcing and collation of relevant documents, which were obtained from:

- ARRB's knowledge database, (which comprises ARRB's MG Lay Library, Rail Knowledge Bank and Australian Transport Index (ATRI) – see http://arrbknowledge.com
- international databases maintained by fellow transport research agencies such as TRB and TRL
- relevant scientific journals and conference proceedings
- relevant specifications, standards and guides
- discussions with industry experts/representatives.

The following key words were used in various combinations for the literature search (in conjunction with geopolymer concrete):

- durability
- performance
- case studies
- specification
- long term
- corrosion
- chlorides
- carbonation
- aggressive/marine environment
- slip resistance
- AAR/ASR/aggregate reactivity.

A preliminary literature list was collated into a register and distributed to the working group for confirmation of requirements and review prioritisation. After feedback was received, a detailed review was carried out, which included additional relevant references being sourced and reviewed in addition to the original list. The preliminary literature register and the selection determined by the working group is included in Appendix A, and a soft copy of all documents incorporated into this review can be found in Appendix B. Outcomes of the review were incorporated into the current project report, which is now presented for discussion.

3 GEOPOLYMER CONCRETE - LITERATURE REVIEW

This section has been set out in the following manner:

- A brief overview of geopolymer concrete, including background, materials and processes.
- Current knowledge identified relating to project objectives (Section 1.2)
    - current applications
    - documented performance
    - how it is specified
    - methods of assessment for performance.
- Current gaps in knowledge, including a summary of issues associated with geopolymer concrete.

3.1 Overview of Geopolymer Concrete

There are several documents and state-of-the-art reviews that provide excellent and more extensive information and details relating to geopolymer concrete, such as Davidovits (2011), Austroads Project TS1835, RILEM TC 224-AAM (Provis & Van Deventer 2014) and Pacheco et al. (2014). This section provides a very brief overview of the background, concepts and key materials and processes for geopolymer concrete.

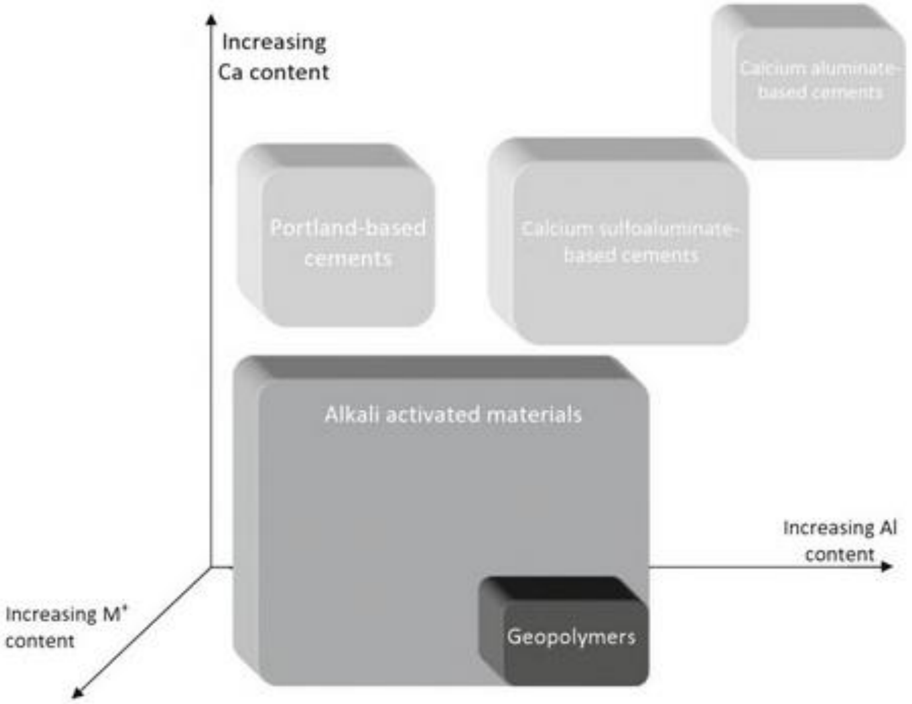
3.1.1 Definition and Background

Geopolymer concrete is a generic term which indicates the incorporation of a geopolymer cement as a replacement binder for OPC. Geopolymer cements are derived from products that are rich in silica and alumina (aluminosilicates), which are typically sourced from raw materials or industry waste by-products, through a geopolymerisation process that is facilitated with alkali activators (Davidovits 2005; Provis & Van Deventer 2014).

The term geopolymer stems from the commercial name patented by Davidovits in the early 1980s. It is generally considered to be a subset of the broader classification of alkali-activated materials (AAM) that define the creation process of a replacement binder product through the reaction of an alkali metal source (solid or dissolved) with a solid silicate source (typically powder) (Figure 3.1) (Provis & Van Deventer 2014). While the terminologies can be interchangeable, geopolymers are predominantly defined by the use of aluminosilicates and are highly structured (reflective of the polymerisation process). The geopolymer terminology is most commonly adopted in Australia and will therefore be adopted herein (unless otherwise specifically required).

The first known application of a type of geopolymer concrete dates back to the early 1900s as explored by Kühl (as cited by (Provis & Van Deventer 2014)). Some additional research was carried out in the former Soviet Union and China in the early 1950s, where shortages of OPC drove the need to seek out alternative cementitious materials. However, significant advancements were initiated in the 1980s with several sources recognising the potential benefits of alkali-activated technology (Davidovits 2011; Provis & Van Deventer 2014).

Figure 3.1: Overview of cement binders classification. Note the classification of geopolymer cements falls inside alkali activated materials (AAM)



Source: Alkali Activated Materials: State-of-the-Art Report (Provis & Van Deventer 2014).

3.1.2 Processes and Materials

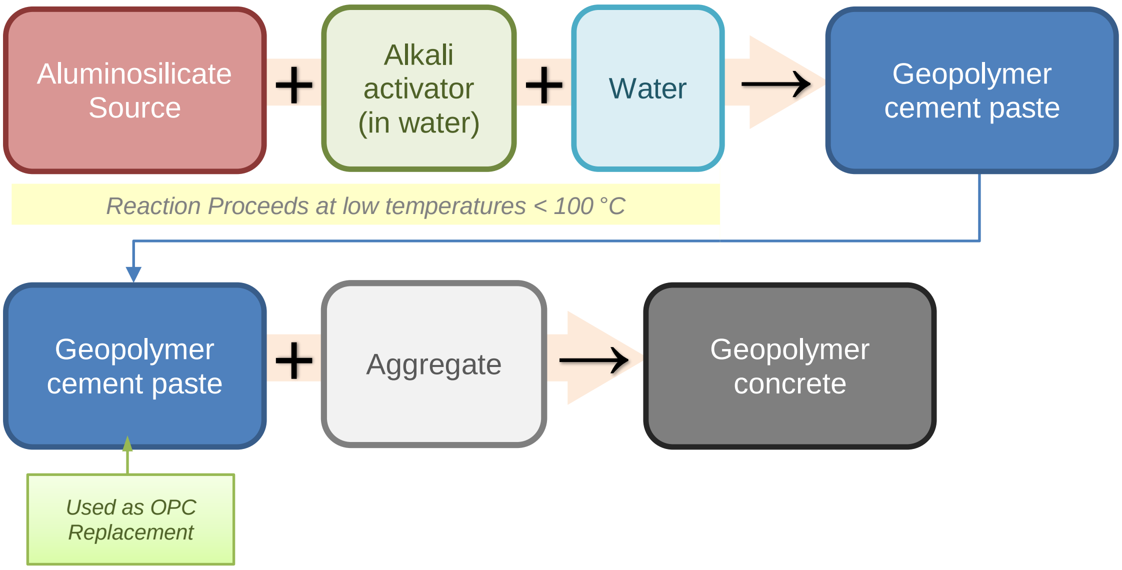
Figure 3.2 provides an overview of the geopolymer cement and concrete process. Detailed information regarding chemical reactions and the polymerisation processes can be reviewed in Davidovits (2011) and Pacheco-Torgal et al. (2014). Aluminosilicate materials are sourced either from raw materials that require minimal processing or industrial waste by-products. These materials are commonly the following (Concrete Institute of Australia 2011; Duxson et al. 2007; Provis & Van Deventer 2014):

- Natural pozzolans
  - volcanic origins (ashes, pumices).
- Industrial waste by-products:
  - granulated blast furnace slag (by-product from iron/steel production process)
  - fly ash (Class F, by-product from coal-fired power stations)
  - calcined clay products. i.e. produced by calcinating kaolinite clay e.g. kaolin, metakaolin
  - other products e.g. steel/copper slags, silica fume, mine tailings, bauxite residue.

Material selection for geopolymer cement production is dependent on availability and the additional processing that may be required. Blending of these materials is also common. Blast furnace slag and in particular fly ash are readily available within Australia and also require minimal alteration for inclusion, and are therefore the preferred waste by-product for geopolymer cement production (Duxson et al. 2007; Van Deventer, Provis & Duxson 2012).

Alkali activators typically take the form of sodium hydroxide or sodium silicate. This additive facilitates the highly alkaline conditions required to dissolve the silica and alumina phases to promote the geopolymerisation process, resulting in a hardened cement product.

Figure 3.2: Geopolymer cement and concrete processes



Source: (Davidovits 2011; McLellan et al. 2011).

3.1.3 Mix Design

At present, no specific mix designs are available in Australia as the majority of geopolymer concrete products have been developed commercially and have been patented. The Concrete Institute of Australia has produced a recommended practice for geopolymer concrete (Concrete Institute of Australia 2011), which provides criteria for a geopolymer mix design but does not provide details regarding percentages or proportion of materials.

The Austroads project TS 1835 is currently in its final year and the outcome from this project will provide guidelines for various jurisdictions and asset managers, which will enable them to assess and select appropriate geopolymer products and applications. Due to ongoing postgraduate studies associated with TS 1835, the interim findings are not able to be published in this report at this time.

3.1.4 Perceived Benefits of Geopolymer Concrete

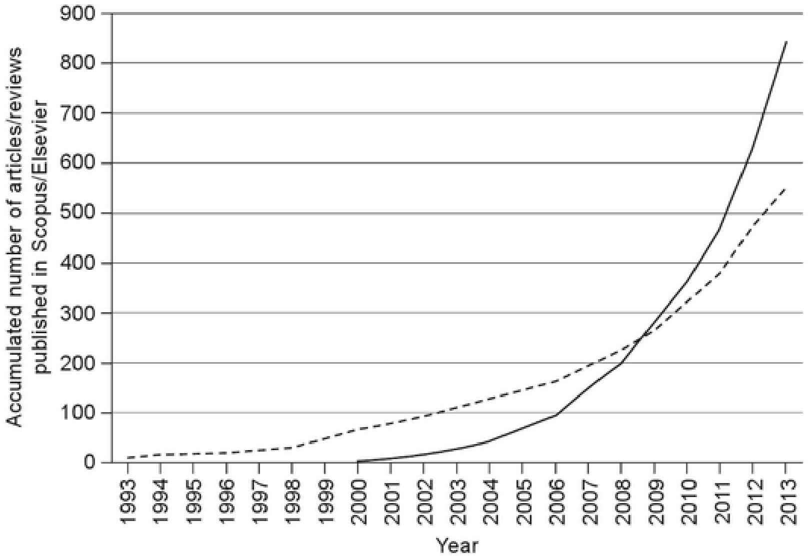
The predominant driver for the development of geopolymer concrete has been the environmental benefits offered by this product. Past studies have noted that the production of conventional concrete using OPC concrete results in approximately 1 t of CO_2 emissions for every tonne of cement produced and that the worldwide production of OPC concrete contributes 5–7% of anthropogenic CO_2 emissions (Chen et al. (2010) as cited by Berndt et al. (2013, p.10)). Geopolymer concrete is believed to have the potential to markedly decrease CO_2 emissions, with estimates that its production may result anywhere from 17% less (Provis & Van Deventer 2014) to 64% less (McLellan et al. 2011) CO_2 emissions. Also, due to the low embodied energy in particular types of geopolymers, studies have found that the production of geopolymer concrete uses 70% less energy than OPC concrete (Tempest et al. (2009) as cited by (Shaikh & Afshang 2014)). Other claimed benefits include:

- Recycling of industrial waste by-products (Duxson et al. 2007; Habert, De Lacaillerie & Roussel 2011; Lloyd & Rangan 2010):
  - representative of a sustainable product
  - reductions in the quantity of commercial waste transferred to landfill.

- Improvements to mechanical and durability properties when compared with OPC concrete. These include (Bligh & Glasby 2013; Davidovits 2011; Provis & Van Deventer 2010):
  - — a more rapid and high early strength gain under specific curing conditions (making it a promising material for precast construction)
  - — improved drying shrinkage properties
  - — improved tensile strength
  - — improved resistance to acid attack and chloride ingress
  - — a lower heat of reaction allowing higher volume single pours.

Based on these factors, there is undoubtedly significant interest in geopolymer concrete. This is demonstrated by the increasing number of suppliers developing proprietary products utilising various waste by-product materials. It is also observed from a significant increase in the number of research articles relating to geopolymer cements and concretes being published (Figure 3.3).

Figure 3.3: Accumulated number of articles published in Scopus/Elsevier journals



Notes: keyword search - dashed line: 'alkali-activated', solid line: 'geopolymer'.
Source: Pacheco-Torgal et al. (2014).

3.2 Documented Applications

International commercial applications of geopolymer and alkali-activated concretes predate Australian applications; however, in recent times Australia has become a prominent leader in this area of research along with efforts towards product commercialisation.

There is an increasing number of projects and applications using geopolymer and similar alkali-activated cement based concretes that have been published. The majority of these are based on international experience; however, there are some examples of applications within Australia that have been successfully implemented. The following sections provide a non-exhaustive and brief list of some of the documented applications to date. The majority of this information has been drawn from the following sources:

- TS1835 literature review documentation (unpublished)
- Aldred and Day (2012)
- RILEM TC 224-AAM (Provis & Van Deventer 2014)
- CIA Z16 - Geopolymer Concrete (Concrete Institute of Australia 2011).

This section discusses national and international experience, with the latter being based predominantly on blast furnace slag and fly ash applications that are relatively younger than international cases. For the purposes of this review, only applications that relate to road and marine infrastructure are considered.

3.2.1 National Experience

Table 3.1 provides a summary of the national real-life application of geopolymer concrete (based on known documented cases). It identifies a number of projects and whether the application was structural or non-structural. CIA Z16 (Concrete Institute of Australia 2011) also provides a brief summary of recent applications up to 2011, along with a brief history of geopolymer/alkali-activated concretes that is replicated in part in Table 3.2. To date, there have been a limited number of structural and non-structural geopolymer concrete applications. The development of geopolymer related specifications and the evolution of academic research centres and industry investigating these materials appears to have been the predominant driver of these applications in Victoria. Specific examples are discussed in more detail below.

Table 3.1: Documented national experience with geopolymer concrete

Authority/ Industry	Experience		Comment
	Structural	Non-structural	
TMR (QLD)	✓	✓	▪ No significant applications have officially been implemented by TMR ▪ Discussions for field trials have taken place between Wagners and TMR ▪ Installation of 2 geopolymer precast wall panels on Eastern Busway, Brisbane (comparative trial)(1,2) ▪ R&D Project for Maritime Safety Queensland: Bundaberg Rocky Point boat ramp (in conjunction with Wagners, Bundaberg City Council) (1,2)
RMS (NSW)	-	-	▪ No response received
TAMS (ACT)	-	-	▪ No response received
VicRoads	✓	✓	▪ Several applications installed: – footway on Salmon St Bridge (Using E-Crete)(1,2) – footpaths along Brady St (South Melbourne) and Kings Road (Taylors Lakes)(1,2) – 450m long retaining wall along M80 Western Ring Road(1,2) – stormwater pipes for Princess Highway duplication, Winchelsea(1,2)
DSG (TAS)	✗	✗	▪ No known applications to date
DPTI (SA)	-	-	▪ No response received
MRWA (WA)	✗	✗	▪ No known applications to date
NTDoT (NT)	-	-	▪ No response received
Local Government	✓	✓	▪ Manningham Shire Council: foot/bike path at Templestowe Village ▪ City of Bendigo, Bendigo Airport: Drainage works(1) ▪ Brisbane City Council: in situ deck on Bundaleer Road Bridge, West Moggill

Authority/ Industry	Experience		Comment
	Structural	Non-structural	
Other	✓	✓	▪ Curtin University: two footpaths for Cooperative Research Centre for Sustainable Resource Processing ▪ Brisbane West Wellcamp Airport: pavement, drainage and precast beam applications(1,2) ▪ University of QLD: 33 floor beams for Concrete Global Change Institute (GCI) building(2) ▪ Port of Melbourne: footpath(1) ▪ Thomastown Recreation and Aquatic Centre: footpaths and driveways(1) ▪ Melton Library, Melbourne: architectural external precast panels[1] ▪ Woronora Cemetery: crypts(1) ▪ Port of Brisbane: test slabs (1,2)
Industry (i.e. CIA Z16, Rocla, Wagners, Zeobond)	✓	✓	▪ Railway Sleepers ▪ Footpaths ▪ In situ precast slabs ▪ Roof tiles ▪ Pavers ▪ Retaining walls ▪ Water tanks ▪ Concrete pipes (stormwater, sewer) ▪ Crypts (Woronora Cemetery) ▪ Tunnel Segments

1 Industry driver/involvement in project.
2 These examples discussed in more detail below.

Table 3.2: Industrial applications of geopolymer concrete noted by Concrete Institute Australia

Application	Year of first implementation (approximately)
9-storey buildings	1960
20-storey buildings	1987
Sewer pipes	1966
Irrigation channels	1962
Breakwater blocks	1965
Road pavement	1984
Railway sleepers	1989
Fire doors	2000

Source: Chapter 6, CIA Z16: Recommended Practice, Geopolymer Concrete (2011).

VicRoads experience

In 2009, VicRoads carried out a series of trial applications using in situ and precast geopolymer concrete (Andrews-Phaedonos 2014; Andrews-Phaedonos 2011; Shayan, Xu & Andrews-Phaedonos 2013). Some are listed below:

- 180 precast geopolymer concrete panels were manufactured and installed on the Salmon Street Bridge over the West Gate Freeway in Melbourne. The concrete used for the fabrication of these panels was required to be equivalent to VR470/55 concrete as set out in Section 610 of VicRoads standard specifications. These panels act as the bridge footway and their in-service performance was monitored for a period of five years following their installation. Minor cracks up to 0.15 mm in width were noted on eight of the 180 concrete panels; however, the nature of these cracks was consistent with early thermal cracking that would have been present since the installation of the panels. Subsequent inspections found no evidence of further crack movement. Structurally, the footway panels have been showing no signs of distress.
- Significant lengths of footpath along Brady Street in South Melbourne and Kings Road in Taylors Lakes were constructed using geopolymer concrete in accordance with the requirements of Section 703 of VicRoads standard specifications. Since their construction they have been found to be performing satisfactorily.

Geopolymer concrete has also been used for the manufacture of precast concrete pipes. Proof and ultimate load testing found they have similar capacities to OPC concrete pipes and are in compliance with the requirements of AS/NZS 4058. As a consequence, VicRoads included geopolymer concrete in its underground stormwater drain specification and geopolymer concrete pipes have since been manufactured and installed as part of the Princess Highway duplication at Winchelsea in Victoria. They have also been used for drainage works along Harley Street in the City of Greater Bendigo and Bendigo Airport in Victoria.

Brisbane West Wellcamp Airport (BWWA)

In November 2014, BWWA near Toowoomba was opened for commercial flights (Glasby et al. 2015). In conjunction with OPC concrete, approximately 40 000 m^3 of Wagner's geopolymer concrete product Earth Friendly Concrete (EFC) was placed for the turning node, apron and taxiway pavements (Figure 3.4). An additional 15 000 m^3 of EFC was used in various other applications in the airport including road barriers, kerbing, stormwater and sewer applications, footings, and two short-span single-lane bridges. This followed a trial period during which EFC was reviewed for mix design and construction method suitability prior to its placement in a private hangar pavement. The concrete specification developed by the consultant engineers specified the following details:

- 4.8 MPa average flexural strength at 28 days of age (AS 1012.11)
- 450 microstrain maximum drying shrinkage at 28 days of age (AS 1012.13)[1].

Other key mix design parameters were:

- total aluminosilicate binder comprising GGBS + fly ash, 415 kg/m^3
- water/binder ratio 0.41
- nominal 40 mm maximum aggregate size, conforming with 28 mm according to AS 2758.1
- chemical activator, 37 kg/m^3 solids content (*Note: no details of product used*)
- proprietary water reducing admixture.

It is unknown how these slabs are performing with regard to cracking, dusting or general durability issues.

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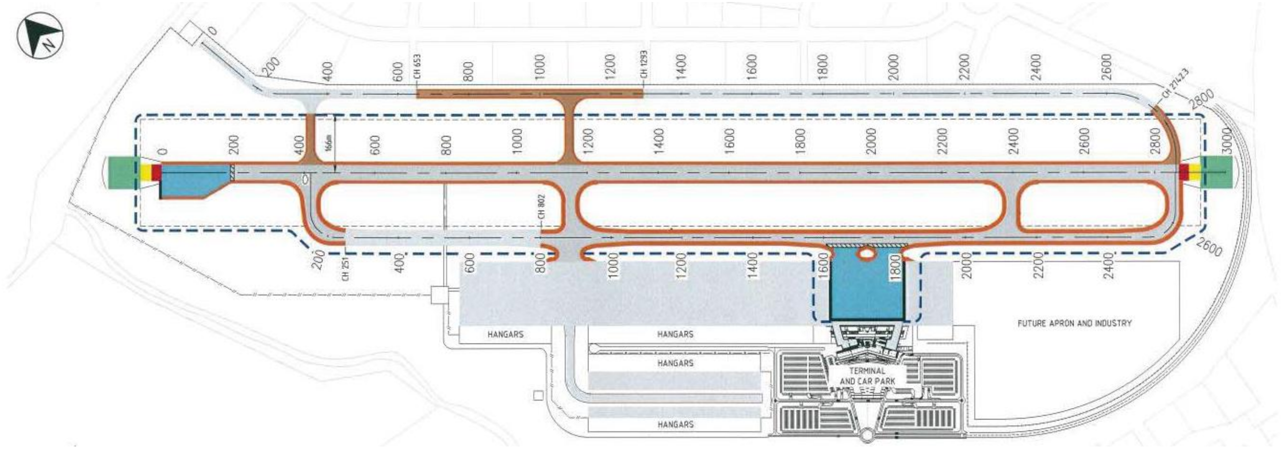
[1] Note that drying shrinkage measured at 28 days may be negligible, indicative of high-strength concrete.

Figure 3.4: Overview of Brisbane West Wellcamp Airport. Sections denoted in blue are those that used geopolymer concrete



Source: Glasby et al. (2015).

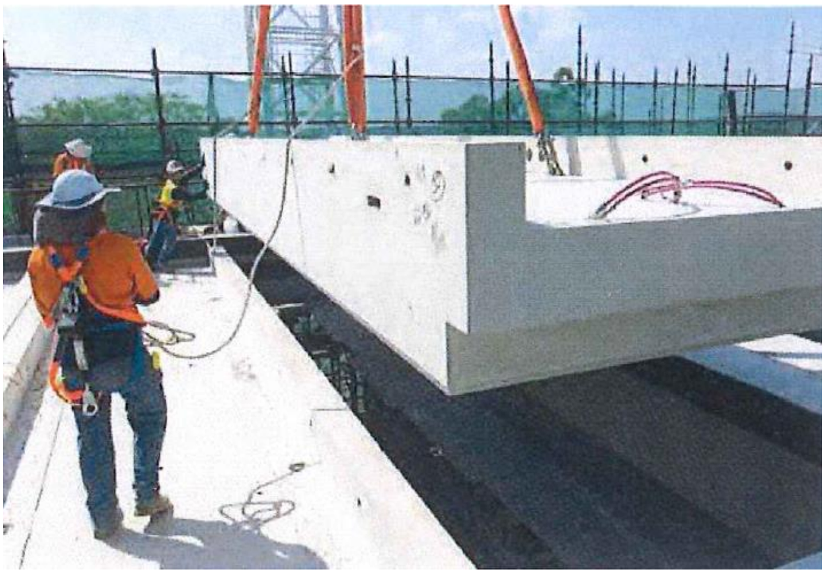
Precast floor panels, Global Change Institute, University of Queensland

As part of the Global Change Institute's (GCI) research goals investigating global sustainability issues, it was proposed to include geopolymer concrete in the construction of the new GCI building, with the aim to demonstrate the use of an innovative and sustainable material (Aldred & Day 2012; Bligh & Glasby 2014; Bligh & Glasby 2013). A total of 33 precast floor panels of 11 m span were fabricated using Wagner's EFC geopolymer product and installed as three suspended floors within the building (Figure 3.5). These were installed after conducting a series of material and structural tests on a prototype component, which included strength properties, creep, fire resistance, and load testing. A project-specific specification was developed for the geopolymer concrete, which incorporated key performance indicators from AS 3600 and specified a compliance testing schedule that included assessment on the following items:

- 28-day compressive strength, flexural strength and indirect tensile strength
- density
- modulus of elasticity
- stress strain curve
- Poisson's ratio
- 56-day drying shrinkage
- creep
- tensile development lengths for reinforcement bar bond
- chloride content
- sulphate content
- alkali aggregate reaction
- load testing of a prototype beam
- fire testing of a loaded floor element.

Testing indicated that the geopolymer concrete had improved performance characteristics when compared to OPC concrete. However, no long-term performance or durability testing was conducted and issues regarding carbonation were not considered to be critical by the authors due to the internal location of the panels. The current performance of these panels is unknown.

Figure 3.5: Placement of the geopolymer concrete suspended precast panels at the new Global Change Institute building

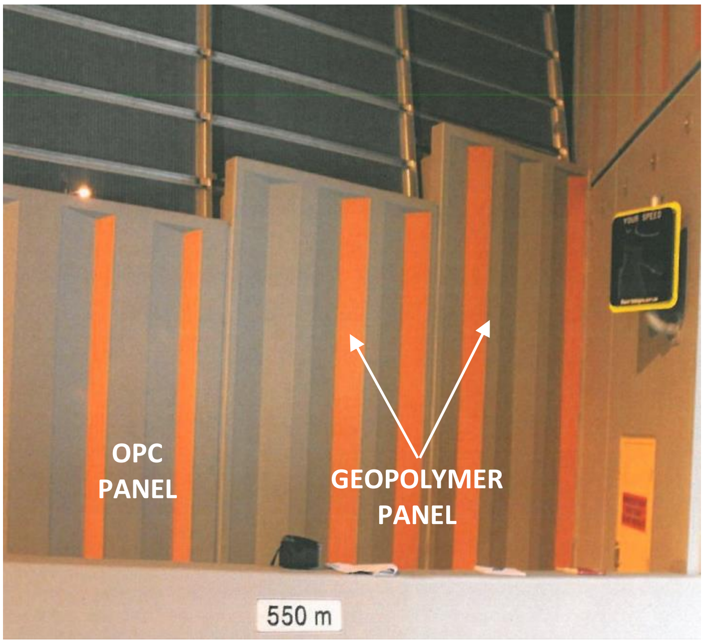


Source: Bligh & Glasby (2013).

Test panels, Eastern Busway, Brisbane

A research trial was initiated by TMR in consultation with Wagners Concrete to install two geopolymer precast wall panels adjacent to OPC panels in the Eastern Busway project (Figure 3.6). The panel sizes are 5250 mm x 2380 mm x 200mm and 4465 x 2380 mm x 200 mm, and the proposed mix design specified a concrete strength of 40 MPa and 180mm slump (Refer TMR Drawing EB2-1-1964-ST-DG-TU721). Panels were cast in December 2010 and installed in 2011. Seven test cylinders were taken at the time of casting and a monitoring program was developed to continuously review the ongoing performance of the panels in comparison to the OPC panels. This includes an inspection regime and future coring requirements. The performance of the panels is currently being confirmed.

Figure 3.6: Geopolymer concrete precast wall panels installed as a trial as part of the Eastern Busway, Brisbane



Source: TMR.

Rocky Point boat ramp, Bundaberg

This project was commissioned by Maritime Safety Queensland in conjunction with Wagners Concrete (Aldred & Day 2012). Precast geopolymer concrete planks of 40 MPa strength were fabricated and placed at the tidal site in late 2011. It also utilised glass fibre reinforced polymer reinforcement. The ramp performance currently being investigated with core samples retrieved for analysis late June. Results of this investigation are pending.

Test slabs, Port of Brisbane

A series of geopolymer concrete test pavement slabs were installed in a weighbridge at the Port of Brisbane in November 2010 at the request of Wagners Concrete (Aldred & Day 2012). The slabs are Grade 32 MPa concrete and are located in an aggressive marine environment (Figure 3.7).

ARRB contacted a representative from Port of Brisbane on 13 January 2016 to discuss the performance of the slabs, and his personal observations are summarised below (email communication from Mr. Lambert Macchion on 13 January 2016):

Workability

- Issues were noted with regard to placing and finishing the product.
- A lower pump pressure was required to place the concrete.

Performance

- The representative recalled there were some early issues relating to dusting.
- It is unknown how the slabs have performed to date.

Figure 3.7: Placement of the geopolymer concrete pavement for a weighbridge at Port of Brisbane

Source: Aldred and Day (2012).

3.2.2 International Experience

The first countries to experiment with alkali-activated materials were the former Soviet Union, Belgium and China in the early 1950s. This was due to supply shortages of Portland cement, driving a need for the development of alternative cementitious binders (Provis & Van Deventer 2014). Several long-term studies have been published based on these early applications (Shi et al. (2006), Xu et al. (2008), Buchwald et al. (2015) and Vanooteghem (2011) as cited by Berndt et al. (2015) and Aldred and Day (2012)). The results of these international studies are shown in Table 3.3.

Table 3.3: Summary of investigation on long-term performance of alkali-activated concrete

Reference (as cited by Berndt et al. 2015)	Location and application	Year of construction	Mix details	Comment on performance
Xu et al. (2008)	▪ Location: Kiev, Ukraine ▪ High-rise building ▪ Underground drainage ▪ Silo ▪ Outdoor precast slab	1964–1982	▪ Alkali-activated slag ▪ Activator: sodium sulphate	▪ Concrete in good condition, no visible defects ▪ Compressive strength variable ▪ pH variable ▪ Carbonation depths less than 8 mm
Vanooteghem (2011), Buchwald et al. (2015)	▪ Location: Belgium ▪ Building	1957	▪ 'Purdocement' ▪ Alkali-activated slag ▪ Small proportion of OPC ▪ Activator: sodium sulphate	▪ Coating evident on concrete ▪ Concrete mostly still sound ▪ Damage associated with water leakage or poor compaction (initial construction) ▪ All cores fully carbonated ▪ Elevated chloride levels, corrosion evident (from flower-box fertiliser)

Source: Berndt et al. (2015).

Other documented international applications include:

- North America:
  - Rapid pavement repair ('Pyrament', 1984) (FHWA 2010; Wilkinson et al. 2015)
  - US military use of pavement coatings to resist heat generated by vertical take-off (Hambling 2009 as cited by FHWA(2010))
- New Zealand:
  - In situ geopolymer concrete path adjacent to ocean inlet in New Zealand (Concrete Institute of Australia 2011)

Zeobond Pty Ltd (producer of E-Crete geopolymer concrete) states that they have provided successful commercial products in the USA, United Arab Emirates and China (Zeobond Pty Ltd 2012).

With regards to the New Zealand application, Fletcher Building's Golden Bay Cement conducted a geopolymer concrete trial to assess weathering performance in an aggressive marine environment. A path in 12 m slab lengths was installed adjacent to an ocean inlet on reactive clay foundations and was subject to light traffic and stock movements. A comparative path using OPC concrete was placed adjacent to the geopolymer trial. During the first 18 months, the path showed good in-service performance with no cracking observed. By comparison, the OPC concrete showed cracking at 3 m centres (Concrete Institute of Australia 2011).

3.2.3 *Other Possible Applications*

There are a number of other applications for which geopolymer concretes have been identified as having potential (Pacheco-Torgal et al. 2014; Provis & Van Deventer 2014):

- binder for toxic or radioactive waste immobilisation/capture/storage
- groundwater barrier system
- repair material or protective coating for OPC concrete
- high-temperature applications (industry, fire-resistant components)
- soil stabilisation (cement product only).

3.3 Performance of Geopolymer Concrete

3.3.1 *Overview*

Research into the performance characteristics of geopolymer concrete is ongoing, particularly in relation to durability and long-term properties; however, from the data collated and reviewed to date there are apparent trends emerging that can be reported with a degree of confidence. Table 3.4 provides an overview of the various criteria commonly used to assess the performance of OPC concrete and the comparative findings for geopolymer concrete.

The trends noted from Table 3.4(a) appear to demonstrate that geopolymer concretes generally exhibit improved strength and performance properties in comparison to OPC concrete (with the exception of the elastic modulus). Results are also promising for the majority of durability requirements, as shown in Table 3.4(b). However, there are areas that still require clarification where ambiguities have been identified or initial results have suggested poorer performance compared to OPC concrete, e.g. carbonation, the volume of permeable voids (VPV), alkali-aggregate reactivity (AAR), time to corrosion initiation and corrosion rate). It is also recognised that many of these findings are still preliminary and require further long-term research and field trials to validate findings.

The following section provides more detail on the current understanding and research relating to geopolymer concrete durability performance characteristics.

Table 3.4: A comparison between geopolymer and OPC concrete performance properties

(a) Strength and workability properties

Property	Geopolymer versus OPC concrete	Example of references
Compressive strength	Similar or higher rate of early strength gain	Bernal et al. (2011); Fernández-Jiménez et al. (1999, 2006); Pan et al. (2011)
Tensile strength	Indirect tensile strength typically higher for similar compressive strength	Sarker (2011); Pan et al. (2011)
Flexural strength	Similar to higher, depending on alkali activator;, higher rate of early strength gain	Diaz-Loya et al. (2011); Fernández-Jiménez et al. (1999, 2006)
Modulus of elasticity	Typically lower	Diaz-Loya et al. (2011); Fernández-Jiménez et al. (2006); Pan et al. (2011)
Density	Similar to lower	Diaz-Loya et al. (2011); Pan et al. (2011)
Poisson's ratio	Typically lower or similar	Diaz-Loya et al. (2011); Pan et al. (2011)
Shrinkage	Lower to similar	Fernández-Jiménez et al. (2006); Andrews-Phaedonos (2011); Sagoe-Crentsil et al. (2012)
Creep coefficient	Lower	Sagoe-Crentsil et al. (2012)

Property	Geopolymer versus OPC concrete	Example of references
Compressive strength	Similar or higher rate of early strength gain	Bernal et al. (2011); Fernández-Jiménez et al. (1999, 2006); Pan et al. (2011)
Bond strength to reinforcement	Similar for similar compressive strengths; higher for higher compressive strengths	Sarker (2011); Fernández-Jiménez et al. (2006)

(b) Durability properties

Property	Geopolymer versus conventional concrete	Example of references
Carbonation coefficient	Higher	Bernal et al. (2010, 2011); Law et al. (2012); Aperador et al. (2009)
Chloride diffusion coefficient	Lower (migration test); lower (core test)	Bernal et al. (2012); Andrews-Phaedonos (2011)
Rapid chloride permeability	Lower to similar depending on mix proportions	Bernal et al. (2011); Law et al. (2012); Andrews-Phaedonos (2011)
Corrosion rate of embedded steel	Limited research, particularly field exposure, prevents conclusive comparison	Aperador et al. (2009); Aperador Chapparo et al. (2012); Miranda et al. (2005); Reddy et al. (2013); Kupwade-Patil and Allouche (in press)
Sorptivity	Higher	Law et al. (2102); Bernal et al. (2011)
Sulphate resistance	Somewhat higher, depends on cation	Bakharev et al. (2002)
Acid resistance	More resistant to organic and inorganic acid attack	Literature reviewed by Pacheco-Torgal et al. (2012); Bakharev et al. (2003)
Alkali-silica reaction susceptibility	Variable based on limited research	García-Lodeiro et al. (2007); Fernández-Jiménez and Puertas (2002); Bakharev et al. (2001); Literature reviewed by Pacheco-Torgal et al. (2012); Kupwade-Patil and Allouche (2013)
Fire resistance	More resistant	Zhao and Sanjayan (2011). Literature reviewed by Pacheco-Torgal et al. (2012)
Freeze-thaw durability	More durable	Literature reviewed by Pacheco-Torgal et al. (2012)
Volume of permeable voids	Varies depending on mix proportions; higher	Bernal et al. (2011); Andrews-Phaedonos (2011)
Water absorption	Similar	Bernal et al. (2011)

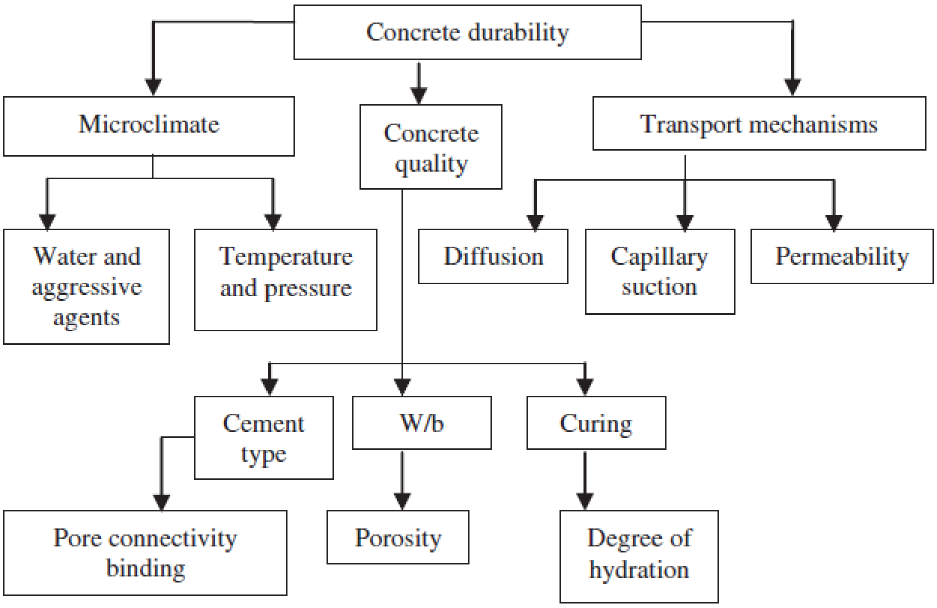
Source: Table 4, 'Pathways For Overcoming Barriers To Implementation Of Low CO_2 Concrete' Report (Berndt, Sanjayan, Foster & Castel 2013)

3.3.2 Durability Performance

Parameters that are influential in the durability performance of OPC concrete are summarised in Figure 3.8. These items have also been identified as key durability parameters for geopolymer concrete (Pacheco-Torgal, Abdollahnejad, Miraldo, et al. 2012).

An industry survey carried out by the Cooperative Research Centre for Low Carbon Living (Berndt, Sanjayan, Foster & Castel 2013) noted that the lack of data regarding the long-term durability of geopolymer concrete (in particular its performance relating to corrosion resistance, acid attack and carbonation) is seen as a key barrier to its widespread implementation and adoption as a suitable construction material. This is echoed in several other publications (Berndt et al. 2015; Provis & Van Deventer 2010; Wallah et al. 2004). However, some research into the durability characteristics of geopolymer concrete exists. Key findings of recent research and where current knowledge gaps exist are summarised in the following sections.

Figure 3.8: Key parameters that influence concrete durability



Source: Bai (2009) as cited by Pacheco-Torgal, Abdollahnejad, Miraldo, et al. (2012).

Corrosion resistance

The corrosion resistance of a material is primarily related to the permeability of the concrete, which is a measure of the ease with which molecules can transport through the pores of the concrete (critical for chloride, water, oxygen and carbon dioxide transport). This can be assessed using tests for volume of permeable voids (VPV), electrical resistance, and tests for porosity and permeability (water and oxygen).

Geopolymer concrete is known to have continuous nanoporosity which remains constant throughout its design life (primarily due to the lack of continuous hydration, which reduces porosity). This raises concerns with regard to the ability of geopolymer concrete to protect embedded steel from corrosive agents such as chlorides. Conflicting conclusions have been determined from various studies, e.g. Cheema (Cheema 2014; Cheema, Lloyd & Rangan 2009), Reddy et al. (2011), Badar (2014), Shaikh and Afshang (2014) and Olivia and Nikraz (2011), particularly in relation to chloride ingress rates, electrical resistance, corrosion rate, and the rate of concrete cracking due to corrosion.

Cheema (Cheema 2014; Cheema, Lloyd & Rangan 2009) found that low-calcium, fly ash-based geopolymer (LCFG) concrete's potential applications should be limited to structures in non-aggressive to mildly aggressive environments that are predominantly dry. These findings were backed up by the levels of chloride ingress that were significantly greater than the threshold limits, indicative that corrosion initiates in LCFG concrete faster than it does in OPC concrete.

Contrary to Cheema's conclusions, Reddy et al. (2011), while investigating the durability of geopolymer concrete in seawater environments, found that geopolymer concrete proved much more effective against chloride penetration than OPC concrete. Significant differences were observed in electrical resistance results between the geopolymer and OPC concrete specimens once cracking had commenced. Unlike OPC concrete, geopolymer samples showed no significant increase in current, indicative of a greater electrical resistivity a measure of improved corrosion resistance. Reddy attributed these findings to corrosion and other reaction products filling cracks in the geopolymer concrete.

Shaikh and Afshang (2014) and Olivia and Nikraz (2011) determined similar findings to Reddy et al., concluding that geopolymer concrete exhibits better corrosion resistance than OPC concrete. Shaikh and Afshang found that, despite the increased rates of corrosion over time in both geopolymer and OPC concrete, the increase in corrosion rate was greater for OPC concrete than that of geopolymer concrete. Olivia and Nikraz found that lower corrosion rates were observed for geopolymer concrete compared to OPC concrete based on accelerate corrosion tests. This was believed to be due to the inclusion of sodium silicate acting as a corrosion inhibitor. Interestingly, it was noted that geopolymer concrete was found to exhibit greater chloride permeability than OPC concrete, which was attributed to the lack of chloride-binding capability of the geopolymer concrete. Half-cell potential results indicated severe corrosion in geopolymer concrete samples; however, limited corrosion activity was physically observed, casting doubts on the applicability of the half-cell potential method to assess geopolymer concrete for corrosion.

Berndt et al. (2013) noted that the VPV in geopolymer concrete was generally higher than in OPC concrete. Conversely, the durability study carried out by (Olivia & Nikraz 2011) found that all geopolymer concrete samples had a lower porosity (approximately 12% VPV) when compared to OPC concrete (8–9% VPV), based on a 91-day accelerated laboratory trial. It was also noted that VPV and porosity values in the geopolymer concrete decreased over time.

Acid attack

Research to date suggests that geopolymer concretes have high acid resistance compared to OPC concrete based upon studies showing limited mass loss when immersed in acid. For example, a study carried out by Gourley and Johnson (2005) - as cited by Pacheco-Torgal, Abdollahnejad, Camões et al. (2012) found that mass losses in OPC concrete samples (with a design life of 50 years) were in the order of 25% after 80 immersion cycles in sulphuric acid. In comparison, geopolymer concrete samples under the same conditions took 1400 immersion cycles to exhibit an equivalent mass loss, corresponding to a service life of 900 years.

Gourley and Johnson’s findings were backed up by Song et al. (2005) - as cited by Pacheco-Torgal, Abdollahnejad, Camões et al. (2012) . After immersing OPC concrete and geopolymer concrete samples in 10% sulphuric acid for four weeks, Song et al. noted that the mass loss for geopolymer concrete samples was 3% compared to 41% for OPC samples.

Pacheco-Torgal et al. also concluded that this is because chemical resistance is influenced by the products of hydration rather than by the porosity of the concrete. Surplus sodium particles that are not part of the hardened material remain in a soluble condition and are leached when in contact with a solution. This increases the binder porosity and temporarily lowers mechanical strength; however, zeolitic precipitates eventually form, which lower the increased porosity by clogging the continuous pores and increasing the mechanical strength.

However, these conclusions are based on short-term accelerated laboratory tests, and longer term field trials would be required to more accurately assess the long-term performance of geopolymer concrete exposed to aggressive acidic environmental conditions, such as acid sulphate soils.

Carbonation

Carbonation is a process where airborne carbon dioxide reacts with alkaline solutions in the concrete pore structure, resulting in a reduction in alkalinity of the concrete, which can destroy the passivity layer between the geopolymer concrete and reinforcement, leading to an environment conducive to corrosion of embedded steel.

Provis and Van Deventer (2010) noted that, to date, there had been a limited number of detailed studies on the effects of carbonation on the properties of geopolymer concrete. They cite a study carried out by Criado et al. in 2005 which found that the formation of sodium bicarbonate in low-calcium fly ash-based geopolymer concrete tended to yield lower carbonation depths. Provis and

Van Deventer note that sodium bicarbonates are more soluble than calcium carbonates (a typical product of carbonation in OPC concrete) and may act as an “alkali sink” and potentially play a buffering role. They also noted that extending curing periods resulted in lower rates of carbonation due to the refined pore structure. Other studies referenced in their investigation find conflicting results, which leads to the conclusion that carbonation can best be controlled by manipulation of the binder phase to minimise its permeability and porosity. Badar and colleagues (Badar 2014; Badar et al. 2014) noted that some fly ash-based geopolymer concretes provide adequate carbonation resistance to mitigate corrosion.

In contrast, there is research to suggest that the carbonation performance of geopolymer concrete is lower than OPC concrete. Research carried out by Law et al. (2015) noted that some geopolymer concrete mixes yielded a lower durability performance with respect to carbonation. In addition, the authors advised caution with regard to the long-term performance of geopolymer concrete due to carbonation and chloride-induced corrosion. Carbonation measurements obtained from older slag-based concrete - see Section 3.2.2 and also Berndt et al. (2015) - also suggest that these materials may be susceptible to higher rates of carbonation than OPC concrete.

Shayan, Xu and Andrews-Phaedonos (2013) also noted that the resistance of geopolymer concrete to carbonation is uncertain simply because the test methods available are not applicable to geopolymer concrete. The phenolphthalein test used to measure carbonation depths in OPC concrete does not give a clear border between coloured and colourless areas of geopolymer concrete, making it impossible to assess carbonation depth. Many studies have noted that further research into testing methods for carbonation is required. Further study is also required to determine the effects of carbonation on geopolymer concrete.

Aggregate reactivity

Limited testing has been carried out on geopolymer concrete regarding its susceptibility to aggregate reactivity. Within the research published there are conflicting results. Research by Kupwade-Patil et al. (2012) noted that OPC concrete exhibited six times the level of expansion due to aggregate reactivity than geopolymer concrete exhibited when immersed in sodium hydroxide solution. A visual inspection of the specimens found that the geopolymer concrete did not show any observable cracks or leaching. Further, it was stated that the amount of AAR expansion in geopolymer concrete in the presence of sodium hydroxide solution would lead to the re-initiation of the geopolymerisation process of unreacted fly ash particles, affording the concrete less porosity and greater strength.

Research by Kupwade-Patil and Allouche (2012) found that the potential for, and severity of, alkali-silica reactivity (ASR) in geopolymer concretes may be lower than for OPC concrete. ASR has been claimed to enhance the tensile strength of geopolymer concretes as it provides a strong bond at the paste-aggregate interface. Their research noted that the silica gel formed by the reaction between the unutilised alkalis and reactive aggregates was not expansive, and was attributed to a lack of available calcium (despite the high levels of alkali content). In contrast, Pacheco-Torgal, Abdollahnejad, Camões et al. (2012) note that numerous authors believe that the presence of calcium is essential for ASR to occur.

Recent research by Tennakoon, Shayan and Sanjayan (2015) shows that geopolymer concretes require at least 30% fly ash to minimise AAR expansion (based on accelerated mortar bar tests). Additional aggregate reactivity results are pending from the affiliated Austroads project TS1835.

Further long-term research is required to provide clarification in this area.

Scaling

Very limited research has been undertaken to determine the susceptibility of geopolymer concrete to scaling. Cheema (2014) found that low calcium fly ash-based geopolymer concrete had low scaling resistance under severe environmental exposure. For example, after three years, concrete cover decreased by 5 mm to 15 mm, which reduced the effective cover and caused reductions in compressive strength.

Efflorescence/leaching

Limited research has been conducted on the evolution of efflorescence in geopolymer concrete. It appears that geopolymer concrete is susceptible to this phenomenon due to its higher alkali content than OPC concrete (Zhang et al. 2013). It is unknown whether this has a significant long-term impact on the durability or performance characteristics of geopolymer concrete.

Some research, based on relatively young samples and short-term, accelerated testing, suggests that efflorescence has the potential to increase the porosity of the concrete microstructure, which may lead to decrease in corrosion resistance and strength development (Zhang, Yang & Wang 2014). Interim results from TS1835 appear to confirm this observation. Alternatively, Burciaga-Diaz et al. (2010) state that, for more mature samples, the occurrence of efflorescence and leaching of alkalis has a small impact on overall strength reduction of the samples. More research is required to quantify the likely long-term effects.

Abrasion resistance

Very little has been done in the way of research for abrasion resistance of geopolymer concrete. Ramujee and Potharaju (2014) carried out a series of accelerated water abrasion tests on OPC and fly ash-based geopolymer concrete samples. The authors concluded that the geopolymer samples provided better abrasion resistance than the OPC concrete samples. Similarly, Hu et al. (2008) reported that geopolymer cementitious repair materials made with slag performed better in terms of mechanical abrasion resistance than those comprising of OPC.

However, these tests were short term and under controlled laboratory conditions (water abrasion tests were conducted over a 24-our period, mechanical abrasion test results were obtained after 5 minutes). Therefore the long-term field performance of geopolymer concrete with regards to abrasion resistance remains unclear.

Abrasion resistance testing results from the Austroads project TS1835 are currently pending and will provide some additional information relating to the slip resistance of geopolymer concrete.

3.4 Specifications, Guidelines and Standards

A survey carried out by the Cooperative Research Centre for Low Carbon Living found that over 60% of respondents cited the lack of coverage in existing standards as the primary barrier to the widespread implementation of geopolymer concrete (Berndt, Sanjayan, Foster & Castel 2013). The lack of specification documentation stems from the commercially driven development of proprietary products (by companies such as Wagners Concrete, Zeobond Pty Ltd and Rocla), which has prevented the publication of mix design parameters and manufacturing processes. The lack of long-term mechanical and durability performance parameters relating to geopolymer concrete has also been inhibitive.

Despite this, there have been a number of guidelines published recognising the use of geopolymer concrete as an alternative construction material. The following sections summarise these advancements and also provide commentary on the applicability and adequacy of AS 3600 *Concrete structures* for geopolymer concrete.

3.4.1 Jurisdictional Specification of Geopolymer Concrete

Table 3.5 provides a summary of the existence of Australian jurisdiction specifications permitting the use of geopolymer concrete for structural and non-structural applications. At present, no jurisdiction currently permits the unrestricted use of geopolymer concrete in structural applications. However, VicRoads and DPTI have recently issued specifications that allow for geopolymer concrete to be used in specific non-structural applications, such as kerbing, drainage and those applications with low-strength requirements. These developments are discussed further below. Detailed information relating specifically to current concrete mix design requirements for various jurisdictions can be found in the 2014 Cooperative Research Centre (CRC) for Low Carbon Living report (Berndt, Sanjayan, Foster & Castel 2013).

Table 3.5: Status of jurisdiction specifications for geopolymer concrete

State/ territory	**Specification**		**Comment**
	Structural	**Non-structural**	
TMR (QLD)	✗	✗	▪ Development of performance specification for geopolymer concrete scheduled in forward NACoE program ▪ Technical Note 59 discusses the emergence of 'green concrete', which acknowledges geopolymer concrete
RMS (NSW)	✗	✗	▪ Currently no provision in concrete materials or application specifications – Moving towards third-party material (ATIC)
TAMS (ACT)	✗	✗	▪ Currently no provision in concrete materials or application specifications
VicRoads (VIC)	✗	✓	▪ Specifications permitting use of geopolymer concrete: – Section 701 *Underground Stormwater Drains* – Section 703 *General Concrete Paving* – Section 705 *Drainage Pits* – Section 711 *Wire Rope Safety Barriers*
DSG (TAS)	✗	✗	▪ Currently no provision in concrete materials or application specifications
DPTI (SA)	✗	✓	▪ Part CC27: *Geopolymer Concrete* – Non-structural applications of strength grades less than 32 MPa – Not permitted in structural applications – Contract document inclusion (i.e. not specification) – No specific mix requirements
MRWA (WA)	✗	✗	▪ Currently no provision in concrete materials or application specifications ▪ In addition to Australian Standards, compliance required with Australian Technical Infrastructure Committee (ATIC) Specification - SP43
NTDoT (NT)	✗	✗	▪ Currently no provision in concrete materials or application specifications
Local govt.	✗	Varies	▪ Most defer to State Road Authority specifications

Department of Transport and Main Roads (TMR) (Queensland)

While TMR does not currently permit geopolymer applications, the interim Technical Note 59 *How 'Green' is our Concrete* was released in late 2015. It acknowledges the recent developments and emerging trends in concrete materials technology, including geopolymer concrete. There is recognition that specifications will be required to govern the specification and use of such products if they are to be adopted for future applications.

Department of Planning, Transport and Infrastructure (DPTI) (South Australia)

In April 2015, DPTI published Specification CC27 that allows for the use of geopolymer concrete for low strength (20 MPa, 25 MPa and 32 MPa), non-structural applications. The general contract Specific Requirements for concrete (DPTI specification CC20) specifies only general purpose (GP) or general purpose blended (GB) concrete can be used in structural applications.

CC27 does not specify any mix design or performance requirements for geopolymer concrete; however, it does specify that a product assessment process shall be followed on all geopolymer concrete produced in accordance with Clause 6.3 of AS 1379. Other key requirements specified are slump, aggregate size and no air entrainment.

With regard to production of the geopolymer concrete, the specification requires that the manufacturer's specifications be satisfied in conjunction with the requirements of Section 17 *Material and Construction Requirements* of AS 3600, using the recommended processes that are described in Standards Australia HB 64 'Guide to concrete construction'. The sole mix design requirement is specified in the definition of geopolymer binder, which specifies that a geopolymer binder shall contain 80% fly ash, ground granulated blast furnace slag or amorphous silica, metakaolin and up to 20% alkaline components.

VicRoads (Victoria)

Following the successful trials of geopolymer concrete in non-structural components such as footpaths and landscape retaining walls (Section 3.2.1), geopolymer concrete was incorporated into the following sections of VicRoads Standard Specifications:

- Section 701 *Underground Stormwater Drains*
- Section 703 *General Concrete Paving*
- Section 705 *Drainage Pits*
- Section 711 *Wire Rope Safety Barriers*.

These are for non-structural applications and predominantly performance based, and have similar requirements to OPC concrete with regards to steel reinforcement, construction tolerances and joints. This is generally in line with requirements outlined in AS 1379. With respect to Section 703, the performance of geopolymer concrete is based solely on compressive strength; however, specific performance requirements for supply, placement, compaction, and curing would be required when specifying any geopolymer concrete use due to issues surrounding quality control of precursor materials (Andrews-Phaedonos 2014).

3.4.2 International Standards (RILEM)

Despite significant work conducted overseas, there are very few specifications that account for geopolymer or alkali-activated concrete. RILEM TC AAM-224 (Provis & Van Deventer 2014) identified the following specifications that could potentially accommodate these materials:

Ukraine/Former Soviet Union

There have been numerous standards that have been developed since 1961 that attempt to acknowledge and progressively regulate the use of new raw materials (such as alkali-activated materials), which was predominantly born out of the shortage of Portland cement in the late 1950s and early 1960s (Section 3.2.2). These standards are unique in that they provide the basis for further research and investigation into a new product to enable its incorporation and integration, and are more aligned with the performance-based standard ethos. However, these standards are not commonly accepted outside this region and represent a methodology fundamentally opposed to those traditionally exercised in Australia, the USA and Western Europe.

ASTM C1157 Standard Performance Specification for Hydraulic Cement (2011)

This standard is the only performance-based standard currently published for hydraulic cements (as opposed to pozzolanic cements). There are no restrictions on the composition of the cement or its constituents, which would therefore accommodate geopolymer cements based purely on performance indicators (such as high early strength or general use). However, this standard is not widely accepted by regulatory authorities in the USA, and other cement standards are traditionally preferred over ASTM C1157.

Canadian Standard CSA A3004-E1 Test methods and standard practices for cementitious materials for use in concrete and masonry (2008)

This standard covers materials that are defined as alternative supplementary cementitious materials (ASCMs) for use in concrete but do not comply with cement requirements outlined in the cement supply standard CSA A3001. It specifies chemical and physical requirements for the material, as well as a comprehensive program of short-term and long-term tests (up to 3 years) to be completed to enable the evaluation of the material's strength and durability properties. It has been noted by RILEM TC 224-AAM (Provis & Van Deventer 2014) that this standard may provide an avenue for the inclusion of geopolymer cements for concrete applications.

EN 206-1: Concrete Part 1: Specification, performance, production and conformity (2000)

There are currently no direct references within this standard that relate to geopolymer cements or similar materials. However, the standard is not explicit in its definition of what constitutes a compliant cement product, which could ultimately be loosely interpreted to include a geopolymer product.

3.4.3 Other Guides

In 2011, the Concrete Institute of Australia (2011) released a recommended practice for geopolymer concrete, CIA Z16. It provides background information on geopolymer chemistry and materials and various material and durability properties of geopolymer concrete. It also provides recommended modifications to current standards based on current research and applications. While this guideline was developed by stakeholders from various engineering sectors (such as Curtin and RMIT Universities and Parsons Brinkerhoff), there is a significant industry input for this document.

The RILEM Technical Committee 224-AAM (Provis & Van Deventer 2014) published a state-of-the-art report in 2013 that provides background information on the development of concretes that incorporate alkali-activated material (AAM), recommended applications for AAM concrete and conclusions from recent research. While this report does not provide recommendations for standards or specifications, it does collate a wealth of knowledge that is recent and useful for those seeking to potentially use this product in future.

3.5 Assessment and Performance Criteria/Requirements

There are several standards that are currently referred to in the use or supply of concrete and cement in Australia:

- AS 3600 *Concrete Structures* (2009)
- AS 3972 *General Purpose and Blended Cements* (2010)
- AS 1379 *Specification and Supply of Concrete* (2007).

AS 3600 is traditionally used to measure and evaluate the performance of a hardened cementitious product based on the following criteria (a more detailed list of specific requirements pertaining to each jurisdiction can be found in the CRC for Low Carbon Living report (Berndt, Sanjayan, Foster & Castel 2013)):

- compressive strength
- tensile strength
- modulus of elasticity
- density
- stress-strain curves
- Poisson's ratio
- coefficient of thermal expansion
- shrinkage
- creep
- bond strength to reinforcement.

In addition, the following durability requirements are often specified as appropriate performance criteria to assess for compliance:

- chloride diffusion coefficient
- carbonation coefficient
- sulphate resistance
- AAR/ASR susceptibility.

Depending on the application, other performance indicators can include:

- fire resistance
- freeze-thaw characteristics
- acid resistance.

Specific performance criteria of particular importance (as identified by the various jurisdictions) are as follows (Berndt, Sanjayan, Foster & Castel 2013):

- volume of permeable voids (VicRoads and DSG)
- rapid chloride permeability (DPTI)
- chloride diffusion coefficient (RMS)
- shrinkage (VicRoads, DPTI, RMS, NTDoT, TMR)
- crack widths (VicRoads, DPTI, RMS).

Additional performance requirements may be specified by the relevant jurisdiction on a project-specific basis (with reference to AS 5100 Part 5 and Part 7 as deemed appropriate).

At present, geopolymer cements or concretes are not represented in AS 3600 or other cementitious standards. Restrictions are in place for mix proportions for blended cements (taking into account fly ash, blast furnace slag and silica fume) and the specification for the inclusion of Portland cement in all cement mixes. However, with the increasing interest in geopolymer concrete, the applicability of the above-mentioned standards in their current format, for the assessment and governance of these new materials, has been questioned. RILEM TC 224-AAM (Provis & Van Deventer 2014) notes that Appendix A in the latest edition of AS 3972 appears to indicate philosophical support for the potential to include geopolymer concrete in the future, with reference to a move towards performance based-standards. Bligh and Glasby (2014) argue that geopolymer concrete falls within the intent of AS 3600, whereby the definition of concrete in AS 3600 is ’a mixture of cement, aggregates and water, with or without the addition of chemical admixtures’, and that the definition of cement does not necessarily subscribe to OPC. Bligh and Glasby note that the material compliance aspects of AS 3600 are largely performance based and, as such, could potentially be applied to geopolymer concrete.

Recent applications and research have shown that many OPC concrete test methods for mechanical properties represent appropriate performance criteria for geopolymer concrete (Aldred & Day 2012; Bligh & Glasby 2013) and may be implemented as per AS 1012 (Concrete Institute of Australia 2011). These properties include:

- compressive strength
- unit weight
- flexural strength
- splitting tensile strength
- drying shrinkage
- creep.

Berndt et al. (2015) also note that several studies have determined that AS 3600 can estimate the flexural and shear capacities of geopolymer concrete beam and column members with reasonable accuracy, leading to suggestions that reinforcing details may be minimised due to high tensile and bond strength performances.

However, there is also recognition that not all specified criteria set out in these standards, particularly AS 3600, provide adequate or, in some cases, applicable criteria to accurately assess the performance of geopolymer concrete. This is predominantly due to the differences between chemical and hydration mechanisms for GP and geopolymer concrete, which lead to fundamentally different material products.

Some examples of these inadequacies are as follows (Berndt et al. 2015; Concrete Institute of Australia 2011; Provis & Van Deventer 2014; Shayan, Xu & Andrews-Phaedonos 2013):

- Due to research suggesting the elastic modulus for geopolymer concrete is less than OPC concrete, serviceability limits set out in AS 3600 may be insufficient.
- The use of the rapid chloride permeability test to assess the long-term chloride resistance of geopolymer concrete as the test method yields inaccurate results (Part, Ramli & Cheah 2015).
- The phenolphthalein test has been found to be unsuitable to assess the depth of carbonation in geopolymer concrete.

- Specified concrete cover (based on exposure classifications) are currently based on extensive and long-term durability data that incorporate carbonation and chloride diffusion rates for OPC concrete. Due to the lack of long-term durability data for geopolymer concrete, the cover recommendations may be invalid (Berndt, Sanjayan, Foster & Castel 2013).
- Numerous studies have found that geopolymer concretes have superior tensile strength to OPC concrete and, as such, it would be conservative to adopt the tensile strength specified by AS 3600.
- The chemistry of the geopolymer concrete points towards the elastic modulus being higher than that of OPC concrete; however, recent research indicates the opposite. As a result, deflection limits imposed by AS 3600 may be invalid.
- Maximum serviceability stresses in reinforcement are based on a maximum crack width of 0.3 mm for OPC concrete. The crack width is dependent on the inherent stress-strain relationship based on extensive data for OPC concrete. This will differ for geopolymer concrete, which will ultimately differ from the maximum serviceability stresses prescribed by AS 3600.

Based on these observations, there is an apparent and increasingly urgent need to develop new and independent performance guidelines suitable for the accurate assessment of geopolymer concrete infrastructure applications.

There are currently a number of research initiatives to address this need. The CRC for Low Carbon Living has embarked on an extensive research program, exploring the application of geopolymer concrete and investigating options to enable the adoption of this alternative construction material (Berndt, Sanjayan, Foster, Sagoe-Crentsil, et al. 2013; Berndt, Sanjayan, Foster & Castel 2013; Heidrich et al. 2015). A key deliverable from this program will be the geopolymer concrete handbook, to be published by Standards Australia. The goal of this handbook will be to provide guidance to end users in the specification and use of geopolymer concrete, and provide specific comments relating to AS 3600, AS 3972 and AS 1379 to allow appropriate modifications for material strength, design and detailing requirements. As part of this handbook, field trials are strongly recommended to fill gaps in knowledge regarding geopolymer concrete and support informed specifications. Existing test methods are also being trialled to determine which are suitable to assess geopolymer concrete performance. For example, tests being trialled for chloride diffusion include:

- semi-natural chloride diffusion test
- rapid chloride permeability test
- rapid chloride migration test
- surface resistivity test
- bulk electrical conductivity test.

This handbook will be a precursor to an additional standard to be developed in future years as more research is carried out and risk areas qualified and mitigated (Berndt, Sanjayan, Foster, Sagoe-Crentsil, et al. 2013). It is also acknowledged that the development of an appropriate standard will be crucial in the more widespread adoption of geopolymer concrete (Berndt et al. 2015; Provis & Van Deventer 2014; Van Deventer, Provis & Duxson 2012).

Similarly, Austroads has commissioned project TS 1835 which is aimed at investigating geopolymer concrete and providing guidance to jurisdictions in the selection and specification of structural and non-structural road infrastructure applications using geopolymer concrete. This project is scheduled for completion in 2016 however interim results are unable to be presented at this time due to ongoing postgraduate studies (see Section 1.4).

3.6 Current Obstacles and Knowledge Gaps

While geopolymer concrete shows promise as an environmentally sustainable and more economical material, its widespread acceptance and use has been hindered by a series of issues related to its practicality and performance, as well as knowledge gaps that require further research. These issues have been broadly summarised and discussed below.

Long-term durability

One of the primary barriers to the widespread implementation of geopolymer concrete that was identified by the industry survey carried out by the CRC for Low Carbon Living was the lack of long-term performance data (Berndt, Sanjayan, Foster, Sagoe-Crentsil, et al. 2013; Heidrich et al. 2015). Many studies have been undertaken that aim to investigate the durability properties of geopolymer concrete, e.g. resistance to acid attack, alkali-silica reaction, corrosion resistance and carbonation, in aggressive environments such as seawater and acid-sulphate soils (Cheema 2014; Law et al. 2015; Olivia & Nikraz 2011; Reddy et al. 2011; Shaikh & Afshang 2014); however, conflicting conclusions between studies have been drawn. Many of these studies are also laboratory based, use accelerated test procedures and take place over a relatively short period of time (Berndt et al. 2015). This does not necessarily reflect actual field conditions and is insufficient in comparison to the long-term data that exists for OPC concrete. In addition, of the laboratory studies conducted, many of the studies have conflicting conclusions for a variety of reasons, including:

- variations in materials and mix designs
- variations in curing methods
- variations in experimental testing methods
- lack of coordination between investigations.

Thus, direct comparisons between experimental results become inconsistent and unreliable. Continuous monitoring of field applications is therefore imperative to confirm the long-term performance of geopolymer concrete, particularly when located in aggressive environments (Berndt et al. 2015; Provis & Van Deventer 2010).

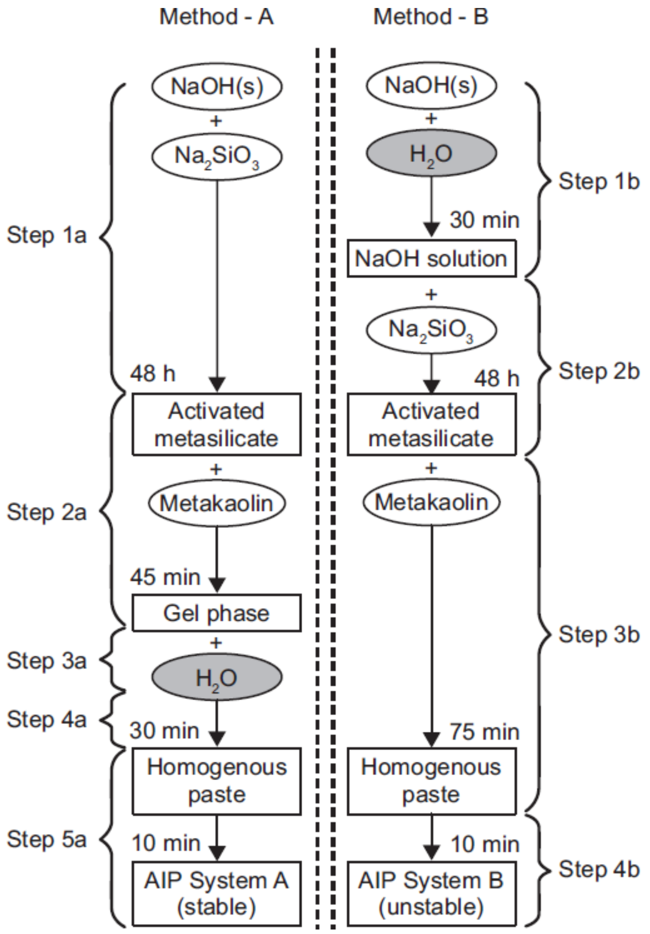
Product quality control

As industrial waste by-products, the quality of fly ash and blast furnace slag can be variable. Widespread adoption of geopolymer concrete will require the development of a waste material logistic network and quality program for improved product take-up (Albitar et al. 2014). Also, during the design of the Global Change Institute building, Bligh and Glasby noted from discussions with industry that the ability to control the quality of geopolymer concrete batches had ‘a long way to go’ (Bligh & Glasby 2013).

Geopolymer cement is manufactured in a two-part format, which consists of a precursor material and an alkali activator. Due to the inherent variability of fly ash and slag composition, mix designs and added alkalis need to be continuously varied, requiring skill and extensive experience with such a product. This hinders the widespread adoption of this material, and would require product centralisation at the binder plant level rather than at batching level. Alternatively, precursor materials and alkali-activators can be combined as a dry mix prior to transport; however significant capital outlay is required to ensure quality controls are met.

Concerns have also been raised regarding the sensitivity of the final hardened geopolymer product to slight changes in the preparation procedures (Kobera et al. 2011). This is demonstrated in Figure 3.9 that shows the vulnerability and stability of a resulting geopolymer product, which is highly dependent on the various processes preceding the end product.

Figure 3.9: Diagram showing the sensitivity of a geopolymer concrete to its preparation process



Source: Kobera et al. (2011)

Geopolymer concrete has subsequently been identified as an ideal material for precast construction due to the more rigorous production and curing controls that exist in comparison to insitu applications (Heath et al. 2013).

Mix design requirements

Many representatives believe that the concrete industry needs to alter the existing standards regime and allow any material that meets given performance standards to be utilised rather than prescribing mix designs and properties. This view is backed up by the knowledge that the term geopolymer covers a wide range of binder materials and, hence, wide variation in properties and performance, which can be confusing to designers and specifiers. Contrary to these views, however, 50% of respondents to the survey carried out by the CRC for Low Carbon Living believed that the lack of proprietary formulations was a significant barrier to the implementation of geopolymer concrete (Berndt, Sanjayan, Foster & Castel 2013).

Specification of concrete for a construction project typically calls for a mix design and/or particular properties in order to cater for the in-service environment and workability requirements (Berndt, Sanjayan, Foster & Castel 2013). CIA Z16 (Concrete Institute of Australia 2011) provides some guidelines for geopolymer mix design criteria including, but not limited to:

- particle size distribution of the aggregate skeleton
- fluids-to-binder ratio by mass
- silicon-to-aluminium ratio by atoms.

Long-term availability of precursor material

It has been noted in the literature that geopolymer concrete production may result in anywhere from 17% (Provis & Van Deventer 2014) up to 64% (McLellan et al. 2011) less carbon dioxide than the production of OPC concrete and, as such, is a suitable measure towards a reduction in carbon dioxide emissions. However, new government energy policy initiatives are seeking ways to further reduce carbon dioxide emissions, with goals of moving to renewable sources of energy supply over those derived from coal-fired power stations. For example, it has been predicted that coal-fired energy supplies in the UK will have decreased by up to 70% by 2030. This shift would result in a substantial decrease in the availability of fly ash (Heath et al. 2013), which would directly impact the geopolymer concrete industry.

Development of testing methods applicable to geopolymer concrete

Currently, standard testing methods which are used to determine mechanical properties of OPC concrete such as compressive strength, unit weight, drying shrinkage and creep, etc. have been proven to be suitable for geopolymer concrete (Concrete Institute of Australia 2011). However, inadequate data exist regarding the applicability of carbonation and chloride testing methods to geopolymer concrete (Shayan, Xu & Andrews-Phaedonos 2013).

The level of carbonation is generally tested by spraying phenolphthalein onto the concrete surface and recording the depth where colour change occurs. Adam et al. (2009) found that the phenolphthalein indicator gave no clear border between coloured and colourless areas of the geopolymer concrete specimens. This was not the case for the control OPC concretes, proving that the phenolphthalein test may not be applicable to geopolymer concrete.

Adam et al. (2009) also tested fly ash-based geopolymer concrete specimens for chloride ingress using the rapid chloride penetration test. It was found that the specimens drew excessive current because of the high concentration of ions present in the pore solution. The test was halted after only 30 minutes. Part, Ramli and Cheah (2015) also concluded that the rapid chloride penetration test was not suitable, as geopolymer concrete specimens were exhibiting rapid rises in temperature, defeating Ohm’s Law.

Curing conditions

The curing conditions required for geopolymer concrete are dependent on the geopolymer binder used. While the literature generally confirms that ambient curing for geopolymer concrete is an added benefit as it requires lower energy requirements for manufacture (Cheema, Lloyd & Rangan 2009; Srinivasan & Sivakumar 2013), current research is showing that some will require elevated curing temperatures to ensure adequate and consistent strength development to match OPC concrete strength performance, e.g. fly ash-based geopolymer concrete (Adam et al. 2009; Albitar et al. 2014; Hardjito 2005).

It has also been noted that the mineral composition of geopolymer concrete is highly dependent on the curing regime, which may impact the consistency of the end product as well as long-term performance and durability properties (Olivia & Nikraz 2011; Provis & Van Deventer 2014; Steins et al. 2012).

It is recognised that geopolymer concrete may be well suited for precast applications where steam curing at elevated temperatures is required due to improved strength development properties compared to OPC concrete (Concrete Institute of Australia 2011; Provis & Van Deventer 2014). However, there are concerns that application of heat may interfere with the geopolymerisation process, which may subsequently influence resulting strength and mechanical properties (Part, Ramli & Cheah 2015). Part et al. also state there is evidence to suggest that curing at elevated temperatures may destroy the granular structure of the geopolymer concrete.

Other issues related to practicality

Further issues related to the practicality of adopting geopolymer concrete include (Aldred & Day 2012; Berndt et al. 2015; Pacheco-Torgal, Abdollahnejad, Miraldo, et al. 2012; Van Deventer, Provis & Duxson 2012):

- regulatory issues
- capital intrinsic set-up of production facilities
- the high cost of alkali-activated binders
- workability and finishing capability of the geopolymer concrete, including the use of specially developed superplasticisers
- handling issues relating to safety in geopolymer cement production
- the shift of pollution from an area concerned with climate change to other areas such as acidification, ecotoxicity and abiotic depletion.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary of Literature Reviewed/Relevant Findings

Geopolymer concretes were reviewed to provide TMR with a brief summary of product definitions, where it is currently used, current research findings, how it is assessed and specified, and what the existing issues and research gaps are relating to geopolymer concrete performance.

Geopolymer concrete is a relatively new construction product that uses geopolymer cement as a majority or whole replacement binder for Ordinary Portland Cement (OPC). Geopolymer cements are derived from materials high in aluminosilicates that are either naturally occurring (pozzolans) or industrial waste by-products (such as fly ash or blast furnace slag), and require minimal processing for inclusion. The benefits of geopolymer concrete are predominantly environmental, e.g. reductions in CO_2 emissions, lower energy requirements and water usage, and the use of readily available natural or industrial waste products. However, there are also potential economic and performance benefits, with the latter based on strength, workability and durability properties when compared to OPC concrete.

The following sections summarise the findings of this literature review in relation to the original project objectives (Section 1.2).

4.1.1 Current Understanding Relating to the Long-term and Durability Performance of Geopolymer Concrete

Research to date indicates that the performance of geopolymer concrete is comparable or exceeds that of OPC concrete in terms of strength development, density, shrinkage and creep, with the exception of modulus of elasticity results. Other identified benefits include low heat of reaction and consistent achievement of high early strength. However, many of these findings are based on controlled and often accelerated laboratory research programs that are short term.

Longer term studies based on laboratory studies have shown favourable results in terms of durability (such as porosity and permeability, corrosion resistance, acid resistance, and chloride diffusion); however, some results are conflicting and clear recommendations remain unknown. Areas requiring further investigation include long-term creep, carbonation, leaching/efflorescence, abrasion resistance, and aggregate reactivity.

4.1.2 Documented Applications in Civil Infrastructure

Various field examples of geopolymer concrete exist nationally and internationally. The majority of applications in Australia are non-structural, e.g. footpaths, stormwater and sewer pipes, kerbs, and are located in non-aggressive environments. Limited structural trials include the following:

- Floor beams in Global Change Institute building (University of Queensland, St Lucia campus).
- Retaining wall structure, M80 Western Ring Road (Victoria).
- Pavements and one short-span bridge at the Brisbane West Wellcamp Airport (Toowoomba).
- Busway panels in Section 2 of the Eastern Busway, Queensland.
- Rocky Point boat ramp, located in an aggressive marine environment (Bundaberg).

The physical performance of these structures is not known.

Widespread acceptance of this product within Australia is still limited due to several research gaps predominantly relating to long-term field results. Restrictions also exist due to the proprietary nature of geopolymer concretes developed from industry, which limits information on mix design and materials for specification and performance assessment.

4.1.3 Specification and Performance Assessment

At present, no document exists for the specification and assessment of geopolymer concrete. VicRoads and DPTI have developed geopolymer-related specifications, but these are predominantly for non-structural applications and on a project-by-project basis subject to approval.

There has been some success in using AS 3600 in some field trials to assess geopolymer concrete for strength, drying shrinkage, unit weight and short-term creep. However, the validity of other assessment criteria to assess the performance of geopolymer concrete remains unknown, e.g. serviceability limits, carbonation rates, corrosion monitoring performance indicators (e.g. chloride penetration, corrosion rates), concrete cover and acceptable crack widths (see Section 3.5).

Combined with the current unknowns and research gaps identified in Section 3.6 and pending the publication of TS 1835 and the Geopolymer Handbook, there is a need to develop a specification that enables the specification, implementation and ongoing performance and durability assessment of geopolymer concrete for infrastructure applications in accordance with TMR’s requirements. This specification would need to provide distinct requirements for both manufacturing and implementation processes. The provision of expected visual and physical performance indicators are also recommended to assist inspectors when in the field and inspecting such applications.

In addition, a specification for a continual monitoring program should be developed in the event that any geopolymer applications are installed, so as to ensure long-term field performance, durability and serviceability data is captured over the life of the asset.

4.1.4 Current Geopolymer Concrete Unknowns and Research Gaps

To date, there are several areas that require further investigation and research relating to geopolymer concrete. These include:

- long-term durability and strength performance (particularly in aggressive environments)
- specification and performance assessment requirements
- material and production quality control
- mix design requirements
- curing requirements
- future availability of precursor materials.

Additional research into these areas, preferably in terms of field trials, will provide additional information to enable TMR to make informed decisions regarding the adoption of geopolymer concrete in road and marine infrastructure.

4.2 Recommendations

Based on the findings of this literature review, the following recommendations are made:

- Conduct a review and gap analysis of TS 1835 and Standards Australia geopolymer handbook once final versions have been published.
  - This will include a review of performance test recommendations and results of any additional laboratory and field tests.
- Obtain information relating to the current performance and condition of the Rocky Point boat ramp in Bundaberg (Section 3.2.1).
- Continue with the collation of field investigation observations (nationally and internationally).

- Develop a continuous monitoring and test program specification prior to any future geopolymer concrete applications or field trials to ensure long-term field performance, durability and serviceability data is captured over the life of the asset.
- Conduct a series of field trials to investigate specific areas identified by TMR, such as the criteria set out in Section 3.5 and other key parameters such as:
  - abrasion/slip resistance
  - long-term corrosion monitoring (in aggressive environments)
  - suitability of geopolymer concrete for structural and non-structural applications.

  This may include the installation of durability-based sensors in geopolymer and OPC concrete specimens to monitor for durability-specific parameters (such as corrosion initiation and rate, moisture content and diffusion characteristics) and a long-term program of non-destructive testing and inspection. Additional test blocks may also be required to enable the retrieval of samples for chloride and carbonation testing. Consideration should also be given to testing the long-term creep and shrinkage of geopolymer concrete under sustained load.

- Develop a TMR-specific performance-based specification for geopolymer concrete applications. This should provide guidance on:
  - manufacturing processes
  - design and installation
  - visual inspection indicators and expectations
  - maintenance and repair requirements.

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APPENDIX A PRELIMINARY LITERATURE SEARCH

Includes literature selected by the working group for detailed review.

S19 Geopolymer Concrete

Literature Search

	Yr	Authors	Title	Publication	Publisher	Volume	Pages	Abstract	Category 1	Category 2	Comments	Priority (H = High, M = Medium, L = Low)	TMR selection
1	?	Various	PATHWAYS FOR OVERCOMING BARRIERS TO IMPLEMENTATION OF LOW CO2 CONCRETE	Cooperative Research Centre for Low Carbon Living	Cooperative Research Centre for Low Carbon Living	Research Project No. RP1004-I	57 pp	The Cooperative Research Centre (CRC) for Low Carbon Living (LCL) aims to overcome market barriers to the adoption of alternative low CO2. As part of the CRC-LCL Program 1: Integrated Building Systems, pathways for adoption of low CO2 concrete are being identified. The objectives of the research described in this report were to examine the current state of the art in the design and specification of concrete in Australia and consider how barriers to implementation of low CO2 concrete, specifically geopolymer concrete, can be overcome. The project reviewed the widely used definitions of concrete and cementitious materials to determine if alternatives may be readily included in existing standards. Current practices with regard to concrete mix design and property requirements in Australian standards and state specifications have been considered as these represent the foundation of structural use of concrete. Other than some VicRoads specifications, most state specifications and AS 3600 implicitly assume that concrete is based on Portland cement and do not provide for use of alternative binders. The exceptions are recent VicRoads specifications that permit use of geopolymers for applications such as general paving and drainage structures. Barriers to implementation of geopolymer concrete and new materials in general to the construction industry were reviewed. Case histories of polymer concrete and fibre reinforced polymer reinforcement were considered to demonstrate how alternatives can be successfully introduced into an established market. An industry survey was performed to better understand barriers particular to geopolymer concrete in Australia and to identify potential pathways to overcoming these barriers. Based on review of prior studies and the industry survey, several actions and pathways were recognised. Highest priority activities were the development of standard specifications, development of new standards specific to geopolymer concrete that include performance requirements, provision for use of in state and local specifications and more independent research on engineering properties and long-term durability. Three near-term research projects were short-listed for future work necessary to accomplish greater use of geopolymer concrete. These were: (1) Development of a handbook (HB) through Standards Australia titled “Guide and Standard Specification for Construction with Geopolymer Concrete”; (2) Investigation of geopolymer concrete durability and field performance; and (3) Construction of a building using geopolymer concrete as a demonstration project for the CRC-LCL	Overview/General	Standards	Overview of what various jurisdictions currently do specifying "low carbon" concrete. Some mix design parameters, references to standards and specifications. Performance based parameters. Property requirements Snapshot of applications and jurisdiction adoption/stance in Australia http://www.lowcarbonlivingcrc.com.au/	H	Y
2	2015	Berndt, M., Sanjayan, J,. Foster, S., Castel, A., Rajeev, P., Heidrich, C	Progress towards a handbook for geopolymer concrete	Concrete 2015: 27th Biennial National Conference of the Concrete Institute of Australia in conjunction with the 69th RILEM Week Conference, Melbourne, Australia, 30 August-03 September 2015	Concrete Institute of Australia		9 pp	Our previous research conducted for the Cooperative Research Centre for Low Carbon Living identified several barriers to the widespread implementation of alternative, low CO2 concrete such asgeopolymers. It was found that the lack of standard specifications, lack of long-term performance data and non-compliance with AS 3600 were major obstacles to adoption. Therefore, current research is addressing these deficiencies through the preparation of a Handbook in association with Standards Australia. The primary purpose of the Handbook will be to assist engineers and end-users in specifying and constructing with geopolymer concrete. The Handbook will include background and properties of geopolymer concrete, a model performance-based specification, case histories and long-term durability studies, recommendations on testing and monitoring, and commentary on compliance with AS 3600. The objectives of this paper are to outline the proposed Handbook content, initiate discussion among stakeholders and seek input	Specification	Standards	Good update on standard/specificaiton progress	H	Y
3	2015	Berndt, MA, Chadbourn, G	Geopolymer and high volume fly ash concrete for pavements	Australian Society for Concrete Pavements Conference (ASCP), 2015, Coffs Harbour, New South Wales, Australia	Australian Society for Concrete Pavements			Much interest has been shown in improving the sustainable performance of concrete. The use of cement replacement materials and geopolymer concrete offers benefits in terms of reduced carbon footprint and enhanced properties. This paper reviews the properties of geopolymer concrete and concrete with high levels of cement replacement materials relevant to pavements and issues to overcome to enable widespread use. Recent progress towards preparation of a handbook in association with Standards Australia to provide guidelines on use and specification of geopolymer concrete are presented.	Overview/General	Standards	Generic paper providing overview. Pavement applications Mention of Standards Australia geopolymer handbook	M/H	M
4	2015	Craig Heidrich, C., Sanjayan, J., Berndt, M., Foster, S., Sagoe-Crentsil, K.	Pathways and barriers for acceptance and usage of geopolymer concrete in mainstream construction	World of Coal Ash (WOCA) Conference in Nasvhille, TN - May 5-7, http://www.flyash.info/	World of Coal Ash (WOCA)		14 pp	Geopolymer [low carbon] concrete offers potential advantages such as structural performance, reduced greenhouse gas emissions, and acid and fire resistance. However, despite these advantages widespread commercial use of geopolymer concrete in the construction industry has encountered numerous technical, economic and institutional barriers. With increasing concerns regarding climate change, designers are keen to use alternatives to ordinary Portland cement-based concrete, but face uncertainties regarding properties, performance and lack of compliance with AS 3600 and related standards. This paper describes ongoing work performed under the Cooperative Research Centre for Low Carbon Living and $3.1 million funded project to identify pathways and barriers for the acceptance and usage of geopolymer concrete in mainstream construction. Current definitions of concrete and the ways in which concrete is commonly specified are examined in order to find potential modifications to include geopolymer concrete. An industry survey was performed and this identified barriers specific to geopolymers and potential actions to overcome raised issues. Lessons from successful introduction of other alternative materials to the construction industry are also considered	Specification	Assessment criteria	Summary of issues	H	Same as #1?
5	2015	DPTI	Specification: Part CC27 Geopolymer Concrete,	Part CC27 Specification		April	3 pp		Specification		Placement advice Some production guidelines provided	H	Y
6	2015	Kumaravel, NS, Girija, P., and Anandha Kumar, B.	Durability Performance Of Various Grade Of Geopolymer Concrete To Resistance Of Acid And Salt	ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) - Technical Note		16 (8)	1185-1191	It is important to durable of structure and reduce CO2 emission through the greater use of substitute for Cement. The processing of geopolymer using fly ash, GGBS and activator solution. After making the concrete mixer of AS and aggregates, such as cube and cylinders. It is cured and tested for compressive strength. The durability of geopolymer concrete is tested by immersion in chemicals that are HCl and MgSO4. Alumina-Silicate is the binder in GPC, which react with acid and salt. The different grade of concrete is used as “M20, M30, M40, M50 and M60”. These specimens are immersed separately in 5% of magnesium sulphate and 5% of hydrochloric acid with 90 days. The change of weight and strength over a 90 days for acid and salt reaction on geopolymer concrete are periodically monitoring surface deterioration and depth. The test results indicate that the geopolymer concrete has an excellent resistance to acid and sulphate attack when compared to conventional concrete.	Durability	Research	Research findings on resistance to acid/sulphate attack Short term trials (90days)	L/M	

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Literature Search

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7	2015	Michael Eliot	The Case for Geopolymer Concrete in Seasteading	Website/Blog					Overview/General	Durability	bLog/opinion/subjective. Does contain some mix proportions and other specific information (such as practicalities in mixing, versatility, perceived issues with product) Also see website: http://discuss.seasteading.org/t/geopolymer-concrete-the-perfect-seasteading-material/240	M/H	
8	2015	Part, WK., Ramli, M., Cheah, CB.	An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products	Construction and Building Materials		77 (Feb)	370-395	The enormous amount of industrial waste ash generated by power generation industry, timber manufacturing industry, iron and steel making industry, rice milling industry, mining industry etc have posed the aforementioned industry players a great challenge when it comes to the disposal of these ash materials due to the environmental, health, scarcity of lands and other issues. The best approach in overcoming the aforementioned waste management problems is to promote large volume recycling/reuse of these waste materials. In recent years, the rapid growth in research and development related to geopolymer binders has indeed indicated that the use of geopolymer offers the greatest potential in solving not only the waste management problems related to the aluminosilicate solid waste materials generated from various industries, but also the environmental degradation related to the use of OPC as primary binder material in the construction industry. Results of recent studies are indicative that geopolymer concrete fabricated using various industrial by-products exhibited similar or better mechanical, physical and durability properties as compared to OPC concrete. This paper presents a concise review of the current studies on the utilization of industrial by-products as the primary binder materials in the fabrication of geopolymer concrete. The effects of a number of major factors such as the use of chemical activator, post fabrication curing regime, particle size distribution of source materials, and aggressive environment exposure on the mechanical strength, physical properties, microstructures and durability properties of the geopolymer concrete are exhaustively deliberated. Besides, the current material design, fabrication procedures and post fabrication treatment procedures were rigorously reviewed to identify the limitations of the current geopolymer technology which impede its wide implementation in the construction industry. It has been identified that the high alkaline content in the material design and requirement for elevated temperature treatment of the contemporary geopolymeric binder are among the major technical challenges which resulted in the limited use of the material in the construction industry. Based upon that, numerous strategies were proposed to overcome the current limitations of the geopolymer technology towards promoting a large scale implementation of the technology in the production of construction materials	Review	Overview/General	Summary of current knowledge, challenges Many material and mechanical properties discussed; limited durability discussion	M/H	Y
9	2015	Singh, B., Ishwarya, G., Gupta, M., Bhattacharyya, S.K.	Geopolymer concrete: A review of some recent developments	Construction and Building Materials		85 (June)	78-90	An overview of advances in geopolymers formed by the alkaline activation of aluminosilicates is presented alongwith opportunities for their use in building construction. The properties of mortars/concrete made from geopolymeric binders are discussed with respect to fresh and hardened states, interfacial transition zone between aggregate and geopolymer, bond with steel reinforcing bars and resistance to elevated temperature. The durability of geopolymer pastes and concrete is highlighted in terms of their deterioration in various aggressive environments. R&D works carried out on heat and ambient cured geopolymers at CSIR-CBRI are briefly outlined alongwith the product developments. Research findings revealed that geopolymer concrete exhibited comparative properties to that of OPC concrete which has potential to be used in civil engineering applications.	Review	Research	Review of current findings; Research into mechanical and materials properties	L/M	
10	2015	TMR	How 'Green' is our Concrete	Technical Note 59			6 pp		Overview/General	Case studies	Generic overview of 'green concrete'. TMR position. Mention of geopolymer trials by Structures	L/M	
11	2015	Una, C.H., Sanjayana, J.G., San Nicolasa, R., van Deventer, J.S.J.	Predictions of long-term deflection of geopolymer concrete beams	Construction and Building Materials		94 (Sep)	10-19	The long-term behaviour of concrete beams constructed with geopolymer concrete (GPC) is investigated. Self-weight and sustained load of 1 kPa are applied on top of the beams at the age of 14 days to simulate construction conditions. Creep tests on cylinders conducted with sustained loading commenced at the ages of 14 days and 28 days. The results from creep tests on GPC show higher creep in the specimens loaded at 14 days than those loaded at 28 days. Predictions of beam deflections are performed by using RCM, EMM and AEMM with input parameters of properties of GPC from experimental data, including elastic modulus, modulus of rupture, creep and shrinkage. These property tests show that GPC can achieve sufficient strength for structural designs, but both compressive strength and flexural tensile strength are affected by drying, which causes differential drying shrinkage and microcracking at the drying surfaces. The predicted deflections by these analysis methods are compared with the experimental results from beams, and show that RCM gives the worse performance of the three methods. The investigation concludes that the AEMM can be used for long-term deflection calculations for GPC beams with minor parameter modifications.	Performance	Research	Tests on deflections (creep) "long term" is 28 days.	L/M	
12	2015	UNSW	A major milestone in the use of geopolymer concrete - Brisbane West Wellcamp Airport	Website		19-May	-		Case studies		Actual application in November 2014 Wagners trial Prof. James Aldred providing advice regarding geopolymers Potential to enquire how concrete is performing	M	

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13	2015	Wilkinson, A; Woodward, D; Magee, B; Tretsiakova-McNally, S	A state of the art review into the use of geopolymer cement for road applications	International Conference on Bituminous Mixtures and Pavements, 6th, 2015, Thessaloniki, Greece	CRC Press, London, United Kingdom, ISBN: 9781138028661		147-52	This paper is a state of the art review of the use of geopolymer cement for road applications. Geopolymer cement is an alternative to Portland cement and is either naturally occurring rock-based or industrial by-product-based. Geopolymer cement has been around for at least the last 30 years. In recent years it has become an attractive potential alternative to Portland cement. The main reason for this renewed interest is the issue relating to the release of carbon dioxide into the atmosphere during the manufacture of Portland cement. It is estimated that 1 tonne of Portland cement produces approximately 1 tonne of CO2 during its manufacture. The use of geopolymer cement can reduce this amount by as much as 90%. It is claimed that this will have a huge potential in reducing national targets in CO2 emissions of many countries around the world. This state of the art review critically evaluates existing literature relating to these claims and focuses on the potential use of geopolymer concrete for road applications. In addition to environmental benefits, the existing literature suggests that geopolymer cement concrete has the potential to provide better mechanical properties than Portland cement concrete. Attractive properties include quicker compressive strength development, higher compressive and flexural strength, minimal shrinkage and resistance to chemical-attack and freeze-thaw cycles. The review will consider the different types of geopolymer cement, its properties and whether it can be used in road applications.	Overview/General	Performance	Pavements related General information, overview Provides useful comparison of OPC vs GPC (Table 1) discusses potential applications	H	
14	2014	A Shayan, C Tennakoon, A Xu	TS 1835 - Specification and Use of Geopolymer concrete in the manufacture of structural and non structural components: Progress Update	Austroads Progress Report	Austroads				Austroads project	Specification	ARRB Project 010712. Research continuing	H	
15	2014	Andrews-Phaedonos, F	Specification and use of geopolymer concrete	Austroads Bridge Conference, 9th, 2014, Sydney, New South Wales, Australia	ARRB Group		12 pp	Geopolymer concrete consists of similar ingredients as conventional concrete except that the cement is wholly replaced by industry by-products such as slag and fly ash and the chemical reaction is promoted by a concentrated solution of alkali-based chemicals such as sodium hydroxide and sodium silicate instead of the conventional hydration reaction. This makes geopolymer concrete a more environmentally sustainable product as it reduces carbon emissions by some 40 % to 80 % whilst maintaining the structural properties of conventional concrete. Whilst conventional concrete is characterised by the formation of calcium silicate hydrates (CSH), geopolymer concrete is characterised by an aluminosilicate (Si-O-Al-O) based microstructure. Although a significant amount of research has been undertaken in Australia over the past 10 to 20 years particularly in Victoria and Western Australia the take up of this technology from laboratory controlled production to on-site field work has been relatively slow. However, 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 lower risk applications. A number of barriers have been suggested as impediments to the wider acceptance of geopolymer concrete including technical, standardisation and regulatory barriers. However, use and monitoring of geopolymer concrete by VicRoads over the past five years has culminated in the definition of geopolymer concrete and inclusion in a number of standard VicRoads specifications, including general paving, reinforced concrete pipes and concrete pits. It is considered that the inclusion of geopolymer concrete in such specifications has assisted in the take up of geopolymer concrete in various commercial applications in Victoria including foundations, slabs and precast panels, and has acted as a precursor to its introduction into other areas of Australia. In general the use, monitoring and specification of geopolymer concrete by VicRoads are considered to provide at least one pathway for increased use of low carbon geopolymer concrete in Australia. This paper describes the evolution of geopolymer concrete from a trial material to its inclusion in a number of standard VicRoads specifications, through to commercial production and its use on more significant structures	Specification	Case studies	How VicRoads use and specify geopolymer concrete	H	Y

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Literature Search

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16	2014	Badar, Mohammad Sufian	THESIS: Selected durability studies of geopolymer concrete with respect to carbonation, elevated temperature, and microbial induced corrosion	Thesis	LOUISIANA TECH UNIVERSITY		141 pp	This thesis reports a comprehensive study related to the experimental evaluation of carbonation in reinforced geopolymer concrete, the evaluation of geopolymer concretes at elevated temperature, and the resistance of geopolymer concrete to microbial induced corrosion (MIC). Carbonation: Reinforced concretes, made of geopolymer, prepared from two class F fly ashes and one class C fly ash, were subjected to accelerated carbonation treatment for a period of 450 days. Electrochemical, microstructure and pore structure examinations were performed to evaluate the effect of corrosion caused due to carbonation. GPC specimens prepared from class F fly ash exhibited lower corrosion rates by a factor of 21, and higher pH values (pH>12) when compared with concrete specimens prepared from class C Fly ash (GPCMN). Microstructure and pore characterization of GPC prepared using class F fly ash revealed lower porosity by a factor of 2.5 as compared with thier counterparts made using GPC-MN. The superior performace of GPC prepared with the class F fly ash could be attributed to the dense pore structure and formation of the protective layer of calcium and sodium alumino silicate hydrates (C/N-A-S-H) geopolymeric gels around the steel reinforcement. Elevated Temperature: Geopolymers are an emerging class of cementitious binders which possess a potential for high temperature resistance that could possibly be utilized in applications such as nozzles, aspirators and refractory linings. This study reports on the results of an investigation into the performance of a fly ash based geopolymer binder in high temperature environments. Geopolymer concrete (GPC) was prepared using eleven types of fly ashes obtained from four countries. High content alumina and silica sand was used in the mix for preparing GPC. GPC was subjected to thermal shock tests following ASTM C 1100-88. The GPC samples prepared with tabular alumina were kept at 1093° C and immediately quenched in water. GPC specimens prepared with certain fly ashes exhibited signs of expansion along with cracking and spalling, while GPC prepared with specific class F fly ash showed superior resistance to thermal shock. Microstructural analysis revealed that the resistance of GPC at elevated temperatures was dependent on the type of fly ash used, its particle size distribution, formation of zeolitic phases such as sodalite, analcime and nepheline, and the overall pore structure of the geopolymer concrete. The work indicates that the chemical composition and particle size distribution of the fly	Durability	Performance	Need to purchase/obtain Research based Provides findings on selected durability performance indicators (carbonation, temperature, MIC)	**M/H**	Y
17	2014	Cheema, DS.	Low calcium fly ash based geopolymer concrete: Long term durability properties.	PhD Thesis	Curtin University		288 pp	Geopolymer concrete is a relatively new material, its widespread acceptance is hindered by a lack of its long term durability properties and limited knowledge about its limitations as an alternative to Ordinary Portland Cement (OPC) concrete. The need to reduce the environmental impacts associated with the production of OPC concrete is widely recognised by the cement and concrete industries. Past research has shown that a low calcium fly ash-based geopolymer (LCFG) concrete has good mechanical properties with the potential for a reduced carbon footprint resulting from the zero-cement content. As such it may be a potential construction material as a greener alternative to OPC concrete. Low calcium fly ash has a typical composition of silicate varying between 48-54% and of aluminate varying between 26-29%. Silica to alumina ratio of low calcium fly ash from Collie Power Plant, Western Australia is approximately close to 2, which normally is the typical Si/Al elemental ratio for geopolymer binder. Geopolymer binder in LCFG concrete is an inorganic material that results from the reaction of source materials rich in silica and alumina and alkaline solution of high alkalinity as a polymeric reaction rather than a calcium- silicate - hydrate (C-H-S) gel structure as found in OPC concrete. Due to the different chemical reaction nature in LCFG concrete, it is likely that its microstructure will be different to OPC concrete. Very limited research is available in terms of LCFG's long term durability properties. That is, its potential to perform satisfactorily with minimal maintenance over the anticipated design life under environmental actions is unknown. Environmental actions may range from non- aggressive to severe. LCFG concrete was investigated in this research to determine the long term durability properties. Laboratory and field-placed culvert specimens were investigated. Laboratory reinforced samples of size 300mm x 300mm x 120mm in thickness (approximately) depending on the cover to the reinforcement and cylinder specimens of size 100 x 200 mm were prepared. For comparison, OPC concrete samples & specimens of equivalent strength were prepared. Prior to this research, a feasibility study was undertaken in co-operation with local pre-cast industry in 2007 for the manufacturing of pre-cast LCFG concrete box culverts. The LCFG concrete box culverts of size 1200 x 1200 x 600 mm from the feasibility study together with OPC concrete box culverts of the same specification were used to assess the long term durability properties in aggressive and non-aggressive field environments in this research. One set of box culvert (comprising of LCFG concrete box culvert and one OPC concrete box culvert) was	Durability	Performance	LONG! Low calcium fly ash geopolymer concrete (LCFG) Box culvert examples set in various environments 3 year trial NDT testing, strength, other tests Research indicates caution for geopolymer in aggressive environments - better for low risk applications? USEFUL	**H**	Y
18	2014	Drechsler, M.	Powerpoint presentation: Geopolymer Concrete Research	powerpoint presentaiton	University of Adelaide				Overview/General	Performance	In conjunction with Worley Parsons Current and future recommended research	**L**	
19	2014	FHWA	Concrete Pavement Technology Program: Geopolymer Concrete	TechBrief	FHWA		1-4		Overview/General		Brief, little additional information	**L/M**	

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20	2014	Neupane, K., Baweja, D., Shrestha, R., Chalmers, D., Sleep, P.	Mechanical properties of geopolymer concrete: Applicability of relationships defined by AS 3600	Concrete in Australia.	Concrete Institute of Australia	40 (1)	50-56	Geopolymers are new inorganic polymer binders, synthesised from aluminosilicate powders such as fly ash and blast furnace slag with alkali activators and producing good binding properties similar to ordinary Portland cement (OPC). This new generation binding material has a potential application in structural and non-structural concretes, fire resistant composites and ceramics. Previous research around the world has suggested that geopolymer binders possess superior engineering, mechanical and durability properties over conventional Portland cement. The process of setting and hardening of geopolymer concrete is based on different chemistry called 'polymerisation' instead of 'hydration' in OPC. The silicon and aluminium oxides in the source materials are activated by a combination of sodium hydroxide and sodium silicate in the presence of water to form a sodium aluminosilicate paste called 'geopolymer' which has binding properties similar to calcium silicate hydrate (CSH) in OPC. In this study, some engineering and mechanical properties of different grades of geopolymer concrete were tested and evaluated according to relevant Australian Standards and compared against the same grade of OPC concrete. AS 3600 has defined some interrelationships between different mechanical properties of Portland cement concrete, such as compressive strength and uniaxial tensile strength, compressive strength and flexural tensile strength etc. From this study, it was found that uniaxial tensile and flexural tensile strengths attained by geopolymer concrete are higher than the prescribed value by AS 3600 for the same grade of concrete. However, modulus of elasticity is found to be almost equal with the calculated value from AS 3600 and similar to the ame grade of OPC concrete	Specification	Standards	Not durability, but relates to AS3600 and a review of geopolymer specification	M/H	
ADDITIONAL LITERATURE IDENTIFIED													
21	2014	Prof. Jay Sanjayan	GEOPOLYMER SPECIFICATION PROJECT						Overview/General	Specification	Useful snapshot of current Australian stance and technology; Related to Item #2, 24	H	Y
22	2014	Rod Bligh, Tom Glasby	Development of geopolymer precast floor panels for the Global Change Institute at the University of Queensland	Concrete in Australia.	Concrete Institute of Australia	40 (1)	44-49	This paper presents the chloride induced corrosion durability of reinforcing steel in geopolymer concretes containing different contents of sodium silicate (Na2SiO3) and molarities of NaOH solutions. Seven series of mixes are considered in this study. The first series is ordinary Portland cement (OPC) concrete and is considered as the control mix. The rest six series are geopolymerconcretes containing 14 and 16 molar NaOH and Na2SiO3 to NaOH ratios of 2.5, 3.0 and 3.5. In each series three lollypop specimens having one 12 mm diameter steel bar cast in a 100ϕ × 200 mm cylinder are considered. The specimens are subjected to cyclic wetting and drying regime for eight weeks. In wet cycle the specimens are immersed in water containing 3.5% (by wt.) NaCl salt for four days, while in dry cycle the specimens are placed in open air for three days. The corrosion activity is monitored by measuring the copper/copper sulphate (Cu/CuSO4) half-cell potential according to ASTM C-876. The chloride penetration depth and sorptivity of all seven concretes are also measured. Results show that the geopolymer concretes exhibited better corrosion resistance than OPC concrete. The higher the amount of Na2SiO3 and higher the concentration of NaOH solutions, the better the corrosion resistance of geopolymer concrete is. Similar behaviour is also observed in sorptivity and chloride penetration depth measurements. Generally, the geopolymer concretes exhibited lower sorptivity and chloride penetration depth than that of OPC concrete	Case studies	Specification	Case study of Australian application Wagners author Potential to review performance of concrete (QLD application)	M/H	Y
23	2014	Sanjayan, J	CRC-LCL Project 2014-2017: Geopolymer Specification Project	Presentation	-		23 pp		Specification	Standards	Useful snapshot of current Australian stance and technology; Related to Item #10	H	Y
24	2014	Shaikh, F. and Afshang, A	Corrosion Durability of Geopolymer Concretes Containing Different Concentrations of Alkaline Solution	Concrete in Australia.	Concrete Institute of Australia	40 (1)	39-43	Wagners EFC (Earth Friendly Concrete) has been successfully utilised for construction of 11 m span precast panels in what is believed to be an Australia first use of suspended geopolymer concrete in the building industry. The design team (Bligh Tanner Consulting Engineers, Lead Consultant Hassell Architects and Arup Sustainability), with the support of University of Queensland worked closely with Wagners to fast track the testing and certification phase of EFC to enable use on this exemplar sustainability project. Adoption of geopolymer to minimise the carbon footprint of this 6 star Greenstar rated project necessitated precasting of the floor panels to ensure quality control of the concrete placement. Use of precast provides opportunities for shaping a vaulted soffit, which improves the efficiency of the cooling systems incorporated in the panels as well as enhancing the space architecturally. The project required close collaboration between the design team, Wagners, the precast fabricator, Precast Concrete, and the builder, McNab, to achieve high quality panels, which are an important visual element in the project. The concrete mix has performed very well with low shrinkage, no visible cracking and good performance in relation to testing of cylinders and load testing of the full panels. The project is very significant in the conference categories of design, sustainability, precast/geopolymer, architecture, and project case study. This paper was presented at the Concrete 2013 conference on the Gold Coast.	Durability	Assessment criteria	Material properties durability tests specified Review of research tests looking at corrosion resistance	M	Y
25	2014	Shayan, A., Xu, A., Andrews-Phaedonos, F	Investigation of a geopolymer concrete used in retaining walls of a bridge	International Conference on Cement Microscopy, 36th, 2014, Milan, Italy	International Cement Microscopy Association (ICMA),		584-601		Case studies	Performance	Case study of Australian application	H	Y
26	2014	Various	MINUTES: Roads Australia Sustainability Chapter - Geopolymer Forum; 18 November 2014	Roads Australia Sustainability Chapter	-	-	17 pp		Case studies	Standards	Minutes; opionions expressed and discussed Useful industry representation Useful case studies referenced	H	Y
27	2013	Heath, A., Paine, K., Goodhew, S., Ramage, M. and Lawrence, M	The potential for using geopolymer concrete in the UK	Proceedings of the Institution of Civil Engineers: Construction Materials		166 (4)	195-203	Geopolymers are a novel class of inorganic polymers, which have the potential to replace Portland cement in a number of different applications. Geopolymers can utilise a higher level of industrial by-products than Portland cement blends and numerous studies have concluded geopolymer concretes have significantly lower embodied carbon dioxide than Portland-cement-based concretes. This paper examines the potential for the use of geopolymer binders as a Portland cement replacement in the UK. The quantities of material required, the major sources of these materials, the environmental implications and the barriers to implementation are discussed	Overview/General	Specification	Summary of issues/views of adopting geopolymer concrete use in UK	M	Y

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Literature Search

	Yr	Authors	Title	Publication	Publisher	Volume	Pages	Abstract	Category 1	Category 2	Comments	Priority (H = High, M = Medium, L = Low)	TMR selection
28	2013	Joseph J. Biernacki, Jeffrey W. Bullard, Daniel Constantiner, Richard C. Meininger, Maria C. G. Juenger, Josephine H. Cheung, William Hansen, William Hansen, R. Douglas Hooton, Andreas Lüttge, Jeffrey J. Thomas	Paving the Way for a More Sustainable Concrete Infrastructure: InfrastructureA Vision for Developing a Comprehensive Description of Cement Hydration Kinet	Special Publication	National Institute of Standards and Technology	Special Publication 1138	35 pp	Concreteis far and away the mostabundantly used man---madematerialontheplanet.Asaconstructionmaterial,itis uniqueinits capacityto beformedandfinished into analmostunlimited variety of shapes,textures,and colors. It can be made on demand with portland cement and inexpensive local materials. With correctplacementand se,concrete canhaveaservice lifeof50 years tomore than 200 years. Improvingtheproperandefficientuseof concreteandportland cement requires betterunderstanding ofthe chemicalprocess ofhydration,and howthat processcan be characterized and modeled –both for pure portland systems and for those containing admixturesand supplemental cementitious materials such as fly ash,slag cement, and others.Having interactive computermodels,based on sound experimental data,for the chemicaland physicalinteraction of cementing compounds, molecules, and ions inthe concretepore---watersolutionswill helpboth toimprove cement manufactureand tooptimize sustainable concrete mixtures. Importantly,concretehas thelowestembodied CO2content of any major material used in construction, including glass,steel,and wood. Butso much concrete isproduced annuallythat itstill accounts forabout 8ofindustrialCO2production.Therefore, reducingboth the CO2contribution and embodied energy ofconcrete is asocietal challenge that must be addressed to ensure asustainable built environment and transportation infrastructure.One way to reduce concrete’s CO2contribution is to loweritsembodiedCO2and energy content and even further,typically by both more efficient production ofcement binder and partialreplacement with supplementary cementitiousmaterialsorfine mineral fillers. This approach is already being used,butoften with uncertainty in the way the binderwill perform.Concrete istypically overdesigned byat least 10 %because oftheinability to ensure the exact performance ofthe binder material.Therefore,the ability to accurately modelcement hydration kinetics and predict and improve the performance ofconcrete as it hydrates could lead to a1%reduction in the mass of cement and concrete used each year and significantly reduce concrete’s embodied CO2content. Achieving these objectives willrequire morecomprehensive and fundamentalknowledge of the hydration process that is responsible for the hardening, strength gain,and ultimate durability ofconcrete. The National InstituteofStandards and Technology (NIST) and the U.S. Federal Highway Administration (FHWA) recognize the importance of obtaining that knowledge through sustained and coordinated research. Paving the Way for aMore Sustainable Concrete Infrastructure isajointNIST/FHWA reportthat provides adetailed vision forfocused experimentaland computational modeling research that will provide the knowledge and	Overview/General	Performance	General overview of 'green concrete' technology; More mechanisms/science based	L	
29	2013	Kupwade-Patil, K., Allouche, EN.	Examination of Chloride-Induced Corrosion in Reinforced Geopolymer Concretes	Journal of Materials in Civil Engineering		25 (10)	1465-1476	The durability of steel reinforced-concrete specimens made from three alkali-activated fly ash (FA) stockpiles and ordinary portland cement (OPC) in cyclic wet-dry chloride environment was evaluated over a period of 12 months. Testing methods included electrochemical methods, chloride diffusion and contents analysis, chemical and mechanical analyses, and visual examination. Geopolymer concrete (GPC) specimens made from Class F FA exhibited lower diffusion coefficients, chloride contents, and porosity compared with their GPC Class C FA and OPC counterparts. Overall, GPC specimens displayed limited signs of leaching and corrosion product formation, whereas OPC specimens exhibited the formation of multiple corrosion products along with significant leaching.	Durability	Research	Research findings on chloride resistivity/corrosion 12 month trials for accelerated corrosion technique	M/H	Y
30	2013	Kupwade-Patil, K., Allouche, EN.	Impact of Alkali Silica Reaction on Fly Ash-Based Geopolymer Concrete	Journal of Materials in Civil Engineering		25 (1)	131-139	This study reports the findings of an experimental investigation for alkali silica reaction (ASR) between reactive aggregates and the geopolymer matrix. Specimens were prepared using one Class C and two Class F fly ash stockpiles. Mechanical testing included potential reactivity of the aggregates via length change and compression test measurements, as per ASTM standards. Results suggest that the extent of ASR reaction due to the presence of reactive aggregates in fly ash-based geopolymer concretes is substantially lower than in the case of ordinary portland cement-based concrete, and well below the ASTM specified threshold. Furthermore, geopolymer concrete specimens appeared to undergo a densification process in the presence of alkali solutions, resulting in reduced permeability and increased mechanical strength. Utilizing ASR-vulnerable aggregates in the production of geopolymer concrete products could contribute to the economic appeal and sustainability of geopolymer binders in regions that suffer from insufficient local supply of high quality aggregates.	Durability	Research	Investigations into ASR in geopolymer concrete	H	Y
31	2013	Rivera, FJM	Strength And Durability Of Fly Ash-Based Fiber-Reinforced Geopolymer Concrete In A Simulated Marine Environment	Masters Thesis	Florida Atlantic University				Durability	Performance	Simulated environment Opportunity for real-life application not great	L/M	
32	2013	Shayan, A.	TS 1835 - Specification and Use of Geopolymer concrete in the manufacture of structural and non structural components: Literature Review	Austroads Progress Report	Austroads		116 pp		Overview/General	Specification	ARRB Project 005568, June 2013 Foundation for current literature review	H	Y

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33	2013	Shayan, A., Xu, A., Andrews-Phaedonos, F	Field performance of geopolymer concrete, used as a measure towards reducing carbon dioxide emission	Concrete Institute of Australia Conference, 26th, 2013, Gold Coast, Queensland, Australia	Concrete Institute of Australia			Portland cement is an energy-intensive material, requiring large amounts of heat in its production. Moreover, manufacture of this material involves burning of limestone, and each tone of Portland cement releases almost one tone of CO2 into the atmosphere. Incorporation of supplementary cementitious and pozzolanic materials, as partial replacement of Portland cement in concrete, is a measure for reducing the utilization of Portland cement in concrete and reduction in CO2 emission. Another benefit of these materials is improvement in the durability of concrete structures. However, geopolymer concrete does not use Portland cement and relies on reactions between some industrial by-products and highly alkaline solutions to generate its binding properties in hardened state. Such materials are, therefore, environmentally friendly and their use in concrete structures is encouraged, where possible. VicRoads recently used a geopolymer concrete, manufactured from blast furnace slag, for the construction of retaining walls around one abutment of a bridge in the Melbourne Area. The present work showed that the geopolymer concrete performed well with respect to electrochemical protection of steel reinforcement, as well as strength and durability properties of concrete. The chemical composition and microstructure of concrete and its permeable void content were also examined	Case studies	Performance	Case studies of Australian applications	H	Y
34	2013	Zaki, RM., Pa, FC., Darus, M.	Corrosion Performance of Reinforcement Bar in Geopolymer Concrete Compare with its Performance in Ordinary Portland Cement Concrete: A Short Review	Advanced Materials Research		795	509-512	Since decades ago, corrosion is the crucial factors for million dollars loss in construction industry. Corrosion of reinforcement bar in ordinary Portland cement (OPC) concrete is mainly due to chloride and acid attack and also due to carbonation process. The degradation of geopolymer (GP) concrete is still widely studied and the mechanisms of degradation are still not conclusive. However, reinforcement bar in GP concrete is reported having lower corrosion rate than in OPC concrete. The fly ash geopolymer has high alkalinity which provides the passivity of the reinforcement bar. The superior properties of GP have encouraged researchers to do further investigation on its performance. This review paper will focus on corrosion performance of reinforcement bar in GP compared to OPC.	Review	Durability	review of durability wrt. Corrosion of reinforcement Some research findings	H	Y
35	2012	Aldred, J. and Day, J.	Is geopolymer concrete a suitable alternative to, traditional concrete?	37th Conference on Our World in Concrete & Structures, 29-31 August 2012, Singapore				Geopolymer concrete is the result of the reaction of materials containing aluminosilicate with concentrated alkaline solution to produce an inorganic polymer binder. While it has a history starting in the 1940's and has attracted significant academic research, geopolymer concrete has yet to enter the mainstream of concrete construction. Most applications to date have been in the precast industry using accelerated curing. However, the use of geopolymer concrete in ready mixed applications is increasing; building on the information currently available and motivated by the considerable sustainability benefits of using a binder system composed almost entirely of recycled materials. A wide range of different geopolymer binder systems are available and discussed in the literature. This creates a potential problem of the satisfactory performance of particular proprietary geopolymers being used to support the use of unproven products under the generic label of geopolymer concrete. Wagners in Australia is supplying a proprietary geopolymer concretefor both precast and in-situ applications.This paper presents data on the engineering properties of this concrete and examples of its application. The paper demonstrates that this particular geopolymer concrete complies with the relevant performance requirements of the Australian Standards and thus provides the Engineer with a viable alternative to Portland cement based concrete allowing greatly reducedthe embodied energy and carbon dioxide footprin	Overview/General		WAGNERS sponsored publication	L	
36	2012	Cheema, DS	Low calcium fly ash geopolymer concrete: a promising sustainable alternative for rigid concrete road furniture	ARRB Conference, 25th, 2012, Perth, Western Australia, Australia	ARRB Group			Geopolymer is a material resulting from the reaction of a source material that is rich in silica and alumina with alkaline solution. This material has been studied extensively over the past few decades and shows promise as a greener alternative to ordinary Portland cement concrete. It has been found that geopolymer has good engineering properties with a reduced carbon footprint resulting from the zero-cement content. Durability parameters depend on the pore structure of concrete matrix. Tests performed to measure compressive strength, volume of permeable void, pore structure and permeability have shown that low calcium fly ash based geopolymer concrete has the potential to be a promising sustainable alternative for rigid concrete road furniture, such as, rigid safety barrier, kerbing, traffic island infill, dual use path (DUP) and parking bay rest areas paving etc with a significant environmental benefits compared to Portland Cement concrete. The research paper highlights potential applications of low calcium fly ash geopolymer (LCFG) concrete in non-aggressive to mild environments			General review	L	
37	2012	Kupwade-Patil, K., Allouche, EN., Vaidya, S., Diaz-Loya, EI.	Chapter 35. Corrosion analysis of reinforced geopolymer concretes	Concrete Solutions 2011 Edited by Ulrich Schneck	CRC Press 2011		267-279		Durability	Performance	Research work, accelerated chloride/corrosion tests. Initial findings relating to chloride resistance	M/H	
38	2012	Pacheco-Torgala, F., Abdollahnejada, Z., Camoes, AF., Jamshidi, M., Ding, Y.	Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue?	Construction and Building Materials		30 (May)	400-405	The alkali activation of alumino-silicate materials is a complex chemical process evolving dissolution of raw materials, transportation or orientation and polycondensation of the reaction products. Publications on the field of alkali-activated binders, state that this new material is likely to have high potential to become an alternative to Portland cement. While some authors state that the durability of these materials constitutes the most important advantage over Portland cement others argue that it's an unproven issue. This paper presents a review of the literature about the durability of alkali-activated binders. The subjects of this paper are resistance to acid attack, alkali–silica reaction, corrosion of steel reinforcement, resistance to high temperatures and to fire, resistance to freeze–thaw. Special attention is given to the case of efflorescences, an aspect that was received very little concern although it is a very important one.	Review	Durability	Alternative perspective regarding durability and highlighting concerns Looking particularly at alkali-activated binders	M/H	Y

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39	2012	Pacheco-Torgala, F., Abdollahnejada, Z., Miraldob, S., Bakloutic, S., Ding, Y.	An overview on the potential of geopolymers for concrete infrastructure rehabilitation	Construction and Building Materials		36 (Nov)	1053-1058	Infrastructure rehabilitation represents a multitrillion dollar opportunity for the construction industry. In USA alone the rehabilitation needs are estimated to exceed 1.6 trillion dollars over the next 5 years. Since the majority of the existent infrastructures are concrete based this means that concrete infrastructure rehabilitation is a hot issue to be dealt with. Besides the sooner concrete deterioration is tackled the lower are the rehabilitation costs. This paper provides a literature review on concrete repair materials, highlighting the current problems face by them. It covers concrete surface treatments, patch repair and FRP strengthening. The case of trenchless rehabilitation of concrete sewage pipelines is also discussed. The potential of geopolymers to overcome those limitations is analyzed.	Review	Assessment criteria	Insights from US perspective. Using geopolymers as repair materials Potentially useful for TMR	M/H	Y
40	2012	Reddy, DV., Edouard, J-B., Sobhan, K.	Durability of Fly Ash-Based Geopolymer Structural Concrete in the Marine Environment	Transportation Research Board 91st Annual Meeting, Transportation Research Board	TRB		11 pp	The use of supplementary cementitious materials as partial replacements of the cement in concrete will play a significant role in the environmental control of greenhouse effects, and the turning down of the global thermostat. Currently, the most widely used supplementary cementitious material in the world, is fly ash, a waste product of the coal-burning power plants. The development of geopolymer concrete (GPC), in which one hundred percent of the Portland cement is replaced by fly ash, in combination with sodium hydroxide and sodium silicate solutions, offers a promising alternative to ordinary Portland cement concrete (OPC). This study evaluated the durability characteristics of low calcium fly ash-based geopolymer concrete subjected to corrosive marine environment. A series of GPC beams, containing fly ash with 8 molar and 14 molar concentrations of NaOH and SiO2/Na2O solutions, and centrally reinforced with ½"Ø rebar, were tested for accelerated corrosion exposure, with wet and dry cycling in artificial seawater, and induced current. The durability was monitored by indication of sudden rise in the current intensity due to specimen cracking. The test results indicated excellent resistance of the geopolymer concrete to chloride attack, with longer time to corrosion cracking, compared to OPC.	Durability	Research	Durability trials of prefabricated small-scale beams accelerated corrosion, laboratory tests looking at resistance to chloride ingress	M	Y
41	2012	Van Deventera, JSJ., Provisa, JL., Duxsonb, P.	Technical and commercial progress in the adoption of geopolymer cement	Sustainability through Resource Conservation and Recycling	Elsevier	29	89-104		Specification	Overview/General	Industry rep (Zeobond)	M	Y
42	2011	Andrews-Phaedonos, F	Geopolymer "green" concrete: reducing the carbon footprint. The VicRoads experience	Austroads Bridge Conference, 8th, 2011, Sydney, New South Wales, Australia	Austroads	AP-G90/11	21 pp	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. 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.	Case studies	Specification	VicRoads opinion of geopolymer concrete	M	Y
43	2011	Cheema, DS	Durability of steel in geopolymer concrete	International Corrosion Conference, 18th, 2011, Perth, Western Australia, Australia				Because of the unique combination of strength and versatility of reinforced concrete, it forms the most common part of our infrastructures (roads, bridges, buildings, airports and wharfs). It is a composite material comprised of steel reinforcing bars encased in a porous matrix of relatively inert aggregates bound together by a cementitious network. The successful performance of reinforced concrete mix depends on the integrity of both these components. While past study has shown that reinforced geopolymer concrete is a desirable construction material that stems from its unique combination of strength, low creep, better resistance to acid and heat but long term durability properties of its composite materials - reinforcing steel bars, encasing matrix of cementitious and inert aggregate material are yet to be understood fully. The research paper aims to develop an understanding of potential passivation mechanism of embedded steel in geopolymer concrete, its durable performance and avenues of further research needs. Preliminary research study has shown that alkaline sodium silicate solution during the initial stages of geopolymer concrete mix synthesisation has the potential to passivate the embedded steel against corrosion processes and opens up further research avenues of optimising it	Durability	Research	Overview of science behind steel passivation processes in geopolymer concrete for corrosion protection Research based	M	
44	2011	CIA	Geopolymer Concrete	Recommended Practice Report	Concrete Institute of Australia	Z16	42 pp		Overview/General		Contributers Holcim, Cement Australia, Wagstaff Piling, RIX group. Biased towards industry	M/H	Y

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45	2011	D.V. Reddy, J-B Edouard, K. Sobhan, S.S. Rajpathak	DURABILITY OF REINFORCED FLY ASH-BASED GEOPOLYMER CONCRETE IN THE MARINE ENVIRONMENT	36th Conference on Our World in Concrete & Structures, Singapore, August 14-16, 2011			11 pp	The use of supplementary cementitious materials as partial replacements of the cement in concrete will play a significant role in the environmental control of greenhouse effects, and the turning down of the global thermostat. Currently, the most widely used supplementary cementitious material, all over the world, is Fly Ash, a waste product of the coal power plants. The development of geopolymer concrete (GPC), a one hundred percent replacement of Portland cement by fly ash, with a combination of sodium hydroxide and sodium silicate, offers a promising alternative to ordinary Portland cement concrete (OPC). This study evaluated the corrosionbased durability characteristics of low calcium fly ash-based geopolymer concrete subjected to the marine environment. Beams (6”x6”x21”) centrally reinforced with 1/2“ϕ rebar, made with 8 molar and 14 molar concentrations of NaOH and SiO2/Na2O solutions, were tested for accelerated corrosion exposure, with wet and dry cycling in artificial seawater, and induced current. The durability was monitored by indication of sudden rise in the current intensity due to specimen cracking. The test results indicated excellent resistance of the geopolymer concrete to chloride attack, with longer time to corrosion cracking, compared to OPC.	Durability	Performance	Experimental test program. Not long term	M	Y
46	2011	Davidovits, J.	Geopolymer Chemistry and Applications	Institut Géopolymère (www.geopolymer.org)	Institut Géopolymère	3rd Edn	33 pp		Overview/General		Very generic, background information	L	
47	2011	Habert, G., d'Espinose de Lacaillerie, J.B., Rousse, N.	An environmental evaluation of geopolymer based concrete production: reviewing current research trends	Journal of Cleaner Production		19(11)	1229-1238	In this study we carry out a detailed environmental evaluation of geopolymer concrete production using the Life Cycle Assessment methodology. The literature shows that the production of most standard types of geopolymer concrete has a slightly lower impact on global warming than standard Ordinary Portland Cement (OPC) concrete. Whilst our results confirm this they also show that the production of geopolymer concrete has a higher environmental impact regarding other impact categories than global warming. This is due to the heavy effects of the production of the sodium silicate solution. Geopolymer concrete made from fly ashes or granulated blast furnace slags based require less of the sodium silicate solution in order to be activated. They therefore have a lower environmental impact than geopolymer concrete made from pure metakaolin. However, when the production of fly ashes and granulated blast furnace slags is taken into account during the life cycle assessment (using either an economic or a mass allocation procedure), it appears that geopolymer concrete has a similar impact on global warming than standard concrete. This study highlights that future research and development in the field of geopolymer concrete technology should focus on two potential solutions. First of all the use of industrial waste that is not recyclable within other industries and secondly on the production of geopolymer concrete using a mix of blast furnace slag and activated clays. Furthermore geopolymer concrete production would gain from using waste material with a suitable Si/Al molar ratio in order to minimise the amount of sodium silicate solution used. Finally, by taking into account mix-design technology, which has already been developed for OPC concrete, the amount of binder required to produce a geopolymer concrete could be reduced.	Overview/General	Review	Environmental stance/impacts review A 'stand-back' approach/perspective Focus on production rather than performance (long-term or durability)	M	Y
48	2011	Olivia, M.	Durability Related Properties of Low Calcium Fly Ash Based Geopolymer Concrete	PhD Thesis	Curtin University		229 pp	Geopolymer material using by-products can lead to a significant reduction of the carbon footprint and have positive impact on the environment. Geopolymer is recognized as an alternative construction material for the Ordinary Portland Cement (OPC) concrete. The mechanical properties of geopolymer concrete are superior for normal exposure environments. In terms of durability in the seawater, a limited number of publications were available. The seawater environment contains chloride ions and microorganisms that are harmful for reinforced concrete structures. Hence, a study of the durability of fly ash geopolymer concrete is essential when this material is to be used in a real application. The present study aims to investigate the durability of fly ash geopolymer concrete mixture in a seawater environment such as seawater resistance and corrosion of steel reinforcement bars. The development of mixtures and their mechanical properties were also presented. The concrete mixtures were developed using the Taguchi optimization method. Three mixtures, labelled T4, T7, T10 and a control mix were investigated further. Mechanical properties such as compressive strength, tensile strength, flexural strength, Young's Modulus of Elasticity were determined for each mix. In addition the water absorption/AVPV and drying shrinkage were also measured. The seawater resistance study comprises chloride ion penetration, change in strength, change in mass, change in Young's Modulus of Elasticity, change in effective porosity and change in length. The corrosion performance of steel reinforcement bars in fly ash geopolymer concrete was determined by measuring the corrosion potential by half-cell potential, accelerated corrosion test by impressed voltage method and microbiologically influenced corrosion incorporating algae. The microstructure of the samples was also investigated using SEM and microscope. It can be summarized that the fly ash geopolymer concrete has an equivalent or higher strength than the OPC concrete. The seawater resistance revealed a high chloride ion penetration into the fly ash geopolymer concrete due to lack of a chloride binding ability and continuous hydration under aqueous medium. The geopolymer concrete had a higher strength and small expansion following exposure to wetting-drying cycles. There was a rapid depassivation of steel reinforcement bars in fly ash geopolymer concrete, although it has a smaller corrosion rate than the OPC concrete. This could delay the pressure in generating cracks in the concrete cover which is not favourable in the long term, due to a sudden loss of load carrying capacity. A novel study on the corrosion performance in algae medium demonstrated a risk of steel bar corrosion in fly ash geopolymer concrete due to the low alkalinity of this concrete. It can be concluded that the low calcium fly ash geopolymer	Durability		LONG!	M	Y
49	2011	Olivia, M., Nikraz, HR.	Durability of Fly Ash Geopolymer Concrete in a Seawater Environment	Proceedings of the Concrete 2011 Conference, Oct 12, Perth, WA	The Concrete Institute of Australia		10 pp	This paper presents the results of a study on the durability of fly ash geopolymer concrete in a seawater environment. In this research, three different geopolymer mixes and a control mix were examined to determine the effective porosity, chloride ion penetration, and corrosion of steel reinforcement bars under open circuit potential and accelerated corrosion tests. High chloride ingress was observed on the geopolymer paste. A depassivation of the passive film of the steel reinforcement bar in fly ash geopolymer was faster than for the OPC concrete. Small corrosion activities were conversely evident in the geopolymer concrete under the accelerated corrosion test at an applied voltage of 30 V. Decreased corrosion rates were observed for the geopolymer concrete. The results obtained from these tests indicate that the nature of the geopolymer paste certainly influences its durability in the seawater environment.				H	Y

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50	2010	FHWA	Advanced High-Performance Materials for Highway Applications: A Report on the State of Technology	FHWA	FHWA	REPORT NO. FHWA-HIF-10-002	69 pp		Overview/General		Brief overview and position on material by FHWA	L	
51	2010	Provis, J., van Deventer, JSJ.	What Controls the Durability of Geopolymer Binders and Concretes?	Sixth International Conference on Concrete under Severe Conditions: Environment and Loading	CRC Press/Balkema		1535-1542	Geopolymer materials, synthesized by alkaline activation of aluminosilicate precursors, have been proposed and investigated as a potential Greenhouse-friendly alternative to Portland cement in construction and other applications. However, there is not yet an extensive data set relating geopolymer performance and durability to service conditions. Numerous claims have been made predicting that geopolymers will show extremely high resistance to aggressive environments, including acid, fire, carbonation, alkali and others. However, the scientific analysis of geopolymer durability is only now beginning to catch up with these claims. Here, the authors present a discussion of the parameters which control geopolymer durability. Binder structure is critical to durability, and the relative distributions of pores, unreacted particles, fully-crosslinked and less-crosslinked binder regions, and impurity elements (in particular calcium) are all important. It is only by combining multiple analytical techniques, and the analysis of both binders and concretes, that a detailed understanding of geopolymer performance may be obtained	Durability	Overview/General	Commercial publication? Discussion on factors influencing durability in geopolymer concrete Potential for determining durabilty performance indicators	M/H	Y
52	2010	VicRoads	SECTION 703 - GENERAL CONCRETE PAVING	Specification	VicRoads	Series 700	9 pp	This section specifies the requirements for the supply of materials and construction of Portland cement-based and geopolymer binder-based concrete paving for edgings, footpaths and other surfacings and any other concrete work not specified elsewhere in the specification, together with the necessary excavation and backfilling. In the context of general concrete paving, portland cement concrete and geopolymer binder concrete are equivalent products. Requirements for structural concrete for bridgeworks and other major concrete components and structures are specified in Section 610.	Specification		Only specified application out of 700 Series - Incidental Construction Specification of mix requirements for geopolymer concrete Note: NOT specified for structural concrete (610)	H	Y
53	2009	Adam, AA.,; Molyneaux, TK., Patnaikuni, I., Law, DW	Chloride penetration and carbonation in blended OPC-GGBS, alkali activated slag, and fly ash based geopolymer concrete	Concrete Institute of Australia Conference, 24th, 2009, Sydney, New South Wales, Australia				Research has shown that alkali activated binders can achieve similar strengths to both ordinary Portland cement (OPC) and blended cements. This study investigated the influence of activator concentration and alkali modulus on chloride penetration and carbonation of alkali activated slag (AAS) and fly ash (FA) based geopolymer concrete. The same tests were also conducted on blended ordinary Portland cement and ground granulated blast-furnace slag (OPC-GGBS) concrete with 30, 50, and 70 per cent partial replacement of OPC by GGBS, and a control, with no replacement material. Results indicate that minimal strength development was observed for both the AAS and FA geopolymer concrete for an alkali modulus above 1.0. The alkali modulus has a major effect on charge passed for AAS concrete, however no significant effect on carbonation was observed for the AAS concrete. The charge passed for the blended OPC-GGBS concrete is reduced but the carbonation rate is increased, as the replacement level is increased. The rapid chloride permeability test (RCPT) was halted on the geopolymer specimens due to the high currents produced while the phenolphthalein gave no clear indication between carbonated and non-carbonated area in geopolymer specimens. The data from this work would indicate that the RCPT and phenolphthalein indicator test should not be applied to geopolymer concrete	Durability	Research	Results of various durability tests	M	Y
54	2005	Bakharev, T.	Resistance of Geopolymer Materials to Acid Attack	Cement and Concrete Research,		35 (4)	658-670	Concretes made with Portland cement and alkali-activated slag are base in nature and deteriorate in an acid environment. Geopolymer materials (synthetic minerals) prepared with class F fly ash contain very low calcium (3 to 4%) and thus may have high durability in the acid environment. This article reports on a study of the durability of geopolymer materials produced using FA and alkaline activators when exposed to a 5% solution of acetic and sulfuric acids. The author focused on the evolution of weight, compressive strength, products of degradation, and microstructural changes. The results demonstrate that the performance of geopolymer materials when exposed to acid solutions was superior to ordinary Portland cement (OPC) paste. However, the author cautions that significant degradation of strength was observed in some geopolymer materials prepared with sodium silicate and with a mixture of sodium hydroxide and potassium hydroxide as activators. Curing temperature was also important; elevated curing temperatures resulted in a better performance. The author concludes that a more-crystalline geopolymer materials prepared with sodium hydroxide was more stable than amorphous geopolymers prepared with the sodium silicate activator. The chemical instability would also depend on the presence of the active sites on the aluminosilicate gel surface, which appeared to increase in the presence of potassium ions	Durability	Performance	Could be useful relating to acid sulphate soils	M	
55	2005	Bakharev, T.	Durability of Geopolymer Materials in Sodium and Magnesium Sulfate Solutions.	Cement and Concrete Research,		35 (6)	1233-1246	Geopolymers are synthetic minerals that are similar to those that form in the Earth’s crust. They possess high strength, thermal stability, high surface smoothness and precision, and high surface hardness. This article reports on a study of the durability of geopolymer materials manufactured using class F fly ash (FA) and alkaline activators in sodium and magnesium sulfate solutions. Three tests were used: immersions for a period of 5 months into 5% solutions of sodium sulfate and magnesium sulfate, and a solution of 5% sodium sulfate+5% magnesium sulfate. The evolution of weight, compressive strength, products of degradation and microstructural changes were studied. In the sodium sulfate solution, significant fluctuations of strength occurred, with strength reduction 18% in the 8FASS material prepared with sodium silicate and 65% in the 8FAK material prepared with a mixture of sodium hydroxide and potassium hydroxide (K) as activators. A 4% strength increase was measured in the 8FA specimens activated by sodium hydroxide. In the magnesium sulfate solution, 12% and 35% strength increase was measured in the 8FA and 8FAK specimens, respectively; and 24% strength decline was measured in the 8FASS samples. Diffusion of alkali ions into the solution caused significant stresses and formation of deep vertical cracks in the specimens prepared using a mixture of sodium and potassium hydroxides. The author concludes that the geopolymer specimens had very different durabilities when exposed to sulfate solutions. Material prepared using sodium hydroxide had the best performance, which is attributed to its stable cross-linked aluminosilicate polymer structure	Durability	Research	Research; Sulphate applications?	L/M	

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Literature Search

	Yr	Authors	Title	Publication	Publisher	Volume	Pages	Abstract	Category 1	Category 2	Comments	Priority (H = High, M = Medium, L = Low)	TMR selection
56	2005	Hardjito, D.	Studies of fly ash-based geopolymer concrete	PhD Thesis	Curtin University		103 pp	This thesis reports the details of development of the process of making fly ash-based geopolymer concrete. Due to the lack of knowledge and know-how of making of fly ashbased geopolymer concrete in the published literature, this study adopted a rigorous trial and error process to develop the technology of making, and to identify the salient parameters affecting the properties of fresh and hardened concrete. As far as possible, the technology that is currently in use to manufacture and testing of ordinary Portland cement concrete were used. Fly ash was chosen as the basic material to be activated by the geopolimerization process to be the concrete binder, to totally replace the use of Portland cement. The binder is the only difference to the ordinary Portland cement concrete. To activate the Silicon and Aluminium content in fly ash, a combination of sodium hydroxide solution and sodium silicate solution was used.	Overview/General	Performance	More materials based; "early days" thesis investigating product properties of fresh geopolymer concrete	**L/M**	
57	2005	Wallah, S E; Hardjito, D; Sumajouw, D M J; Rangan, B V.	Performance of Geopolymer Concrete Under Sulfate Exposure	ACI Journal			27-36	The performance of fly ash based geopolymer concrete under sulfate exposure was studied by soaking the specimens in sodium sulfate and sulfuric acid solutions. By observing the change in compressive strength, mass, and length of the specimens, the results showed that in form of sodium sulfate, sulfate attack did not have significant effects on geopolymer concrete, but the sulfate attack in the form of sulfuric acid damaged the surface of the specimens and reduced the compressive strength of geopolymer concrete. Tests are continuing for at least one year in order to substantiate the trends observed so far	Durability	Case studies	Could be useful relating to acid sulphate soils	**M**	

APPENDIX B SOURCED LITERATURE

Includes soft-copy of literature reviewed.