# PATHWAYS FOR OVERCOMING BARRIERS TO IMPLEMENTATION OF LOW $CO_2$ CONCRETE

Research Project: RP1004-I

An Australian Government Initiative

| | |
|---|---|
| Authors | |
| Title | PATHWAYS FOR OVERCOMING BARRIERS TO IMPLEMENTATION OF LOW $CO_2$ CONCRETE |
| ISBN | |
| Format | |
| Keywords | |
| Editor | |
| Publisher | CRC for Low Carbon Living |
| Series | |
| ISSN | |
| Preferred citation | |

# CRC PARTICIPANTS INVOLVED

## *Research Team*

Prof. Marita L. Berndt, Research Associate, Swinburne University of Technology, School of Civil Engineering, Centre for Sustainable Infrastructure

Prof. Jay Sanjayan, Project Leader, Swinburne University of Technology, School of Civil Engineering, Centre for Sustainable Infrastructure

Prof. Stephen Foster, Project Leader, University of New South Wales, School of Civil and Environmental Engineering, Centre for Infrastructure Engineering and Safety

Assoc. Prof. Arnaud Castel, University of New South Wales, School of Civil and Environmental Engineering, Centre for Infrastructure Engineering and Safety

## *Partner Investigators*

Australasian (Iron and Steel) Slag Association

- Craig Heidrich
- Marc Smith

Ash Development Association of Australia

- Craig Heidrich
- Roy Butcher

## *Project Advisor*

Prof. Kwesi Sagoe-Crentsil, Swinburne University of Technology, School of Civil Engineering, Centre for Sustainable Infrastructure and CSIRO Manufacturing Science and Engineering

## Acknowledgements

The financial support of the Cooperative Research Centre for Low Carbon Living is appreciated. Thanks are also due to Olivia Yeatman from the HBM Group Pty Ltd for assistance with the industry survey. Support and suggestions from the Australasian Iron and Steel Slag Association and Ash Development Association of Australia have been helpful. Finally, the participants in the industry survey are thanked for their input.

# CONTENTS

# LIST OF TABLES

## LIST OF FIGURES

# EXECUTIVE SUMMARY


Construction of the built environment involves use of natural resources and creation of greenhouse gas emissions. In particular, concrete based on Portland cement is viewed as a major contributor to emissions and recent research has been directed at improving the sustainability of concrete. The use of supplementary cementitious materials such as fly ash and blast furnace slag to improve properties and reduce the $CO_2$ impact of concrete is now well established. Further reductions in emissions are feasible with the use of alternative binders to Portland cement. One such binder is based on aluminosilicates and commonly termed “geopolymer”. However, widespread uptake of alternative low $CO_2$ concrete materials has yet to occur.

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 $CO_2$ 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.

# INTRODUCTION

Construction of the built environment involves use of natural resources and creation of greenhouse gas emissions. As awareness of resource depletion and climate change grow, so too does the need for the construction industry to adopt more sustainable materials and technologies. Reduction in emissions can be achieved through appropriate material selection. However, widespread uptake of alternative materials has yet to occur. The Cooperative Research Centre (CRC) for Low Carbon Living was launched in 2012 and aims to provide government and industry with social, technological and policy tools to overcome identified market barriers preventing adoption of alternative products and services, while maintaining industry competitiveness and improving quality of life. One component of the CRC research is to identify pathways for commercialisation of low CO2 emission concrete and contribute to reduction of emissions in the built environment. The objectives to this report are 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 $CO_2$ concrete, specifically geopolymer concrete, can be surmounted.

In this report "geopolymer concrete" refers to concrete with an aluminosilicate based binder. This binder is produced by reacting aluminosilicates with an alkali activator such as sodium hydroxide or sodium silicate. Sources of aluminosilicates include fly ash, blast furnace slag and metakaolin. Alkali-activated slag and alkali-activated fly ash are synonymous terms to geopolymer in this context.

# BACKGROUND ON LOW CO2 CONCRETE

## Emissions Associated with Conventional Cement and Concrete

Production of Portland cement involves considerable generation of $CO_2$. In fact, cement production accounts for approximately 5-7% of anthropogenic $CO_2$ emissions worldwide (Chen et al, 2010). Various authors in different countries have calculated the emissions due to cement and concrete production.

Detailed analysis of energy input and $CO_2$ emissions associated with the manufacture of cement in the US is given by Marceau et al (2006). This analysis included transportation of raw materials to cement plants. The average total energy input was calculated to be 4.8 GJ/tonne of cement. The highest energy input was for wet cement processing with an energy input of 6.4 GJ/tonne of cement. The average total $CO_2$ emissions were determined to be 0.927 tonne/tonne of cement. The wet process was calculated to have 1.1 tonne $CO_2$-e/tonne of cement. By comparison, Masanet et al. (2005) estimated the $CO_2$ emissions for cement manufacture in California to be 0.932 tonne $CO_2$-e/tonne of cement. The Centre for Sustainability (2006) developed a $CO_2$ estimator tool for roads in which the energy input value for cement was 4.78 MJ/tonne and the emissions factor was 0.801 tonne $CO_2$-e/tonne of cement. These figures were based on consideration of UK and European data.

Damtoft et al (2008) reported emissions and energy associated with both fuels and materials in European cement production. Figures given for fuel-derived emissions and energy ranged from 0.31 kg $CO_2$-e/kg clinker and 3.1 GJ/tonne clinker for a modern, efficient rotary kiln to 0.6 kg $CO_2$-e/kg clinker and 6 GJ/tonne clinker for an inefficient wet kiln. The materials-derived $CO_2$ was reported as 0.53 kg/kg clinker.

In Australia Flower and Sanjayan (2007) analysed data specifically for Melbourne and found a $CO_2$ emissions factor of 0.82 tonne $CO_2$-e/tonne of cement. This figure includes emissions associated with transportation. The calculated emissions for 32 MPa concrete with 100% Portland cement was 0.322 tonne $CO_2$-e/m$^3$. Emissions are higher for higher strength grade concretes. Using the same factors as Flower and Sanjayan (2007), a 50 MPa concrete with 450 kg/m$^3$ Portland cement would have estimated emissions of 0.720 tonne $CO_2$-e/m$^3$ and a 40 MPa concrete with 390 kg/m$^3$ Portland cement would have estimated emissions of 0.691 tonne $CO_2$-e/m$^3$.

As can be seen from the above studies and given the volume of concrete used, $CO_2$ emissions from Portland cement production have a major impact on emissions associated with the built environment.

## Reducing the CO2 Impact of Portland Cement and Concrete

Various strategies can be used to reduce the energy requirements and $CO_2$ impact of Portland cement (Gartner, 2004; Damtoft et al, 2008, Hasanbeigi et al, 2012; Cement Sustainability Initiative, 2009; Worrell et al, 2008). For example, the efficiency of the cement making process can be improved. In particular, reducing the amount of clinker burnt through use of blast furnace slag can have significant impact. This is quantified by Josa et al (2004) for European countries. Damtoft et al (2008) discuss the use of alternative fuels in cement production to reduce $CO_2$ emissions in addition to waste materials as replacement for limestone. Of the latter, only blast furnace slag has significant impact.

It is now common practice to use significant amounts of pozzolanic or supplementary cementitious materials such as fly ash, blast furnace slag, silica fume, rice husk ash and metakaolin as partial replacements for Portland cement. These materials also offer potential reductions in emissions from concrete production due to reduced cement contents, as well as other well-established benefits such as durability.

Alternatives to Portland cement are also being explored. These materials include alkali-activated slag and fly ash to form “geopolymers”. The emissions associated with production of geopolymer concrete have been studied by several authors including Duxson et al (2007), Stengel et al (2009), Weil et al (2009), Witherspoon et al (2009), McLellan et al (2011), Turner and Collins (2012) and Yang et al (2013). Calculated values of emissions depended on raw materials and proportions and whether factors such as transportation were taken into account. Stengel et al (2009) calculated the greenhouse gas emissions of different 45 MPa geopolymer concrete mixes as 0.112 to 0.151 tonne $CO_2$-e/$m^3$ whereas McLellan reported emissions of 0.271 to 0.425 tonne $CO_2$-e/$m^3$ for 40 MPa mixes including transportation. Turner and Collins (2012) calculated emissions of 320 kg $CO_2$-e/$m^3$ for 40 MPa geopolymer concrete compared with 354 kg $CO_2$-e/$m^3$ for 40 MPa concrete with 100% Portland cement. Steam curing and alkali activators were significant contributors to the emissions of geopolymer concrete (Turner and Collins, 2012). It is clear that the calculated emissions data depends on exactly how the material system is analysed, the actual raw materials, transportation and whether curing is considered. Conflicting emission data is regarded as detrimental to adoption of geopolymer concrete as it may confuse end-users.

Cements based on calcium sulphate have also been discussed as potential binders with low $CO_2$ emissions (Gartner, 2004). Magnesium oxycarbonate, calcium carbonate and calcium sulphoaluminate cements as low $CO_2$ alternatives are described by Gartner and Macphee (2011).

Strategies for reduction of emissions from concrete production in addition to those specific to cement include use of recycled concrete aggregate and optimisation of mix proportions and cement content for the given application. It is typical in Australia to use cement contents far higher than necessary in order to ensure that minimum strength requirements are achieved. Thus, concrete with a specified 28 day compressive strength of 50 MPa may actually have a strength in excess of 70 MPa owing to the high cement content.

Current requirements for concrete and opportunities for the use of geopolymer concrete as a low $CO_2$ construction material are covered in the following sections.

## DEFINITIONS OF CONCRETE IN STANDARDS

In order to better understand how alternative concretes may be integrated into existing standards and practices, it is useful to examine the common definitions of concrete. The Oxford Dictionary defines concrete by as "a building material made from a mixture of broken stone or gravel, sand, cement, and water, which can be spread or poured into moulds and forms a stone-like mass on hardening". Traditionally, the term "concrete" is used in the engineering field to describe material using Portland cement as the binder. Neville (1996) describes cement as "a material with adhesive and cohesive properties which make it capable of bonding mineral fragments into a compact whole". Portland cement is a hydraulic cement chemically based on calcium silicates, tricalcium aluminate and tetracalcium aluminoferrite. Hydration of Portland cement results in formation of calcium silicate hydrates, tricalcium aluminate hydrate and calcium hydroxide.

Various types of Portland cement exist (e.g., ordinary, high early strength, sulphate resisting etc). Supplementary cementitious materials such as fly ash, ground granulated blast furnace slag and silica fume are commonly used in concrete to improve properties. Examples of other types of cements besides Portland include:

- High alumina (calcium aluminate or aluminous)
- Calcium sulphoaluminate (expansive hydraulic)
- Magnesium phosphate
- Calcium phosphate
- Sulphur
- Sorel (magnesium oxychloride)
- Magnesium oxysulphate

The definitions of concrete in commonly used standards and guides are summarised in Table 1.

Salient points from Table 1 include the following:

- AS 3600, AS 1379 and AS 5100 and BS EN 206 do not specifically nominate Portland cement. However, inclusion of water implies that the cement is hydraulic.
- ASTM C 125 refers to a binding medium which could be interpreted including other materials besides than Portland cement.
- ASTM C 125 specifically defines hydraulic cement concrete.
- ACI 116R has a similar definition of concrete to ASTM C 125. The term "Portland cement" is used rather than "hydraulic cement". However, the new ACI CT-13 Standard on Concrete Terminology produced in January 2013 uses "hydraulic cement". Hence, there has been a change in definition.
- ACI 116R and ACI CT-13 have a specific definition for polymer concrete which uses a polymer resin as the binder rather than hydraulic cement.

It is apparent from the above review that the binding phase in standard definitions of concrete is not exclusively Portland cement. This potentially opens opportunities for alternative cements and binders to be considered in production of concrete and included in existing standards. However, in the construction industry it is tacitly assumed that "concrete" refers to material with Portland cement as the binder unless stated otherwise. Consequently, the lack of specific nomination of Portland cement may not necessarily represent a loophole through which alternative binders can be used.

Table 1: Definition of Concrete in Standards

| Organisation/Standard/Document | Definition |
| --- | --- |
| AS 3600 – 2009 "Concrete Structures" | Mixture of cement, aggregates and water, with or without the addition of chemical admixtures. |
| AS 1379 – 1997 "Specification and Supply of Concrete" | A mixture of cement, aggregates, and water with or without the addition of chemical admixtures or other materials and defined as follows:<br>(a) *Plastic concrete*—concrete in the state between completion of mixing and initial set as defined in AS 1012.18.<br>(b) *Hardened concrete*—concrete after initial set, as represented by test specimens which have been subjected to a specified process and duration of curing.<br>(c) *Normal-class concrete*—concrete which is specified primarily by a standard compressive strength grade and otherwise in accordance with Clause 1.6.3.<br>(d) *Special-class concrete*—concrete which is specified to have certain properties or characteristics different from, or additional to, those of normal-class concrete and otherwise in accordance with Clause 1.6.4. |
| AS 5100.5 – 2004 "Bridge Design Part 5: Concrete" | A mixture of cement, aggregates, and water, with or without additional chemical admixtures. AS 5100.5 also allows for the use of alternative materials as per Clause 1.5.1 "Provided that the requirements of Section 2 are met, this standard shall not be interpreted so as to prevent the use of materials or methods of design, or construction not specifically referred to herein. Note: Where intended use is subject to the control of an authority, approval for the use of alternative materials or methods will need to be obtained from the authority". |
| AS 3735 - 2001 "Concrete Structures for Retaining Liquids" | As for AS 3600 |
| CCA&A/Standards Australia HB 64 - 2002 "Guide to Concrete Construction" | Concrete is a mixture of cement (Portland or blended), water and coarse aggregates (sand and crushed rock or natural gravel), which is plastic when first mixed, but which then sets and hardens into a solid mass. |
| ASTM C 125 – 07 "Standard Terminology Relating to Concrete and Concrete Aggregates" | A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate; in hydraulic-cement concrete the binder is formed from a mixture of hydraulic-cement and water. |
| ACI 116R-00 "Cement and Concrete Terminology" (Reapproved 2005, discharged 2007) | Concrete: A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate; in Portland-cement concrete, the binder is a mixture of Portland cement and water, with or without admixtures. |
| ACI CT-13 "ACI Concrete Terminology" 2013 | Concrete: mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials. |
| ACI 116R-00 "Cement and Concrete Terminology" (Reapproved 2005, discharged 2007) | Polymer Concrete: Concrete in which an organic polymer serves as the binder; also known as resin concrete; sometimes erroneously employed to designate hydraulic cement mortars or concretes in which part or all of the mixing water is replaced by an aqueous dispersion of a thermoplastic copolymer. |
| ACI CT-13 "ACI Concrete Terminology" 2013 | Polymer Concrete: Concrete in which an organic polymer serves as the binder. |
| BS EN 206-1:2000 " Concrete - Part 1: Specification, Performance, Production and Conformance" | Material formed by mixing cement, coarse and fine aggregate and water, with or without the incorporation of admixtures or additions, which develops its properties by hydration of the cement. |

## DEFINITIONS OF CONCRETE AND CEMENTITIOUS MATERIALS IN AUSTRALIAN SPECIFICATIONS

In addition to the standards reviewed in the above section, construction projects in Australia may follow state-specific requirements. This is particularly the case for transportation infrastructure. Transportation authority specifications are also often applied to other projects involving concrete. Hence, definitions of concrete and cementitious materials in state specifications have been examined. The definitions are compared in Table 2.

Table 2: Definitions of Concrete and Cementitious Materials in Australian State Specifications

| Organisation/ Document | Definition |
|---|---|
| VicRoads Standard Specification Section 610: Structural Concrete (2012) | Concrete using general purpose Portland cement Type GP or blended cement Type GB shall comply with the requirements of AS 3972 'Portland and Blended Cements'. In addition, blended cement Type GB shall consist of a specified minimum quantity of Portland cement in combination with any one or two of Ground Granulated Blast Furnace Slag (Slag), Fly Ash or Amorphous Silica and as specified in this section. All concrete shall be special class performance concrete in accordance with Appendix B of AS 1379 'The Specification and Supply of Concrete'.<br>**Blended Cement:** General purpose blended cement Type GB complying with the requirements of AS 3972 and as specified in this section.<br>**Cement:** Material complying with the requirements of AS 3972 and as specified in this section.<br>**Cementitious Material:** Portland cement or a mixture of Portland cement with one or more supplementary cementitious materials or in combination with other supplementary material as approved by the Superintendent. |
| VicRoads Section 703: General Concrete Paving (2010) | 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.<br>**Alkaline Component:** Combinations of alkali and alkali earth containing salts, minerals and glasses.<br>**Cement:** Material complying with the requirements of AS 3972 and as specified.<br>**Cementitious Material:** Portland cement or a mixture of Portland cement with one or more of Fly Ash, Ground Granulated Blast Furnace Slag (GGBF Slag), or Amorphous Silica complying with the requirements of AS 3582.1, AS 3582.2 and AS 3582.3 respectively.<br>**Geopolymer Binder:** Binder containing greater than 80% Fly Ash, Ground Granulated Blast Furnace Slag (GGBF Slag) or Amorphous Silica complying with the requirements of AS 3582.1, AS 3582.2 and AS 3582.3 respectively, metakaolin and up to 20% alkaline components.<br>**Geopolymer Concrete:** Concrete which comprises geopolymer binder, aggregates, water and admixtures.<br>**Portland Cement:** General purpose Portland cement Type GP complying with the requirements of AS 3972. |
| VicRoads Section 701: Underground Stormwater Drains (2013) | This section covers the requirements for the supply, delivery, transport, and installation of underground stormwater drains, referred to as culverts, together with the construction of inlet and outlet structures (endwalls, catchpits, basins, etc.), erection of marker posts, and the removal and/or relaying of existing culverts, as shown on the drawings or as specified.<br>**Precast Reinforced Concrete Pipes**: pipes manufactured from Portland cement-based concrete or geopolymer binder-based concrete as specified in Section 703. In the context of the manufacture of reinforced concrete pipes, Portland cement concrete and geopolymer binder concrete are equivalent products.<br>Geopolymer binder-based precast reinforced concrete pipes shall comply with the requirements of AS 4058 and this section, except that the concrete used shall comply with the requirements of Section 703 for geopolymer concrete with compressive strengths appropriate to the nominated load class performance requirements. |

| Organisation/ Document | Definition |
|---|---|
| VicRoads Section 705: Drainage Pits (2013) | This section specifies the requirements for the supply of materials and construction of drainage pits including the associated excavation, backfilling, culvert (Section 701) connections and supply and fitting of covers and associated components.<br>The supply of concrete and construction of items covered by this section shall comply with the requirements of Section 610.<br>Geopolymer binder-based concrete as defined in Section 703 may be used for the construction of drainage pits provided the supply of geopolymer concrete and construction comply with the requirements of Section 610 and satisfy the concrete grade requirements of Table 705.041. |
| South Australian Department of Planning, Transport and Infrastructure, DPTI Master Specification, Division 3: Concrete, Part 320: Supply of Concrete (2011) | Concrete and its constituent materials shall be supplied and tested in accordance with the following:<br>• AS 1012 Methods of testing concrete<br>• AS 1141 Methods of sampling and testing aggregates<br>• AS 1379 Specification and supply of concrete<br>• AS 1478 Chemical admixtures for concrete<br>• AS 2758.1 Aggregates and rock for engineering purposes - Concrete aggregates<br>• AS 3582 Supplementary cementations materials for use with portland and blended cement<br>• AS 3972 Portland and blended cements<br>Unless specified otherwise, the definitions in AS 1379 shall apply to this Part. |
| NSW Roads and Maritime Services (RMS) QA Specification B80: Concrete Work for Bridges (2012) | Materials for concrete, cement mortar and grout must conform to Section 2 of AS 1379 and Clause 2.<br>Cement used in the Works must be Shrinkage Limited Type SL or General Purpose Blended cement Type GB conforming to this Specification and RMS 3211.<br>Supplementary cementitious materials (SCMs) and proportions must conform to Specification RMS 3211.<br>Use only cement and SCMs that have been pre-registered under the Australian Technical Infrastructure Committee (ATIC) Scheme.<br>**Cement:** Material conforming to Specification RMS 3211. It comprises General Purpose cements, Blended cements and supplementary cementitious materials (SCMs).<br>**Concrete:** A thoroughly mixed combination of cement, aggregates and water, with or without the addition of chemical admixtures or other materials, all of which separately and when combined conform to this Specification. |
| Queensland Department of Transport and Main Roads (DTMR) Main Roads Technical Standard MRTS70: Concrete (2010) | All concrete shall be manufactured and supplied in accordance with the requirements of AS 1379 and the additional requirements of this Standard.<br>Unless otherwise stated, all concrete shall be composed of cementitious material, fine aggregate, coarse aggregate, additives if approved, and water, proportioned and mixed as detailed in this Standard. All such materials shall conform with the requirements of this Standard.<br>All cement used shall comply with AS 3972.<br>The type of cement used shall be Type GP or GB unless otherwise designated in the Contract or approved by the Administrator.<br>All mixes shall contain a minimum mass of Portland cement equal to 55% of the total mass of cementitious material. Type GP cement shall have a maximum total alkali content (measured as $Na_2O$ equivalent) of 0.6%. |
| Main Roads Western Australia (MRWA) Specification 820: Concrete for Structures (2012) | Concrete shall comply with AS 1379, except as varied by this Specification.<br>Unless specified otherwise, all cement used in the Works shall comply with the requirements of Type GP cement as specified in AS 3972 and Australian Technical Infrastructure Committee (ATIC) Specification SP43.<br>Blended cement shall be a combination of Type GP cement and ground granulated iron blast furnace slag complying with AS 3582.2 and ATIC Specification SP43. The densified silica fume to be added to the blended cement shall be finely divided and comply with AS/NZS 3582.3 and ATIC Specification SP43. |

| Organisation/ Document | Definition |
|---|---|
| Tasmanian Department of Infrastructure, Energy and Resources, Bridgeworks Specification, B10: Supply of Concrete (2006) | All concrete shall be Special Class Performance concrete in accordance with Appendix C Clause C4.2 of AS 1379.<br><br>Cement shall be general purpose Portland cement Type GP or blended cement Type GB, complying with the requirements of AS 3972 "Portland and Blended Cements".<br><br>Supplementary Cementitious Binder shall be Silica Fume complying with the requirements of AS 3582.3, or Fly Ash complying with the requirements of AS 3582.1, or Ground Granulated Blast Furnace Slag (GGBF Slag) complying with the requirements of AS 3582.2<br><br>**Cementitious Binder:** Portland cement or a mixture of Portland cement with one or more supplementary cementitious binders.<br><br>**Supplementary Cementitious Binder:** Silica Fume, Fly Ash or Ground Granulated Blast Furnace Slag (GGBF Slag). |
| Northern Territory Department of Infrastructure, Technical Specifications, Bridgeworks, B06: Concrete (2012) | Comply with the material, construction, and testing requirements of AS 3600: Concrete Structures and substitute it where other Standards refer to AS 1480.<br><br>Comply with any additional requirements of the Austroads Bridge Design Code if public traffic will use or could impact on the works.<br><br>Use Class GP cement unless otherwise specified or approved.<br><br>All mixes shall contain a minimum mass of Portland cement equal to 55% of the total mass of cementitious material. GP cement shall have a maximum total alkali content (measured as $Na_2O$ equivalent) of 0.6%. |
| ACT Trunk Road Infrastructure Technical Specification No. 10: Bridges and Related Structures (2012) | The Australian Capital Territory has adopted the NSW Roads and Maritime Services (RMS - formerly RTA NSW) specifications for concrete works (RMS QA Specification B80 – Concrete Work for Bridges). These works must be carried out according to the referenced RMS specifications with the exception of items detailed below:<br><br>• Admixtures are supported for use include specifically fly ash<br>• Fly ash should partially substitute cement content.<br>• Aggregates used in bridge construction shall be non-reactive.<br>• Local quarries should be tested or in an approved quarries list.<br>• List of Roads ACT approved concrete mixes, if available.<br>• Register of Roads ACT approved concrete mixes. |
| Australian Technical Infrastructure Committee (ATIC) Specification Section SP43: Cementitious Materials for Concrete (2009) | This Section sets out the technical requirements for the manufacture and supply of cementitious materials (ie: cement or hydraulic cement), consisting of Portland cement, or of mixtures of Portland cement and one or more of fly ash, ground granulated iron blast-furnace slag (slag) and amorphous silica, for use in special class concrete, grouts, mortars for all types of durable infrastructure, including risk limitation from both salinity and alkali-silica reactive (ASR) aggregates. This Section may also be used for normal class concretes.<br><br>MANUFACTURE: Portland and blended cements to AS 3972, and where in combination with one or more supplementary cementitious materials (SCM), that is fly ash, slag and amorphous silica (includes silica fume), to AS 3582 Parts 1 and 2, and AS/NZS 3582 Part 3, respectively (also referred to herein as the “AS 3582 Series”). |

Of the above state specifications only VicRoads Section 703: General Concrete Paving, Section 701: Underground Stormwater Drains and Section 705: Drainage Pits specifically refer to geopolymer concrete and it is understood that changes are currently being made to other VicRoads specifications to permit the use of geopolymers. It is understood that changes are currently being made to other VicRoads specifications to permit the use of geopolymers. Further details of the experiences of VicRoads with geopolymer concrete are described by Andrews-Phaedonos (2012).

Other specifications generally refer to AS 1379 and AS 3972 and require or assume Portland cement. Therefore, if AS 1379 is modified to include geopolymer concrete this will assist in adoption at a state level. Modification of existing state specifications as has been performed by VicRoads would also create a pathway for use and greater adoption of geopolymer concrete.

## CONCRETE MIX DESIGN AND PROPERTY REQUIREMENTS IN AUSTRALIAN SPECIFICATIONS

Specification of concrete for a construction project typically calls for a mix design and/or particular properties. Thus, engineers are familiar with specifying requirements such as minimum cementitious content, maximum water/cementitious material (w/cm) ratio and minimum 28 day compressive strength. Table 3 reviews the mix design and property requirements in commonly used state concrete specifications.

Table 3: Concrete Mix Design and Property Requirements in State Specifications

<table>
<tr><th>Organisation / Document</th><th>Requirements</th></tr>
<tr><td>VicRoads Standard Specification Section 610: Structural Concrete (2012)</td><td>
Mix Design:<br>
The minimum mass of total cementitious material per cubic metre of finished concrete and the corresponding maximum water/cementitious material ratio shall be as shown in Table 610.071.<br>
Table 610.071
<table>
<tr><th>Concrete Grade</th><th>Cementitious Material Content (min (kg/m$^3$)</th><th>Water/Cementitious Material Ratio (max)</th></tr>
<tr><td>VR330/32</td><td>330</td><td>0.50</td></tr>
<tr><td>VR400/40</td><td>400</td><td>0.45</td></tr>
<tr><td>VR450/50</td><td>450</td><td>0.40</td></tr>
<tr><td>VR470/55</td><td>470</td><td>0.36</td></tr>
</table>
The cementitious material content of concrete to be placed under water shall not be less than 400 kg/m$^3$, with a maximum water/cementitious material ratio of 0.45.<br>
The water/cementitious material ratio of the proposed concrete mix design shall not be less than 0.30 for concrete cast in situ works and 0.28 for concrete utilised in precast works.<br>
Minimum Compressive Strength:<br>
The minimum compressive strength requirements for each concrete grade are shown in Table 610.051.<br>
Table 610.051
<table>
<tr><th rowspan="2">Concrete Grade</th><th colspan="3">Minimum Compressive Strength (MPa)</th></tr>
<tr><th>3 days</th><th>7 days</th><th>28 days</th></tr>
<tr><td>VR330/32</td><td>14</td><td>20</td><td>32</td></tr>
<tr><td>VR400/40</td><td>17</td><td>26</td><td>40</td></tr>
<tr><td>VR450/50</td><td>23</td><td>35</td><td>50</td></tr>
<tr><td>VR470/55</td><td>25</td><td>40</td><td>55</td></tr>
</table>
Maximum Volume of Permeable Voids (VPV) Values at 28 Days:<br>
The maximum VPV values at 28 days for each concrete grade for both test cylinders and test cores including sprayed concrete are shown in Table 610.061.
</td></tr>
</table>

| | |
|---|---|
| | ***Table 610.061*** |

| Concrete Grade | Maximum VPV Values at 28 Days (%) | | |
|---|---|---|---|
| | Test Cylinders (compacted by vibration) | Test Cylinders (compacted by rodding) | Test Cores |
| VR330/32 | 14 | 15 | 17 |
| VR400/40 | 13 | 14 | 16 |
| VR450/50 | 12 | 13 | 15 |
| VR470/55 | 11 | 12 | 14 |

**Cementitious Material Content and Water/Cementitious Material Ratio:**

The minimum mass of total cementitious material per cubic metre of finished concrete and the corresponding maximum water/cementitious material ratio shall be as shown in Table 610.071.

***Table 610.071***

| Concrete Grade | Cementitious Material Content (min) ($kg/m^3$) | Water/Cementitious Material Ratio (max) |
|---|---|---|
| VR330/32 | 330 | 0.50 |
| VR400/40 | 400 | 0.45 |
| VR450/50 | 450 | 0.40 |
| VR470/55 | 470 | 0.36 |

**Maximum Acceptable Crack Widths:**

The concrete shall have no cracks at any stage after construction measured at the concrete surface of width greater than the relevant value given in Table 610.241 for the corresponding exposure classification. Where such cracks exist, they shall be identified as a non-conformance.

Notwithstanding the requirements of this clause the acceptable crack width at the concrete surface of pre-cast pre-stressed concrete elements shall not exceed 0.1 mm.

***Table 610.241***

| Exposure Classification | Maximum Acceptable Crack Widths (mm) |
|---|---|
| A | 0.20 |
| B1 | 0.20 |
| B2 | 0.15 |
| C, U | 0.10 |

**Shrinkage:**

The shrinkage strain of each sample, as determined from the average value of the 3 specimens, shall not exceed 750 x $10^{-6}$ after 56 days of drying. Drying shrinkage requirements for special applications shall be as specified on the drawings and in this specification.

| | |
|---|---|
| VicRoads Section 703: General Concrete Paving (2010) | **Minimum Compressive Strength:** The minimum compressive strength requirements for each strength grade shall be as shown in Table 703.101. |

*Table 703.091*

| Portland Cement Concrete Strength Grade | Geopolymer Binder Concrete Strength Grade | Minimum Compressive Strength at 28 days (MPa) |
|---|---|---|
| N20 | 20 | 20 |
| N25 | 25 | 25 |
| N32 | 32 | 32 |

**Slump:**

The consistency of the concrete shall be determined by a slump test of each concrete strength sample in accordance with AS 1012.3 and Clause 5.2 of AS 1379. The concrete represented by the samples shall be deemed to comply with the nominated concrete slump if the measured slump is within the limits given in Table 6 of Clause 5.2 of AS 1379.

South Australian Department of Planning, Transport and Infrastructure, DPTI Master Specification, Division 3: Concrete, Part 320: Supply of Concrete (2011)

**Mix Design:**

Unless specified otherwise, all concrete supplied in accordance with this Contract shall be Special-Class Concrete. The minimum cementitious content and the maximum water-cement ratio for each particular grade of concrete shall be accordance with Table 4.1.

***TABLE 4.1 CEMENT AND WATER CONTENT***

| Class of Concrete | Minimum Cementitious Content (kg/m$^3$) | Maximum Water/Cement Ratio |
|---|---|---|
| 20 | 240 | 0.70 |
| 25 | 280 | 0.65 |
| 32 | 320 | 0.58 |
| 40 | 380 | 0.50 |
| 50 | 460 | 0.40 |

**Crack Width Limits:**

At all times after placement of the concrete, the width of any crack measured at the concrete surface shall not exceed:

a) pre-cast pre-stressed concrete: 0.10 mm;

b) all other concrete: the relevant value specified in Table 6. 1

***TABLE 6.1***

| Exposure Classification | Maximum Acceptable Crack Widths (mm) |
|---|---|
| A | 0.20 |
| B1 | 0.20 |
| B2 | 0.15 |
| C, U | 0.10 |

**Durability:**

High durability concrete shall have a chloride permeability of less than 1500 coulombs as measured by TP541 Rapid Determination of the Chloride Permeability of Concrete (refers AASHTO T277 and ASTM C1202).

NSW Roads and Maritime Services (RMS) QA Specification B80: Concrete Work for Bridges (2012)

**Mix Design and Durability:**

***Table B80.6 – Durability Requirements for Concrete***

| **Exposure Classifica-tion** | **Min. Cement Content ($kg/m^3$)** | **Max. Cement Content ($kg/m^3$)** | **Max. Water/ Cement Ratio (by mass)** | **Min. Water/ Cement Ratio (by mass)** | **Max. Chloride Test Coefficients at 20°C (x $10^{-12}$ $m^2/s$)** | | **Min. Strength for Durability $f_{c,\ min(d)}$ (MPa)** | **Actions Required** |
|---|---|---|---|---|---|---|---|---|
| | | | | | **NT Build 443 ($D_e$)** | **NT Build 492 ($D_{RMC}$)** | | |
| *Cast in Place Concrete* | | | | | | | | |
| A | 320 | 400 | 0.56 | 0.4 | N/A | N/A | 24 | N/A |
| B1 | 320 | 450 | 0.50 | 0.4 | N/A | N/A | 32 | N/A |
| B2 | 370 | 500 | 0.46 | 0.32 | 3.5 | 8.0 | 40 | 25% FA or 50% BFS |
| C | 420 | 550 | 0.40 | 0.32 | 2.0 | 4.0 | 50 | 65% BFS |
| U | In accordance with Annexure B60/A1 | | | | | | | |
| *Precast Concrete* | | | | | | | | |
| A, B1 | 320 | 600 | 0.5 | 0.28 | N/A | N/A | 40 | N/A |
| B2 | 370 | 600 | 0.46 | 0.28 | 3.5 | 8.0 | 60 | Blended cement |
| C | 420 | 600 | 0.40 | 0.28 | 2.0 | 4.0 | 60 | Blended cement |

**Target Strength:**

Design the concrete mix to achieve a target strength $f_{c.md}$ such that:

$$\mathbf{f_{c.md} \geq f_{c.min} + M_{control}} \text{ and}$$

$$\mathbf{f_{c.max} \leq f_{c.min} + 2.0\ M_{control}}$$

where:

(a) $f_{c.min}$ is the greater of $f_{c.min(s)}$ and $f_{c.min(d)}$ ;

(b) $f_{c.min(s)}$ is the specified minimum 28 day compressive strength as stated on the Drawings, or elsewhere in the Specification;

(c) $f_{c.min(d)}$ is the minimum 28 day compressive strength required for durability obtained from Table B80.6;

(d) $M_{control}$ is the margin nominated for variations in strength as defined in Clause 4.1; and

(e) $f_{c.max}$ is the maximum 28 day compressive strength test result permitted for the trial mix, unless otherwise approved by the Principal.

Unless otherwise specified on the Drawings or approved by the Principal:

(i) the target strength $f_{c.md}$ for cast-in-place deck concrete must not exceed 42 MPa except for exposure classification B2 where it must not exceed 50 MPa;

(ii) the target strength fc.md for all other concrete must not exceed 75 MPa; and

(iii) $M_{control}$ must not exceed 10 MPa.

**Target Slump:**

Unless otherwise specified on the Drawings, or approved by the Principal, the concrete slump of the nominated mix (nominated slump) must not exceed 180 mm. Where a nominated slump in excess of 180 mm is proposed, demonstrate by way of a Test Member in accordance with Clause 5.3.2, that the concrete may be placed, compacted and finished without deleterious effects. Unless otherwise approved by the Principal, the above limitations on slump may be waived only for the bridge members specified in Annexure

**Shrinkage:**

Shrinkage of the concrete specimens after either of the 3 or 8 weeks drying periods must conform to Table B80.8.

***Table B80.8 – Maximum Shrinkage Strain of Concrete Specimens***

| Exposure Classification | Maximum Shrinkage Strain (Microstrain) | |
|---|---|---|
| | Drying Period | |
| | 3 Weeks | 8 Weeks |
| A | 570 | 690 |
| B1, B2 | 500 (600[#]) (650[§]) | 630 (720[#]) (760[§]) |
| C | 430 (530[#]) (550*) (650[§]) | 560 (650[#]) (670*) (760[§]) |
| U | In accordance with Annexure B80/A1 | |

Note: [#] For self-compacting concrete, [§] For concretes with slag-blended cement, * For precast members where the specified corrosion inhibitor has been included in the mix

**Crack Width:**

At the completion of the curing period the concrete must have no cracks of width greater than 0.05 mm, measured at the concrete surface. Where such cracks exist, they must be identified as a nonconformity.

At 28 days after placement or later the concrete must have no cracks of width greater than 0.1 mm, measured at the concrete surface. Where such cracks exist, they must be identified as a nonconformity.

Queensland Department of Transport and Main Roads (DTMR) Main Roads Technical Standard MRTS70: Concrete (2010)

Concrete of characteristic strength less than 25 MPa shall not be used for reinforced concrete.

**Mix Design (Table 11.2):**

| Exposure Classification | Minimum Cementitious Content (kg/m$^3$) | Maximum Water/Cementitious Ratio | Strength Grade (MPa) |
|---|---|---|---|
| B1 | 320 | 0.56 | 32 |
| B2 | 390 | 0.46 | 40 |
| C | 450 | 0.4 | 50 |

**Target Compressive Strength:**

The minimum target strength shall be calculated from the equation:

$$f'_t = f'_c + 1.65\ s$$

where $f'_t$ = target strength (MPa)

$f'_c$ = characteristic strength (MPa)

s = standard deviation

**Target Slump:**

The target slump nominated by the Contractor for each Class of concrete used in the Works shall be a value which falls within the range given in Table 11.4.

Super Workable Concrete (SWC) may be approved only by the Director Concrete Technology for Precast Concrete Elements subject to the precaster and concrete supplier meeting the conditions prescribed by the Director Concrete Technology and demonstrating that the concrete can be consistently produced.

| | |
|---|---|
| | ***Table 11.4 – Permissible Target Slump*** |

| Characteristic Strength (MPa)/Application | Target Slump Range (mm) |
|---|---|
| 20/Cast In-Situ | 70-120 |
| 25/Cast In-Situ | 70-120 |
| 32/Cast In-Situ | 70-150 |
| 40/Cast In-Situ | 60-150 |
| 50/Cast In-Situ | 50-150 |
| 32-50/Pumped Concrete | 100-150 |
| 32-50/Sprayed Concrete | Slump to suit equipment |
| 32-50/Extruded Concrete | Slump to suit equipment |
| 32-50/Tremie Concrete:<br>-Dry conditions<br>-Wet conditions | <br>150-180<br>180-220 |
| 32-50/Precast Concrete Elements | 80-180 |

Main Roads Western Australia (MRWA) Specification 820: Concrete for Structures (2012)

**Mix Design:**

All concrete for the Works shall be as specified in Table 820.2 except that blinding concrete and make-up concrete shall be Class N20 in accordance with AS 1379.

***Table 820.2***

| CONCRETE CLASS | S35 | S40 | S50 |
|---|---|---|---|
| Nominated strength | 35 MPa | 40 MPa | 50 MPa |
| Target strength for mix design | 42 MPa | 48 MPa | 58 MPa |
| Maximum aggregate size | 10 mm | 20 mm | 20 mm |
| Minimum aggregate/cement ratio | 3.2 | 4.0 | 3.0 |
| Maximum water/cement ratio | 0.45 | 0.43 | 0.40 |
| Minimum Cement Content | 350 kg/m$^3$ | 400 kg/m$^3$ | 420 kg/m$^3$ |

**Slump:**

The maximum slump of any concrete mix shall be 100mm unless a super-plasticising admixture is used in which case 100 mm shall be the maximum slump before addition of the admixture. For concrete containing high range water reducer (HRWR), the initial slump prior to its addition shall not be less than 40 mm unless otherwise approved by the Superintendent.

**Shrinkage:**

Concrete specimens shall be prepared from the nominated mix in accordance with AS 1012.13 for the purpose of shrinkage testing. The shrinkage of the specimens shall be measured in accordance with AS 1012.13. The shrinkage strain of the concrete specimens after 56 days of drying shall not exceed 600 x $10^{-6}$.

Tasmanian Department of Infrastructure, Energy and Resources, Bridgeworks Specification, B10: Supply of Concrete

**Mix Design:**

The minimum mass of total cementitious binder per cubic metre of finished concrete and the corresponding maximum water/cementitious binder ratio shall be as shown in Table B10.2.

The cementitious binder content of concrete to be placed under water shall not be less than 400 kg/m$^3$, with a maximum water/cementitious binder ratio of 0.45.

The minimum mass of Portland cement in concrete mixes containing either GGBF Slag or Fly Ash shall be 60% or 75% respectively, of the total mass of cementitious binder in the concrete mix. The inclusion of GGBF Slag, Fly

(2006)

Ash or Silica Fume in concrete mixes shall be in binary or ternary combination with Portland cement.

In no case shall more than 40 kg/m$^3$ of silica fume be added.

Where required by the Project Specification samples of concrete design mix shall be taken and tested in accordance with the relevant standard test methods for VPV. The maximum VPV values at 28 days for each concrete grade are shown in Table B10.2

Standard grades are shown in Table B10.2.

***Table B10.2***

| Grade ($f'_c$) | Minimum Cementitious Binder (kg/m$^3$) | Maximum Water/Cementitious Binder Ratio | Maximum VPV at 28 days (%) Test cylinders |
|---|---|---|---|
| S15 | 200 | 0.9 | |
| S20 | 260 | 0.75 | |
| S25 | 350 | 0.55 | |
| S32 | 400 | 0.5 | 15 |
| S40 | 440 | 0.45 | 14 |
| S50 | 470 | 0.4 | 13 |
| S55 | 500 | 0.36 | 12 |

**Compressive Strength:**

The characteristic compressive strength of concrete ($f'_c$) shall be determined at 28 days after placing by tests carried out on standard test specimens made, cured and tested in accordance with AS 1379 Appendix B Clause 3.4 and AS 1012:8 and 9.

**Slump:**

The slump shall be 60 mm $\pm$ 15 or within the range nominated in the Mix Design for concrete containing superplasticiser.

---

Northern Territory Department of Infrastructure, Technical Specifications , Bridgeworks, B06: Concrete (2012)

**Mix Design:**

Use concrete which is normal grade except where the durability requirements dictate more stringent cement contents and water/cement ratios.

The minimum cementitious content and maximum water/cementitious ratio shall be as shown in the table below:

***Minimum Cement Proportions for Durability and Strength***

| Exposure Classification* | Minimum Cement Content (kg/m$^3$) | Maximum Water/Cement Ratio |
|---|---|---|
| B1 | 320 | 0.56 |
| B2 | 390 | 0.46 |
| C | 450 | 0.40 |

* As defined in AS 3600.

**Minimum Compressive Strength:**

The minimum target strength shall be calculated from the equation:

$$f'_t = f'_c + 1.65s$$

where $f'_t$ = target strength (MPa)

$f'_c$ = characteristic strength (MPa)

s = standard deviation

**Slump:**

| | |
|---|---|
| | The slump determined on the site in accordance with AS1012, Part 3 shall lie within the range established using the approved slump and tolerances specified in Table 6 of AS 1379.<br>**Shrinkage:**<br>Where specified, use shrinkage compensated concrete to entirely counteract long term shrinkage assuming that ordinary concrete exhibits 500 microstrain shrinkage. |
| ACT Trunk Road Infrastructure Technical Specification No. 10: Bridges and Related Structures (2012) | The Australian Capital Territory has adopted the NSW Roads and Maritime Services (RMS - formerly RTA NSW) specifications for concrete works (RMS QA Specification B80 – Concrete Work for Bridges). |

As can be seen from Table 3, practitioners ranging from concrete suppliers to engineering consultants are conversant with specifying concrete in terms of mix proportions and properties. Thus, transition to alternative concretes would be facilitated by use of similar and appropriately modified terminology.

The concrete property requirements in Table 3 vary from state to state. For VicRoads Section 703: General Concrete Paving, the requirement for geopolymer concrete is based on compressive strength alone.

## Prescriptive versus Performance-Based Specifications

In addition to prescriptive specifications typically used in Table 3 whereby concrete ingredients and proportions are specified (e.g., cementitious type and content, w/cm ratio, aggregate/cement ratio), performance-based specifications are also used in Australian state specifications. The most commonly specified performance requirement is compressive strength. Other performance specifications are related directly or indirectly to durability. Examples of these requirements are:

- Volume of permeable voids (VPV) (VicRoads and Tasmanian DIER)
- Rapid chloride permeability (South Australian DPTI)
- Chloride diffusion coefficient (New South Wales RMS)
- Shrinkage (VicRoads, SA DPTI, NSW RMS, NT DoI, Qld TMR)
- Crack widths (VicRoads, SA DPTI, NSW RMS)

State specifications, AS 3600 and AS 5100 also use performance specifications by requiring certain grades of concrete for the exposure classification of a structure or element (i.e., A, B1, B2, C and U). As indicated in Table 3, the minimum cementitious content and maximum water/cementitious material ratios for a given exposure classification are similar but not identical for all states.

Project-specific requirements are also used, particularly when the design life exceeds that in AS 3600 and AS 5100 (e.g., New Gateway Bridge, Brisbane) or for aggressive environments. Bickley et al (2006a, b) and Aïtcin and Mindess (2011) note the trend towards performance-based specifications in order to achieve adequate durability of concrete in a nominated exposure. In addition to properties controlling durability, sustainability of concrete in terms of greenhouse gas emissions is a potential performance specification (Bickley et al, 2006a; Aïtcin and Mindess, 2011).

Successful adoption of geopolymer concrete will require a change of thinking from prescriptive specification of conventional concrete mix proportions to performance-based specifications. It will also be necessary to determine what values of particular properties are relevant for achieving durability of geopolymer concrete. For example, a maximum chloride diffusion coefficient of $2.0 \times 10^{-12}$ $m^2/s$ specified to achieve a design life in a marine environment controlled by reinforcement corrosion may not necessarily be directly applicable to geopolymer concrete. This would be the case if the threshold concentration of chloride ions required to initiate corrosion of reinforcement differs between Portland cement concrete and geopolymer concrete. The concrete strength and depth of cover requirements in atmospherically exposed concrete in AS 3600 and AS 5100 are based on assumed carbonation rates. If carbonation rates differ significantly for geopolymer concrete then these requirements may need modification. Similarly, durability design often assumes a certain corrosion rate of reinforcement and a corrosion propagation period before cracking and spalling occur. If the corrosion rates and fracture properties for conventional and geopolymer concrete differ substantially then current specified concrete quality and cover requirements may not be valid. Consequently, long-term properties and behaviour of geopolymer concrete need to be understood and defined to develop appropriate performance-based specifications or modify existing specifications.

## PROPERTY REQUIREMENTS FOR CONCRETE IN AS 3600

Design of plain, reinforced and prestressed concrete in codes and standards such as AS 3600 implicitly assume that the concrete is based on Portland cement. Therefore, adoption of geopolymer concrete will necessitate understanding of behaviour and if there are any substantial differences from current design standards. An example of where design codes have been developed to deal with alternative materials is ACI 440.1R-06 (Guide for the Design and Construction of Structural Concrete Reinforced with Fiber Reinforced Polymer Bars).

This section reviews the state of the art for concrete design in Australia and identifies which properties are relevant if current standards are to be modified to include geopolymer concrete. The design property requirements are covered in Section 3 of AS 3600. These requirements are summarised below. Further details are provided in the standard.

### Characteristic Compressive Strength

The characteristic compressive strength of concrete at 28 days ($f'_c$) shall be either—

(a) taken as equal to the specified strength grade, provided the appropriate curing is ensured and that the concrete complies with AS 1379; or

(b) determined statistically from compressive strength tests carried out in accordance with AS 1012.9.

The characteristic compressive strengths of the standard strength grades are 20 MPa, 25 MPa, 32 MPa, 40 MPa, 50 MPa, 65 MPa, 80 MPa and 100 MPa.

### Mean In-Situ Compressive Strength

In the absence of more accurate data, the mean value of the in situ compressive strength ($f_{cmi}$) shall be taken as 90% of the mean value of the cylinder strength ($f_{cm}$) or shall be taken as those given in Table 3.1.2 of AS 3600.

### Tensile Strength

The uniaxial tensile strength ($f_{ct}$) is the maximum stress that concrete can withstand when subjected to uniaxial tension. The uniaxial tensile strength shall be determined from either the measured flexural tensile strength ($f_{ct.f}$) or from the measured splitting tensile strength ($f_{ct.sp}$) using:

$f_{ct} = 0.6f_{ct.f}$ or $f_{ct} = 0.9f_{ct.sp}$

where $f_{ct.f}$ and $f_{ct.sp}$ are determined statistically from:

(a) flexural strength tests carried out in accordance with AS 1012.11; or

(b) indirect tensile strength tests carried out in accordance with AS 1012.10, respectively.

In the absence of more accurate data, the characteristic flexural tensile strength of concrete ($f'_{ct.f}$) and the characteristic uniaxial tensile strength of concrete ($f'_{ct}$) shall be taken as:

$f'_{ct.f} = 0.6\sqrt{f'_c}$ and $f'_{ct} = 0.36\sqrt{f'_c}$ at 28 days and standard curing, and where the mean and upper characteristic values are obtained by multiplying these values by 1.4 and 1.8, respectively.

### Modulus of Elasticity

The mean modulus of elasticity of concrete at the appropriate age ($E_{cj}$) shall be either:

(a) taken as equal to:

i. $(\rho^{1.5}) \times (0.043\sqrt{f_{cmi}})$ (in megapascals) when $f_{cmi} \leq 40$ MPa; or

ii. $(\rho^{1.5})\times(0.024\sqrt{f_{cmi}}+0.12)$ (in megapascals) when $f_{cmi}$ > 40 MPa, consideration being given to the fact that this value has a range of ±20%;

(b) determined by test in accordance with AS 1012.17; and

(c) for Standard strength grades at 28 days determined from AS 3600 Table 3.1.2

**AS 3600 Table 3.1.2: Concrete Properties at 28 Days**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **$f'_c$ (MPa)** | 20 | 25 | 32 | 40 | 45 | 65 | 80 | 100 |
| **$f_{cmi}$ (MPa)** | 22 | 38 | 35 | 43 | 53 | 68 | 82 | 99 |
| **$E_c$ (MPa)** | 24,000 | 26,700 | 30,100 | 32,800 | 34,800 | 37,400 | 39,600 | 42,200 |

## Density

The density of concrete ($\rho$) shall be determined by test in accordance with either AS 1012.12.1 or AS 1012.12.2. For normal-weight concrete, the density may be taken as 2400 kg/m$^3$.

## Stress-Strain Curves

The stress-strain curve for concrete shall be either:

(a) assumed to be of curvilinear form defined by recognised simplified equations; or

(b) determined from suitable test data.

For design purposes, the shape of the in situ uniaxial compressive stress-strain curve shall be modified so that the maximum stress is $0.9f'_c$.

## Poisson's Ratio

Poisson's ratio for concrete ($v$) shall be either:

(a) taken as equal to 0.2; or

(b) determined by test in accordance with AS 1012.17.

## Coefficient of Thermal Expansion

The coefficient of thermal expansion of concrete shall be either:

(a) taken as equal to $10 \times 10^{-6}$/°C, consideration being given to the fact that this value has a range of ±20%; or

(b) determined from suitable test data.

## Shrinkage

### Calculation of Design Shrinkage Strain

The design shrinkage strain of concrete ($\varepsilon_{cs}$) shall be determined:

(a) from measurements on similar local concrete;

(b) by tests after eight weeks of drying modified for long-term value, in accordance with AS 1012.13; or

(c) by calculation in accordance with AS 3600 Clause 3.1.7.2.

### (AS 3600 Clause 3.1.7.2) Design Shrinkage Strain

When the design shrinkage strain of concrete ($\varepsilon_{cs}$) is to be calculated, it shall be determined as the sum of the chemical (autogenous) shrinkage strain ($\varepsilon_{cse}$) and the drying shrinkage strain ($\varepsilon_{csd}$):

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$$

The autogenous shrinkage strain shall be taken as:

$$\varepsilon_{cse} = \varepsilon^{*}_{cse} \times (1.0 - e^{-0.1t})$$

where $t$ is the time (in days) after setting and $\varepsilon^*_{cse}$ is the final autogenous shrinkage strain given by:

$$\varepsilon_{cse}^{*} = (0.06 f_c' - 1.0) \times 50 \times 10^{-6}$$

At any time *t* (in days) after the commencement of drying, the drying shrinkage strain shall be taken as:

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b}$$

and $k_1$ is obtained from Figure 3.1.7.2 in AS 3600 and $k_4$ is equal to 0.7 for an arid environment, 0.65 for an interior environment, 0.6 for a temperate inland environment and 0.5 for a tropical or near-coastal environment.

The basic drying shrinkage strain ($\varepsilon_{csd.b}$) is given by:

$$\varepsilon_{csd.b} = (1.0 - 0.0008 f_c') \times \varepsilon_{csd.b}^{*}$$

where the final drying basic shrinkage strain ($\varepsilon^{*}_{csd.b}$ ) depends on the quality of the local aggregates and shall be taken as 800 × $10^{-6}$ for Sydney and Brisbane, 900 × $10^{-6}$ for Melbourne and 1000 × $10^{-6}$ elsewhere.

Further information is given in Table 3.1.7.2 of AS 3600.

## Creep

The creep strain at any time (*t*) caused by a constant sustained stress ($\sigma_o$) shall be calculated from:

$$\varepsilon_{cc} = \varphi_{cc} \sigma / E_c$$

where

$E_c$ = mean modulus of elasticity of the concrete at 28 days

$\phi_{cc}$ = design creep coefficient at time (*t*) determined in accordance with Clause 3.1.8.3 of AS 3600.

The basic creep coefficient of concrete ($\phi_{cc.b}$) is the mean value of the ratio of final creep strain to elastic strain for a specimen loaded at 28 days under a constant stress of $0.4f'_c$ and shall be:

(a) determined from measurements on similar local concrete; or

(b) determined by tests in accordance with AS 1012.16; or

(c) taken as the value given in Table 3.1.8.2 of AS 3600.

The design creep coefficient for concrete at any time, *t*, ($\phi_{cc}$) shall be determined from the basic creep coefficient ($\phi_{cc.b}$) by any accepted mathematical model for creep behaviour, calibrated such that $\phi_{cc.b}$ is also predicted by the chosen model.

In the absence of more accurate methods, $\phi_{cc}$ at any time shall be taken as:

$\phi_{cc} = k_2 k_3 k_4 k_5 \phi_{cc.b}$

where $k_2$ and $k_3$ are obtained from Figure 3.1.8.3(A) and Figure 3.1.8.3(B) of AS 3600 respectively; $k_4$ = 0.70 for an arid environment, 0.65 for an interior environment, 0.60 for a temperate inland environment and 0.50 for a tropical or near-coastal environment; $k_5$ is a modification factor for high strength concrete and shall be taken as:

$k_5$ = 1.0 when $f'_c \leq 50$ MPa;

or

$k_5 = (2.0 - \alpha_3) - 0.02(1.0 - \alpha_3) f'_c$ when 50 MPa < $f'_c \leq$ 100 MPa

The factor $\alpha_3 = 0.7/(k4\ \alpha_2)$; and $\alpha_2$ is defined as Figure 3.1.8.3(A) in AS 3600.

Consideration shall be given to the fact that $\phi_{cc}$ has a range of approximately ±30%. This range is likely to be exceeded if:

(a) the concrete member is subjected to prolonged periods of temperature in excess of 25°C; or

(b) the member is subject to sustained stress levels in excess of $0.5f'_{cc}$.

The final design creep coefficients ($\phi^{*}_{cc}$) (after 30 years) predicted by this method for concrete first loaded at 28 days are given in Table 3.1.8.3 of AS 3600.

## Summary of AS 3600 Design Requirements

Inclusion of geopolymer concrete in AS 3600 will need knowledge on design properties if this material is to be used in structural applications. Properties of interest include:

- Compressive strength
- Tensile strength
- Modulus of elasticity
- Density
- Stress-strain curves
- Poisson's ratio
- Coefficient of thermal expansion
- Shrinkage
- Creep
- Bond strength to reinforcement

Furthermore, durability properties such as chloride diffusion coefficient, carbonation coefficient and sulphate resistance require consideration in order to comply with AS 3600 durability design.

Models predicting concrete behaviour are used extensively in the design basis described in AS 3600 and it would be necessary to verify applicability to geopolymer concrete or modify if geopolymer concrete is to gain widespread acceptance for structural use.

## COMPARISON BETWEEN GEOPOLYMER AND CONVENTIONAL CONCRETE PROPERTIES

Table 4 compares broadly the properties of geopolymer and conventional Portland cement concrete. Since properties of any concrete are highly dependent on mix proportions and constituent materials, only general comparisons have been made. In the case of durability properties, comparisons are typically made for concretes with similar compressive strengths. More details can be found in the references and further reviews are provided in Petermann et al (2010) and Shayan (2013).

Table 4: Broad Comparison between Geopolymer and Conventional Concrete Properties

| Property | Geopolymer versus Conventional Concrete | Examples of References |
|---|---|---|
| Compressive Strength | Similar, 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) |
| Bond Strength to Reinforcement | Similar for similar compressive strengths; higher for higher compressive strengths | Sarker (2011); Fernández-Jiménez et al (2006) |
| 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) |

| Property | Geopolymer versus Conventional Concrete | Examples of References |
|---|---|---|
| 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) |

Table 4 indicates that the differences in properties and behaviour or geopolymer concrete compared with conventional Portland cement concrete are not always clear. This is frequently due to variation in materials, particularly activator concentrations and chemistry. Research between different organisations has not been coordinated, hence definitive comparisons are not always possible. Compressive, flexural and tensile strength tend to be higher for geopolymers and show higher rates of strength gain, whereas elastic modulus is lower. Bond to reinforcement is similar to higher, although research is limited. Shrinkage of geopolymer concrete is generally lower. Comparison of durability properties is sometimes variable and highlights the need for greater understanding and verification of properties controlling service life in realistic exposure environments. It is also necessary to consider whether conventional test methods and procedures are applicable to geopolymer concrete.

The development or adaptation of models appropriate for predicting behaviour and performance is also required. Existing models assume that concrete is based on Portland cement and have been developed and refined over many years. Equivalent models need to be modified or developed for geopolymer concrete if widespread use in structural applications is to be accomplished.

# CURRENT DEVELOPMENTS IN RECOMMENDED PRACTICES AND STANDARDS FOR LOW CO2 CONCRETE

The majority of research and development on low $CO_2$ concrete, particularly geopoymer concrete, is published in journals and conference proceedings. There are currently several activities and resources aimed at disseminating practical information and developing standards for geopolymer concrete. The Concrete Institute of Australia (CIA) has produced a recommended practice for geopolymer concrete (CIA, 2011). This document provides background information on geopolymer chemistry and materials and properties of geopolymer concrete. Recommendations on modification to current standards are given.

RILEM Technical Committee 224-AAM on Alkali-Activated Materials has an objective of developing performance-based specifications and recommendations for development of standards for these materials. The scope includes alkali-activated slags and ashes, geopolymer and other emerging technologies. The Committee aims to deliver recommendations on performance-based requirements for alkali-activated materials which can be used by national Standards bodies. It is expected that the committee will finalise a document in 2013. The RILEM Committee also plans to conduct a durability testing programme.

ASTM Committees C01 (Cement) and C09 (Concrete and Concrete Aggregates) are considering standards for non-Portland cement binders such as geopolymers and related alkali-activated aluminosilicates. Such standards should increase user confidence with these materials.

# BARRIERS TO IMPLEMENTATION OF GEOPOLYMER CONCRETE

Implementation of low $CO_2$ concrete materials on a large scale requires identification of barriers to use. Adoption of new or different materials in the construction and other industries also face barriers and examination of these is relevant. Barriers considered for geopolymer concrete and new materials in general are discussed in this section.

## Geopolymer Specific Barriers

Several authors have highlighted technical, regulatory, economic and supply chain barriers specific to widespread commercialisation of geopolymer concrete. For example, van Deventer et al (2012) identified the following barriers compared with concrete based on ordinary Portland cement:

- Variability in source materials
- Development of suitable admixtures
- Required operator skill at batch plants
- Capital intensive set up of processing facilities
- Existing prescriptive standard framework based on Portland cement binder rather than performance
- Lack of long-term durability data, particularly field performance
- Development of appropriate tests methods
- Risk of supply chain issues such as reduced availability of suitable fly ash and blast furnace slag

Duxson and Provis (2008) stated that "*The main impediment facing the uptake of new construction materials is the existing standards regime, where prescriptive standards specify particular mix designs for concrete rather than allowing any material which meets given performance standards to be utilised*".

Acceptance of geopolymer concrete was also considered by Aldred and Day (2012), in addition to review of properties and case histories of use in Australia. It was noted that the term "geopolymer" covers a wide range of binder materials and, hence, wide variation in properties and performance. This can be confusing to designers and specifiers. The use of prescriptive standards and codes and exclusion of non-Portland cement binders in these regulations were identified as an impediment to acceptance of geopolymers.

Perera (2007) cited the following barriers for widespread use of geopolymers:

- Conservatism of end user
- Lack of historical and long-term durability data
- Lack of investment in geopolymer plants
- Lack of pure precursors to study and improve scientific understanding
- Variability
- Use of ambiguous terminology

RILEM Technical Committee 224-AAM has listed the major obstacle hindering the widespread uptake of alkali-activation technology in the construction industry as the lack of uniformly accepted standards.

The Federal Highway Administration (FHWA) produced a TechBrief on geopolymer concrete as part of the Concrete Pavement Technology Program (FHWA, 2010). This document considered current limitations for geopolymers as follows:

- Difficulty and care required in working with available systems
- Safety risk associated with alkalinity of activating solution
- Processing of high alkalinity solutions and associated energy consumption and greenhouse gas generation
- Temperature sensitivity
- Elevated temperature curing under strict control

It was suggested that geopolymer concrete in the transportation industry is best suited to precast applications until the above limitations are overcome.

In efforts to meet long-term $CO_2$ reduction targets in Europe, the Cement Sustainability Initiative investigated a range of means of reducing emissions associated with cement production (Cement Sustainability Initiative, 2009). Geopolymer binders were also considered and barriers to implementation were listed as:

- Properties of geopolymer cement strongly depend on the starting material. This can lead to variations in the workability and other properties of the concrete
- Durability of the concrete has yet to be demonstrated
- Reactive components, like fly ash and slag, are industrial waste products and their availability depends on the future of coal fired power plants and future steel production
- Operational safety working with highly alkaline conditions has to be assured
- Production quantities and costs for the alkaline activator (e.g., sodium silicate) will play an important role in the production of geopolymer cements

Whilst geopolymer concrete offers potential benefits in terms of greenhouse gas reduction compared with Portland cement concrete, sustainability and reduced emissions could be viewed as intangible. Improvement in tangible properties such as cost, strength or durability is likely to be more readily understood by end users than greenhouse gas emissions.

## Industry Survey on Barriers to Geopolymers

A survey consisting of six questions was proposed to obtain input from representatives of the concrete and affiliated industries. Participants were asked to identify barriers to the implementation of geopolymer concrete and determine potential pathways for overcoming these barriers. The survey questions are presented below.

Q1. What is your primary role? (Tick one only)

- Engineering consultant
- Academic/Research
- Government
- Contractor
- Material supplier
- Industry association
- Designer/Architect
- Sales/Marketing
- Other

Q2. What is your familiarity with geopolymer concrete?

- None at all
- A little knowledge
- Moderate knowledge
- Detailed knowledge

Q3. What do you think are the barriers to widespread implementation of geopolymer concrete? (Tick all that apply)

- Lack of awareness
- Lack of industry guidelines or recommended practices
- Lack or standard specifications
- Lack of education and training
- Lack of demand
- Geopolymer concrete is not covered in existing Australian Standards (e.g., AS 3600)
- Geopolymer concrete is not covered in state or local specifications
- Cost
- Proprietary formulations
- Lack of long-term performance data
- Constructability or productivity issues
- Risk/liability

- Supply chain or availability issues
- Safety during production
- Contractual issues
- Other (please add comments)

Q4. What actions do you think should be taken to overcome the barriers to implementation of geopolymer concrete? (Tick all that apply)

- Seminars and workforce training
- Development of standard specifications
- Modification of existing design methods
- Modification of existing Australian Standards for concrete to include geopolymers
- Development of new Australian Standards specific to geopolymer concrete
- Development of performance-based standards
- Provision for use of geopolymer concrete in state and local specifications and contracts
- Financial incentives
- Greater recognition of Green Star, LEED or similar environmental reward schemes
- Cost competitive with conventional concrete
- More research on engineering properties and long-term durability
- More field demonstrations
- Use of inspection and non-destructive testing or sensors to monitor in-situ performance
- Development of risk management and assignment strategies
- Increased availability of suitable products
- Improved safety
- Other (please comment)

Q5. What applications do you think offer the highest volume use of geopolymer concrete in the near future? (Tick all that apply)

- Precast
- Non-structural
- Structural
- Footpaths and bike or shared paths
- Residential slabs and driveways
- Industrial slabs (e.g., warehouses)
- Roads
- Pipes
- Railway sleepers
- No-fines (pervious) concrete
- Fire resistant applications (e.g., tunnel linings)
- Chemical resistant applications (e.g., acid bunds, sewers)
- Stabilisation of hazardous waste
- Bricks, masonry blocks
- Other (please comment)

Q6. Do you have any other comments? (Please add)

## Results of Industry Survey

There were 42 total respondents to the survey and 40-42 responses to each question. As shown in Figure 1, the majority of survey respondents were material suppliers, government, academic/researchers or engineering consultants. A significant proportion of respondents were in the “other” category. The roles of these people were retired/author, asset manager, coal power generators and construction materials consultant. Figure 2 indicates that most respondents were knowledgeable on geopolymer concrete to some degree and that the majority had a moderate level of knowledge. The responses to the question regarding barriers are presented in Figure 3 and discussed in Section 9.4.

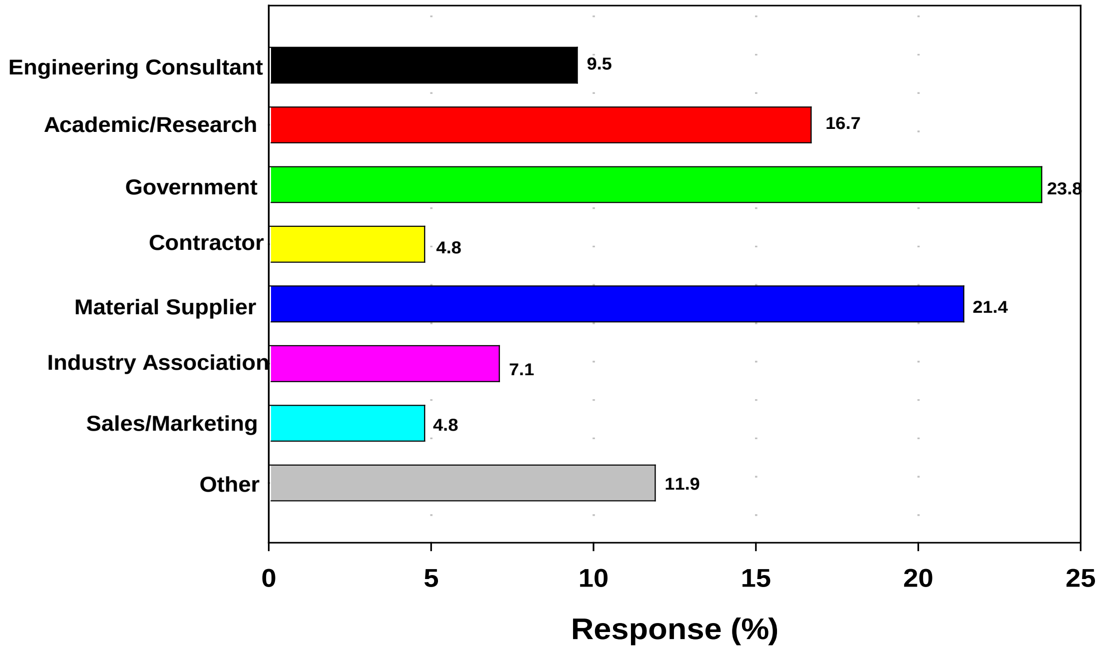


Figure 1: Responses to "What is your primary role? (Tick one only)"

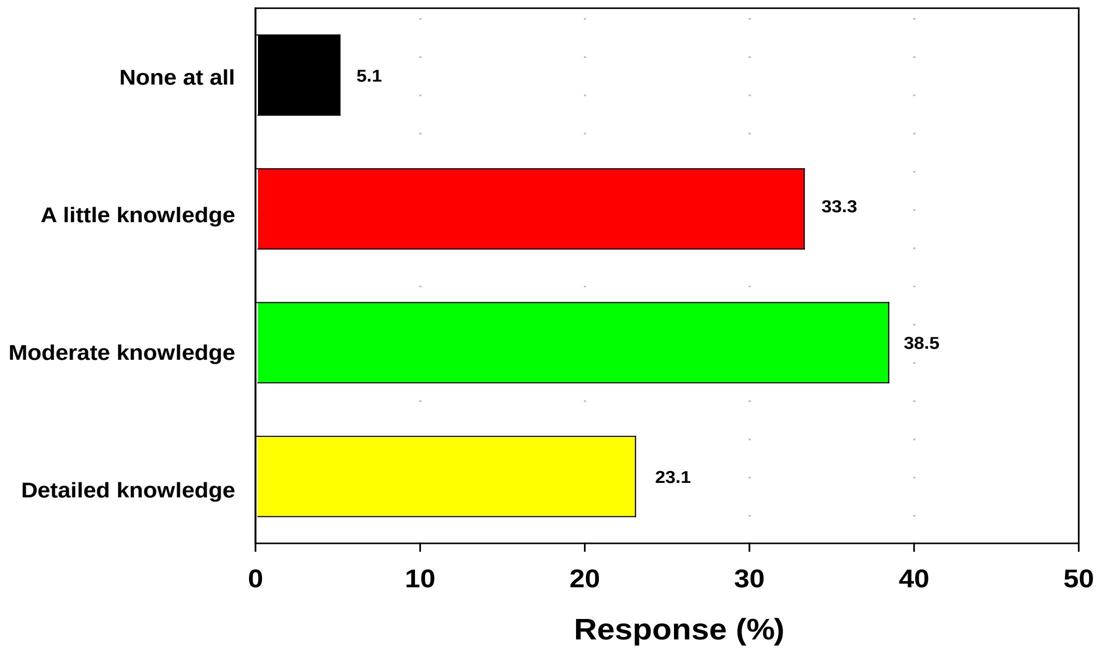


Figure 2: Responses to "What is your familiarity with geopolymer concrete? (Tick one only)"

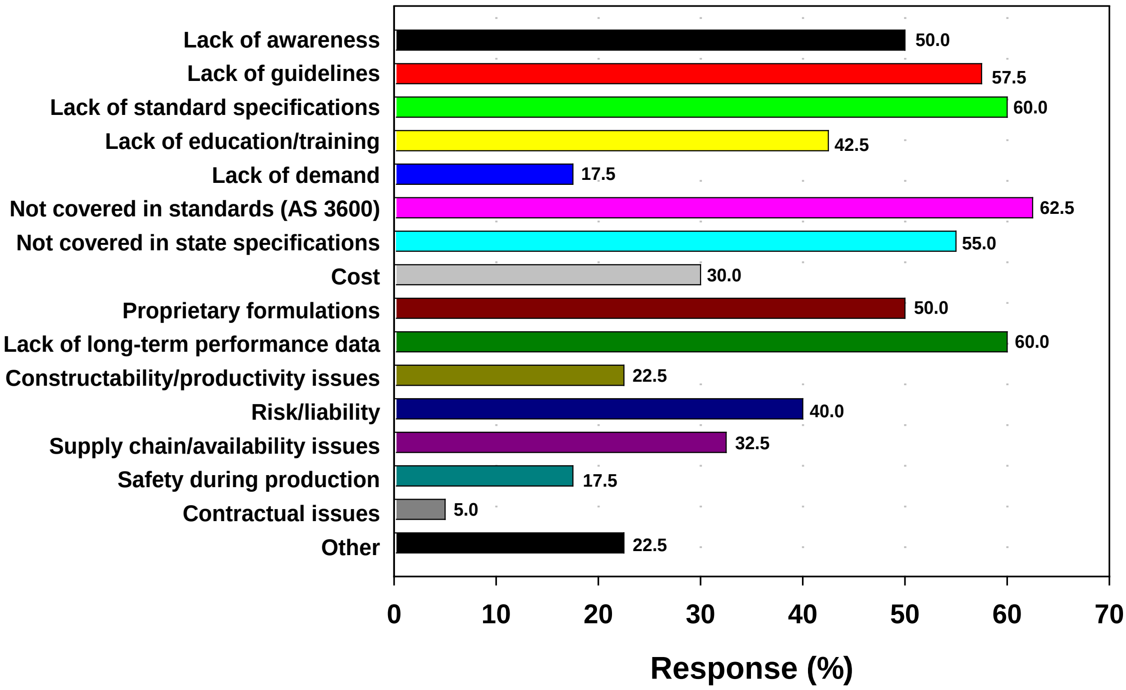


Figure 3: Responses to "What do you think are the barriers to widespread implementation of geopolymer concrete? (Tick all that apply)"

Other comments the participants made in response to Question 3 on barriers are listed below:

- *(1) Need for elevated temperature curing to achieve strength; (2) high carbon footprint of the alkali activators (NaOH and sodium silicate); (3) workability*
- *Unreliable material supply*
- *A unwillingness by cement companies to endorse this type of product and perhaps even downplay its good points for fear of losing profits*
- *WHS (Workplace Health and Safety) handing*
- *Designers won't specify geopolymer as an alternative*
- *Not being pushed by the main concrete suppliers*
- *Determination by the cement industry to maintain the status quo for as long as possible and to control when and how the concrete industry inevitably shifts from calcium silicate cements to alumino silicate cements.*
- *I am aware of past reports on the material that over rate the material properties. I believe carbonation needs to be addressed better. A lot more data is needed in support of it as a structural reinforced concrete material*
- *Cement companies locking up technology with cartel behaviour*

The industry survey also asked participants whether particular actions would assist in overcoming barriers to implementation of geopolymer concrete and what applications are likely to see widespread use in the near future. The responses are summarised in Figures 4 and 5 and discussed in Section 10.5.

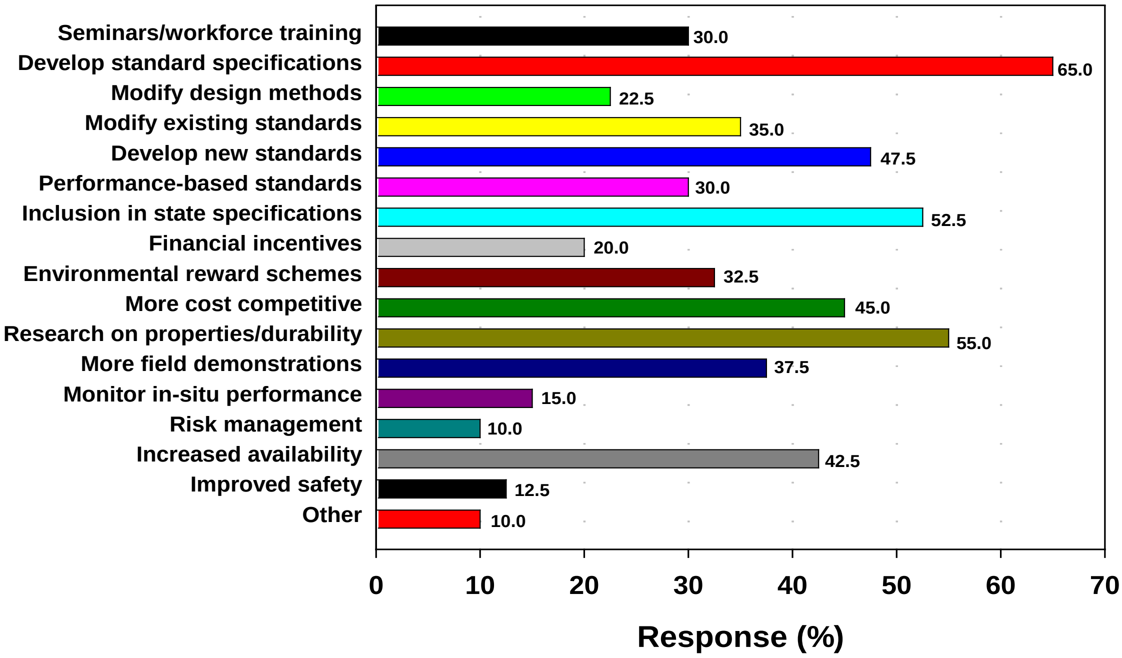


Figure 4: Responses to "What actions do you think should be taken to overcome the barriers to implementation of geopolymer concrete? (Tick all that apply)"

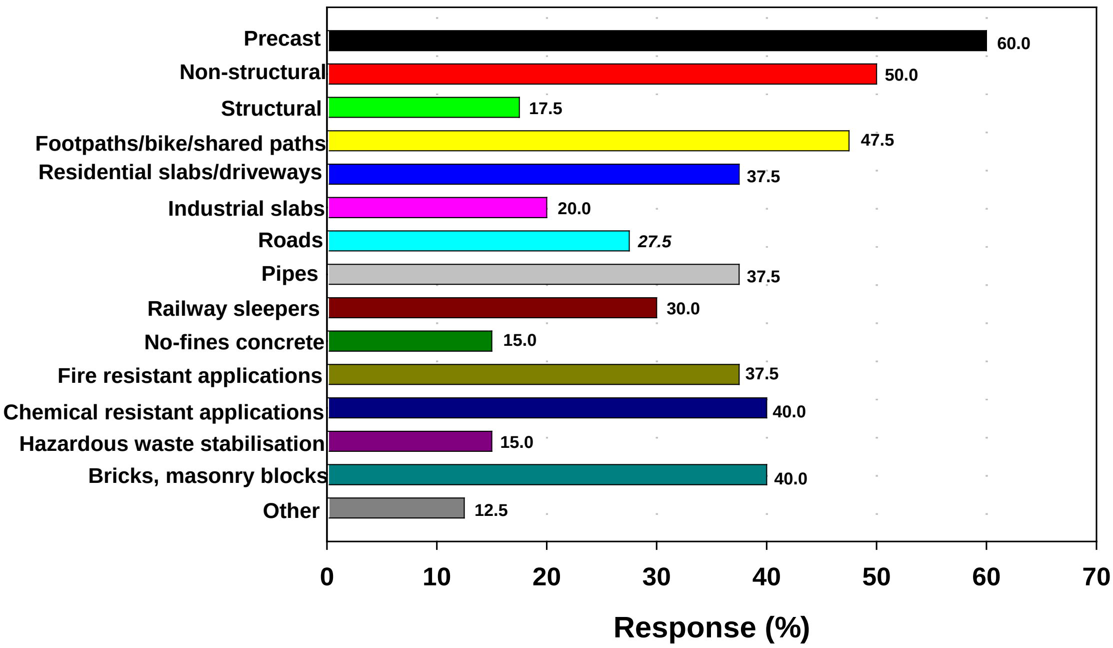


Figure 5: Responses to "What applications do you think offer the highest volume use of geopolymer concrete in the near future? (Tick all that apply)".

Other responses to Question 4 on actions to overcome barriers included:

- *Program to help develop product on a site by site basis*
- *Remove trademarks and patents - share IP (Intellectual Property), partner with SRAs (Sponsored Research Agreements)*
- *Independent research by people without an interest in the material - people who don't want to "gild the lily"*
- *Demonstrate/trial the use of in low risk applications - walkways, footpaths, retaining walls*

Additional comments in response to Question 5 on highest volume applications in the near future included:

- *Mine backfill*
- *Sewerage infrastructure (pipes, manholes, digestion tanks)*
- *I don't know enough about the volume of available applications to offer comments on the other options.*
- *School/Government Buildings and infrastructure*

Respondents were asked to provide any additional comments in Question 6. Responses received are as follows:

- *Development of niche markets where there is a technical advantage over Portland cement and blended cement concrete*
- *The possibility that by-products such as blast furnace slag and fly ash from power stations will be used, e.g., for geopolymer concrete, roadbase depends on local circumstances, e.g., access to market, cost of competing materials, local knowledge. In view of this it's difficult to see a common solution. My thinking is that the organisations that produce the by-products e.g., smelters and power companies are generally rich. In view of this they have the resources to investigate the best (and most profitable) use of their waste and should be pressured and encouraged to do so.*
- *Need to consider supply, logistics, and other components required for the manufacture*
- *The process to develop geopolymer concrete from fly ash specific to individual power stations is going to vary according to physical properties. The market would develop quickly if the formula to make product was available to all end users.*
- *I think we need to understand that geopolymer is not a replacement for concrete. I think there a place for both. Geopolymer by its nature requires for technical assistance in preparation not like concrete which every handyman can safely play with and come up with a reasonable product. Hence I think the main focus should be in other products which lend themselves to QA control in a factory setting. Hence blocks sleepers footpaths, special applications e.g., acid bunds etc*
- *Consolidate the warring factions - divided, Geopolymer will fall!*
- *Intellectual Property and specification issues are a significant barrier to moving forward.*
- *Governments need to push and customers need to pull the demand for geopolymer concrete so that industry can see its long term benefit as an alternative (not a replacement) to OPC. The pioneering work being done by Wagners in Qld should be applauded by the industry!!*
- *I believe that it is inevitable that the concrete industry will move to the use of alumino-silicate cements once the cement industry gives in to community pressure to reduce its carbon footprint. This transition will probably take 20 or 30 years to complete and will only be speeded up by community pressure, authority acceptance and continued industrial research.*
- *Being aware of a previous report produced supposedly independently but which contained errors and is guilty of "gilding the lily" and also aware of a thesis from XXX University that also contained errors, I feel I can't trust the literature that's being*

*produced. The amount of data, level of detail of the work performed, and accuracy of the data just aren't sufficient at the present time, in my opinion, to support the material being used for structural applications. What's needed is very good quality research by persons without any vested interests - by persons who are more interested in producing good research rather than promoting the product.*

- *Carbon footprint very high. Not really environmentally friendly when proper life cycle analysis is performed. Has a number of health and safety risks during manufacture. Very costly.*
- *Happy to explore the use of Yallourn Ash in Geopolymer development*

## Analysis of Barriers Identified in Industry Survey

Respondents to the industry survey clearly identified the lack of inclusion of geopolymer concrete in existing Australian standards (e.g., AS 3600) and state or local specifications and lack of industry guidelines or recommended practices, lack of standard specifications, and lack of education and training as significant barriers (Figure 3). In particular, 62.5% of respondents rated the absence of coverage in existing Australian standards as the primary obstacle. Lack of long-term performance data and lack of awareness were also significant. Proprietary formulations were regarded as problematic to widespread implementation. Risk/liability, supply chain or availability issues and costs were considered as barriers to a lesser, but still substantial, degree. Several (17.5-22.5%) respondents rated constructability/ productivity issues and safety during production as barriers. 22.5% of respondents added “Other” barriers and these were related to material processing and properties, carbon footprint of alkali activators, material supply reliability, problems with cement companies and concrete suppliers, handling, unwillingness of designers to specify geopolymers, and conflicting, overrated and insufficient property data. The responses to the question regarding barriers distinctly demonstrate that there are important issues and concerns that need to be addressed if geopolymer concrete is to realise large-scale use.

## LinkedIn Survey on Geopolymer Concrete

In addition to the survey conducted under the CRC project, an informal survey posed by the Cement, Concrete and Construction discussion group on LinkedIn (2013) asked the question “Will geopolymer binders be the next best thing in construction?”. Of the 65 respondents, 41% voted “Yes”, 26% voted “Unsure”, 18% voted “No” and 13% indicated “I don’t know what they are”. Barriers and potential pathways noted in the LinkedIn survey comments included:

- Need for field versus laboratory data
- All mixes whether or not geopolymer should be the result of extensive trial mixes by the producer and initial supply to non-critical uses
- Less familiarity with geopolymer mixes requires more caution than typical mixes
- Lack of standardised ingredients and procedures
- Conservatism of consultants and current codes of practice
- Inconsistent data on CO2 savings
- Raw material availability
- Institutional barriers
- Health and safety issues with alkali activators
- Production needs to be well controlled, making it more difficult and/or more expensive for mass manufacturing
- The major issue is carbonation. Corrosion in reinforced geopolymer concrete has not been conclusively proved to be any lesser menace compared to Portland cement concrete. Since the major utilities of concrete are for building blocks or reinforced concrete, geopolymer concrete needs more studies. The aspects of plastic shrinkage and rapid setting and development of suitable admixtures

for tailoring the workability are real issues to be answered.

- Let credible authorities use life cycle assessment to determine the correct values of geopolymer concrete versus OPC/SCM concrete, not the suppliers of the materials
- Exploit those niche markets where enhanced performance gives a market advantage rather than replacing Portland cement
- Focus on precast that delivers final products first

## Barriers to Other New or Sustainable Materials in Construction

Lessons can also be learnt from introduction and adoption of other new, alternative, innovative, more sustainable and recycled materials to the conservative construction industry. Such materials have faced similar barriers and some published examples have been reviewed.

The Transportation Research Board (TRB) produced a research agenda for transportation infrastructure as a conference outcome (TRB, 2009). One component of the agenda was “Innovative Materials for Preservation, Restoration, and Reconstruction”. With respect to recycled and alternative materials, it was noted that there the global trend towards sustainable infrastructure requires increased use of these materials in construction. However, despite the demand and wealth of research and information, uptake on a large scale has faced barriers. Cited impediments to high volume use of recycled and alternative materials included (TRB, 2009; Reid, 2002):

- Potential environmental impact
- Safety
- Constructability
- Lack of long-term performance data
- Lack of functional specifications and guidelines
- Lack of test methods
- Reliability and quality control issues
- Environmental concerns
- Waste regulations
- Conditions of contract
- Planning
- Supply and demand
- Economics
- Lack of awareness

The TRB agenda (TRB, 2009) also examined application of innovative, advanced and smart materials in transportation infrastructure. However, the potential application areas were regarded as currently limited. Costs, the highly risk averse nature of the transportation infrastructure construction industry and the lack of engagement in research has resulted in slow adoption of new material technologies. It was pointed out that the massive size and scale of the transportation industry means that any improvement in materials performance could result in significant economic impact.

A National Cooperative Highway Research Program project identified “Implementation of the Use of New Materials into Highway Construction Practice” as an area requiring research (Russell et al, 2002). Identified barriers to implementation included:

- Limited availability of long-term performance data
- Past unsuccessful experience with new materials
- High initial costs
- High risks
- Costs and time requirements of performance testing to achieve acceptance by regulatory agencies

A study of sustainable practice and materials in the Japanese Concrete Industry by Henry and Kato (2012). Barriers identified are summarised in Table 5. These are specific to Japan and may not necessarily be directly applicable to Australia. However, the barriers are similar to many of those for geopolymers and other new materials.

Table 5: Barriers to Sustainable Practice and Materials in Japanese Concrete Industry (Henry and Kato, 2012)

| Category | Barriers |
|---|---|
| Institutional | • Lack of standardised code<br>• No transparency in calculating inventory data<br>• Lack of consideration of full life cycle<br>• Focus on initial cost<br>• Bidding system cannot evaluate additional value<br>• Balance among different criteria |
| Social | • No motivation to use sustainable materials<br>• Reluctance to utilise new materials/technology<br>• Perception of recycled materials as low quality<br>• Perception of concrete as not sustainable |
| Organisational | • Lack of vertical integration<br>• Conflict of interest among stakeholders |
| Economic | • Difficult to balance company benefits versus society<br>• Adopting sustainable practice reduces profits |
| Technological | • Difficult to evaluate durability<br>• Low level of technology |
| Knowledge | • Lack of information on environmental impact<br>• Lack of knowledge on sustainability<br>• Doubts about $CO_2$ and climate change |

In summary, there are numerous potential barriers to widespread use of geopolymer concrete. Some of these barriers are similar to those encountered during introduction of other new or alternative materials to an established industry. It is therefore necessary to identify means of overcoming these barriers and determine which actions are likely to have the greatest impact.

# POSSIBLE PATHWAYS FOR OVERCOMING BARRIERS

Greater acceptance of geopolymer concrete requires that concerns and issues are addressed in a thorough and acceptable manner. The gap between research and routine field use needs to be bridged.

## Acceptance and Commercialisation of New Materials

In discussion of new and innovative materials in general, Maine et al (2005) noted the long period of gestation (typically around 20 years) before widespread acceptance and substitution. This includes materials now in common use such as polyethylene. Maine et al (2005) presented a methodology for viability analysis of new materials including technical feasibility, production cost modelling, value analysis and market assessment. For materials proposed for substitution into a particular application, performance and cost are key factors. For materials with enhanced performance but higher costs or vice versa, Maine et al (2005) suggested that establishment of a market niche required information on how the market values performance. In the case of geopolymer concrete, this may require analysis of the importance of greenhouse gas reduction to the construction industry and greater dissemination of potential benefits to end users.

Market assessment of new materials can follow two broad strategies (Maine et al, 2005):

- Search for new markets or applications created by the new material; or
- Explore substitution into existing markets

Substitution steps for new materials include:

- Identify potential markets by comparing properties of new material with existing materials and noting the most promising property combinations of the new material
- Identify size of potential markets
- Prioritise potential markets according to size and type of substitution
- Assess utility of different markets and/or applications for performance-cost attributes
- Use logistics curves to estimate time of market penetration
- Choose toe-hold market for rollout

## Future of Low CO2 Cements

In summarising the future of low $CO_2$ cements, Gartner (2004) stated the following: *"Clearly, if any alternative cementing system is ultimately to have a real impact on global $CO_2$ emissions related to the construction industry, it will have to have performance and durability characteristics at least as good as the current generation of Portland-based cements, and probably even better, because it is likely to be, at least initially, more expensive to the consumer. The establishment of the performance and durability of alternative cements and concretes to the level required for the introduction of the appropriate new standards and construction codes is likely to be a very expensive undertaking because a large number of tests (and committee meetings) will be required. It will evidently require the full participation and cooperation of industry, government, the scientific community and members of the general public. It is only by such a concerted effort that our society can hope to bring about the long-term changes necessary to make our built environment truly sustainable."*

The above statement is highly pertinent to geopolymer concrete and emphasises key elements of performance characteristics, appropriate standards and collaboration required to gain widespread acceptance.

## Previous Studies on Pathways for Geopolymer Concrete

Specific to geopolymer concrete, van Deventer et al (2012) identified strategic development of standards, particularly cement and concrete standards, as being pivotal to commercialisation. Working with relevant stakeholders was proposed as a means of achieving this. Other strategies recognised by van Deventer et al (2012) included securing supply chain of materials, large scale demonstration and industry projects and development of specific durability tests. An example of using a commercial geopolymer concrete for VicRoads projects in Melbourne was given and this involved regulatory, asset management, liability and industry stakeholder engagement in addition to satisfaction of technical requirements. A flow diagram for the commercialisation of geopolymer concrete has been constructed by van Deventer et al (2012) and is reproduced in Figure 6 below.

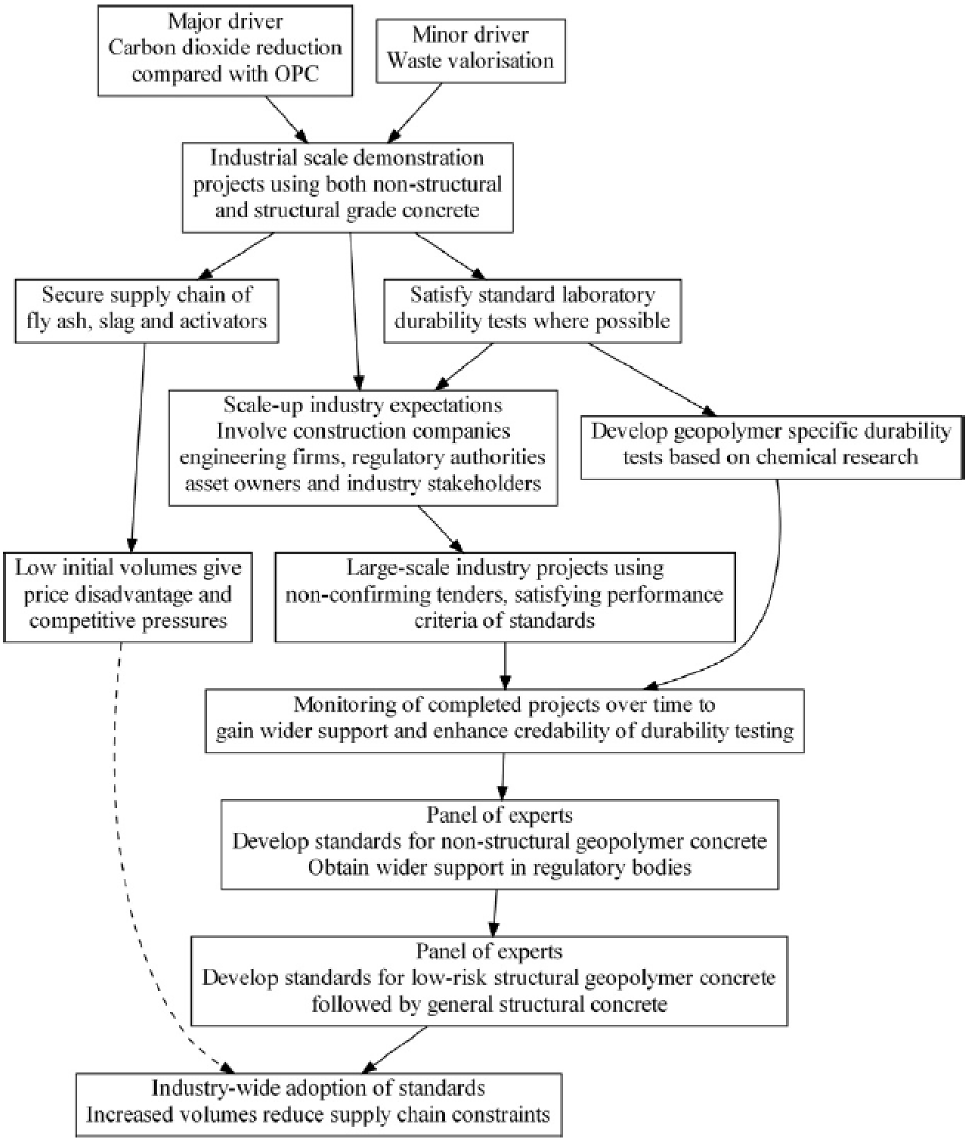


Figure 6: Flow Diagram for Commercialisation of Geopolymer Cement and Concrete by van Deventer et al (2012)

Duxson and Provis (2008) supported the development of performance-based standards for greater acceptance of low $CO_2$ concrete in general. Acceptance by consulting engineers was also regarded as important.

With respect to consulting engineers, architects and clients may have interest in alternative concrete, but approval by conservative and risk averse engineers can prevent use in projects. This situation has been encountered by the author on a number of major projects where there has been a desire or requirement to reduce greenhouse gas emissions and therefore geopolymer concrete has been proposed for either widespread or selected substitution for conventional concrete. However, the perceived risks and liability of using an alternative to Portland cement concrete, particularly with regard to long-term performance, typically result in geopolymer concrete only being used for minor, non-structural applications, if at all. If appropriate standards and specifications are developed at state and national levels, in addition to long-term durability data, then the obstacle presented by consulting engineers could be overcome.

From technical and safety perspectives, the FHWA (2010) suggested that low-alkali activating solutions and curing in reasonable time under ambient conditions would address barriers to use of geopolymer concrete. The production of cost-effective geopolymer cements that can be mixed and hardened essentially like Portland cement was regarded as a “game changing” advancement with potential for revolutionising construction of transportation infrastructure.

## Examples of Actions and Pathways for Other Materials

The TRB research agenda (TRB, 2009) proposed actions to address specific barriers to implementation of new and innovative materials and technologies in the transportation industry. These actions are also worth consideration for overcoming barriers to use of geopolymer concrete. Examples of actions include:

- Outreach to raise awareness
- Education
- Workforce training
- Improved strategies for workforce development
- Dissemination of best practices
- Application of existing standards for natural materials to alternative materials
- Development of new or modified material, design and construction standards and specifications
- Development of performance-based standards and specifications
- Assess constructability using standard equipment
- Collect data and develop reliable life-cycle costs
- Develop inspection standards and policies
- Evaluate risk
- Risk assignment and management
- Risk based inspection
- Develop processes and policies for better decision making
- Obtaining buy-in through demonstration, prototypes and partnerships
- Continued development of infrastructure and performance sensors

### Polymer Concrete

Two examples of new materials development in the concrete field are polymer concrete and fibre reinforced polymer (FRP) reinforcement. The pathways to use and acceptance of these materials are relevant. Polymer concrete, polymer impregnated concrete and polymer modified concrete were the subject of extensive research and development at Brookhaven National Laboratory (BNL) from the mid-1960s until the late 1990s. This work, together with research at other organisations, resulted in the development of commercial products for numerous applications. The ability to formulate polymer concrete from different resins resulted in a wide range of properties and versatile uses.

BNL's work on polymer concrete included:

- Laboratory preparation and thorough testing of different formulations for engineering, physical and durability properties
- Evaluation of properties and identification of potential applications
- Independent economic assessment
- Development of specific materials for a particular need
- Scale-up and field demonstrations in collaboration with regulatory agencies, industry partners and end-users
- Monitoring of field demonstrations and evaluation of material performance
- Development of user guidelines and specifications
- Testing to meet requirements of specific codes and standards in order to demonstrate gain approval
- Technology transfer through publications, conference presentations, field demonstrations, active membership of technical committees, support and training
- Technology transfer to commercial applicators
- Contribution to ACI Committee 548 and development of ACI guidelines and specifications for polymer and polymer modified concrete

The primary focus of research and development of polymer concrete was applications where superior performance compared with Portland cement concrete could be readily achieved. Examples include durability in aggressive environments, high temperature performance, rapid setting, high strength, adhesion, low permeability, wear resistance, versatility and aesthetics. Owing to economics, polymer concrete cannot realistically replace Portland cement concrete in conventional construction. However, there is significant demand for polymer concrete in precast applications, overlays for concrete protection, concrete repair, decorative floors and other specialised uses where performance benefits or life-cycle costs outweigh initial cost.

For geopolymer concrete, reduced greenhouse gas emissions and improved performance in particular applications are the key benefits. Unlike polymer concrete, geopolymer concrete has the potential for greater volume use, in addition to niche applications. The approach used by BNL, other research institutions, government organisations and private industry in the development of polymer concrete show that considerable effort and resources over a sustained period of time are required to take a material from the laboratory to widespread use and acceptance.

### Fibre Reinforced Polymer Reinforcement

Another example of introduction of a new material to an established market is the use of fibre reinforced polymer (FRP) reinforcement as an alternative to steel. The use of FRP reinforcement in concrete is of growing interest primarily due to its resistance to corrosion and damage associated with steel reinforcement, especially in aggressive environments. Owing to the relatively short track record of FRP reinforcement in concrete compared with conventional steel, questions arise as to its performance and durability. Extensive research on the performance of FRP has been conducted including accelerated laboratory tests and monitored field demonstrations to address raised concerns. This research has focused on properties such as degradation in alkaline environments, moisture absorption, creep, relaxation, thermal behaviour, fire resistance, bond strength, fatigue and behaviour of FRP reinforced structures under static and dynamic loads.

Key to greater acceptance of FRP reinforcement has been publication of research results, devoted conference streams, field demonstrations involving collaboration between research institutions and transportation agencies, and production of informative reports, specifications and design guidelines. In particular, ACI Committee 440 has produced a number of documents including ACI 440R-07 "State-of-the-Art Report on Fiber Reinforced Plastic Reinforcement for Concrete

Structures", ACI 440.1R-06 "Guide for the Design and Construction of Concrete Reinforced with FRP", 440.3R-04 "Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures", and 440.5-08 "Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars". Design guidelines for FRP reinforcement are also covered in several international standards.

The example of how FRP reinforcement has overcome barriers to acceptance highlights the necessity for targeted research, engagement with regulatory agencies and development of design standards, specifications and guidelines. Similar actions, particularly on production of standards, are required for greater adoption of geopolymer concrete.

## Pathways Identified in Industry Survey

The key action to overcome barriers rated by 65% of respondents was the development of standard specifications for geopolymer concrete (Figure 4). More research on engineering properties and long-term durability, inclusion in state/local specifications and development of new Australian standards specific to geopolymer concrete were rated very highly (>50%). Improving the cost competitiveness compared with conventional concrete and increased availability of suitable products were regarded by more than 40% of respondents as appropriate actions. More field demonstrations, seminars and workforce training and greater recognition of environmental reward schemes (e.g., Green Star, LEED) were of moderate importance (30.0-32.5%). Development of performance-based standards and modification of existing standards and design methods were regarded as of less importance than development of new standards. Other responses included removal of trademarks and patents, independent research, demonstration in low risk applications (footpaths, retaining walls) and a program to help develop the product on a site by site basis.

The survey also asked what applications were likely to offer highest volume use of geopolymer concrete in the near future. The responses are shown in Figure 5. Precast (60%) and non-structural applications (50%) were rated highest, along with footpaths or bike/shared paths (47.5%). Moderately rated applications (>30%) were chemical and fire resistant uses, pipes, residential slabs/driveways, bricks or masonry blocks and railway sleepers. Roads and industrial slabs received responses in the 20-30% range. Other suggested applications were mine backfill, sewerage infrastructure (pipes, manholes, digestion tanks and school/government buildings and infrastructure.

From the survey and review of prior studies, it is suggested that the highest priority actions to increase the use of geopolymer concrete in Australia are:

- Development of standard specifications for use by engineers
- Development of new standards specific to geopolymer concrete that include performance requirements
- Provision for use of geopolymer concrete in state and local specifications
- More independent research on engineering properties and long-term durability to reduce risk
- Focus on precast, non-structural and fire and chemical resistant applications

Other important actions accompanying the above include:

- Reduce costs and increase availability
- More field demonstrations, particularly low risk applications such as footpaths, shared paths and retaining walls
- Education and dissemination of information
- Greater involvement from concrete suppliers
- Credit for geopolymer concrete in environmental rewards schemes
- Non-proprietary mixes

## Recommended Near-Term Pathways

Analysis of introduction of new materials into the construction industry and the industry survey show that many tasks need to be undertaken in an integrated manner to make geopolymer concrete, or other low $CO_2$ concrete formulations, accepted and used widely. In the near-term (i.e., three years), efforts should concentrate on gaining acceptance for geopolymer concrete through production in controlled environments (i.e., precast) and either low risk, non-structural applications or applications where superior properties of geopolymer concrete are advantageous. These efforts need to be coordinated between all stakeholders to ensure successful and productive outcomes.

### Development of Handbook for Geopolymer Concrete

Pathways for addressing the highest priority actions identified in the previous section have been considered. The first of these is the development of a handbook (HB) through Standards Australia titled "Guide and Standard Specification for Construction with Geopolymer Concrete". This handbook will be an appropriate authoritative document to provide engineers and end-users with practical information and specification clauses necessary for integrating geopolymer concrete into construction projects. The handbook will also include relevant performance-based specifications and test methods to meet service requirements. The validity of applying existing tests for conventional concrete to geopolymers will be assessed and any necessary modifications in methods and acceptance criteria will be proposed. It is intended that the handbook be similar to an *fib* Model Code and will have potential to evolve into an Australian Standard specific to geopolymer concrete. Such a standard could then be incorporated into state specifications. The handbook would address the identified needs for standard specifications for use by engineers, applicable performance-based specifications and testing, and would provide a foundation for future development of state specifications and a national standard.

### Durability of Geopolymer Concrete in Aggressive Environments

The second proposed pathway would examine the durability of geopolymer concrete in aggressive environments and focus effort on knowledge gaps in the performance of geopolymers. This research is needed to reduce perceived risks in using geopolymers and to demonstrate independently that durable materials can be produced. Aggressive environments where geopolymers may have an advantage over conventional concrete include acidic conditions such as sewers and chemical exposure sites. It is also possible that geopolymers may be more durable in marine environments but this is yet to be unequivocally proven and current research lacks sufficient depth and relationship to practice. Current research has identified carbonation as a potential problem with geopolymer concrete and this aspect needs to be investigated further.

As part of a study on durability of geopolymer concrete it would be valuable to investigate and monitor existing applications of geopolymers that have already been in service for some years. The durability study pathway needs to be integrated with the task on development of a handbook so that properties and behaviour of geopolymer concrete is better understood and appropriate performance-based specifications can be developed or modified.

### Demonstration Building Constructed with Geopolymer Concrete

The third pathway would use the opportunity through the CRC for Low Carbon Living to construct a building such as a house with geopolymer concrete. This would increase awareness of geopolymer concrete as a building material to both the construction industry and the public and also provide the opportunity for in-situ monitoring of behaviour and properties. The building could be used to showcase other state-of-the-art technologies being explored as part of the CRC to improve sustainability. Benefits of geopolymer concrete such as reduced emissions, use of industry by-products, strength development and rapid construction could be demonstrated in a high profile fashion and disseminated to end-users.

## Other Recommended Pathways

As found in the investigation presented in this report, there are many other tasks that need to be performed to achieve greater acceptance of geopolymer concrete. A coordinated approach involving the full spectrum of interested parties is necessary. Longer-term and other pathways to address current gaps and barriers include:

- Independent study of long-term behaviour of geopolymers in practical applications
- Optimisation of mixes to reduce costs, improve safety and workability, reduce emissions and increase availability
- Development of non-proprietary formulations
- Development of models predicting behaviour and performance for structural applications in a manner similar to the approach used in AS 3600
- Ongoing technology transfer, education and training
- Engagement of cement and concrete suppliers to view geopolymer concrete as a niche, alternative material rather than a competitor to conventional concrete

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Alternative, low $CO_2$ concrete materials offer potential benefits in reducing the greenhouse gas emissions associated with conventional concrete based on Portland cement. However, conventional concrete is a long-established material entrenched in the construction industry and the use of alternatives such as geopolymer concrete faces many barriers. These barriers are similar to those encountered for other alternative or new materials in infrastructure applications. The barriers have been analysed to determine pathways so that geopolymer concrete can be used in large volumes with greater confidence and less risk. Based on review of prior studies and an industry survey, there are many issues and concerns that need to be addressed. Of these, 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 are regarded the highest priority. However, it is also important to consider and address other identified problems. In the short-term, it is likely that the greatest volume uses for geopolymer will be precast and non-structural applications, footpaths and shared paths, pipes and fire or chemical resistant purposes.

An integrated approach to actions and pathways involving all stakeholders is recommended to overcome existing barriers to implementation of low $CO_2$ concrete and, in particular, geopolymer concrete. Pathways that can realistically be accomplished in the near-term (i.e., three years) to address highest priority items identified in the industry survey include:

- Development of a handbook (HB) through Standards Australia titled “Guide and Standard Specification for Construction with Geopolymer Concrete”. This handbook would provide engineers and end-users with practical information and specification clauses necessary for integrating geopolymer concrete into construction projects. The handbook would also include relevant performance-based specifications and test methods to meet service requirements. It is intended that the handbook be similar to an fib Model Code and would have potential to evolve into an Australian Standard specific to geopolymer concrete and provide a basis for state specifications.
- Investigation of geopolymer concrete durability in aggressive environments and focus effort on knowledge gaps in the performance of geopolymers. This research would reduce perceived risks in using geopolymers and to demonstrate independently that durable materials can be produced. As part of a study on durability of geopolymer concrete it would be valuable to investigate and monitor existing applications of geopolymers that have already been in service for some years. This would provide important field data necessary to verify satisfactory performance and remove a significant barrier to specification and use.
- Construction of a building using geopolymer concrete as a demonstration project for the CRC for Low Carbon Living. This would be used to increase awareness of geopolymer concrete as a building material to both the construction industry and the public and also provide the opportunity for in-situ monitoring of behaviour and properties.

# REFERENCES


Aïtcin, P-C. and Mindess, S., Sustainability of Concrete, Spon Press, New York, 2011.

Aldred, J. and Day, J., Is Geopolymer Concrete a Suitable Alternative to Traditional Concrete?, 37th Conference on Our World in Concrete and Structures, Singapore, 29-31 August 2012.

Andrews-Phaedonos, F., Reducing the Carbon Footprint-The VicRoads Experience, Concrete in Australia, Vol. 40, No.1, pp. 40-48, 2012.

Aperador, W., de Gutiérrez, D.M. and Bastidas, D.M., Steel Corrosion Behaviour in Carbonated Alkali-Activated Slag, Corrosion Science, Vol. 51, pp. 2027-2033, 2009.

Aperadror Chapparo, W., Ruiz, J.H.B and Gómez, R.D.J.T, Corrosion of Reinforcing Bars Embedded in Alkali-Activated Slag Concrete Subjected to Chloride Attack, Materials Research, Vol. 51, No. 1, pp. 57-62, 2012

Bakharev, T., Sanjayan, J.G. and Cheng, Y-B., Resistance of Alkali-Activated Slag Concrete to Alkali-Aggregate Reaction, Cement and Concrete Research, Vol. 31, No. 2, pp. 331-334, 2001.

Bakharev, T., Sanjayan, J.G. and Cheng, Y-B., Sulfate Attack on Alkali-Activated Slag Concrete, Cement and Concrete Research, Vol. 32, No. 2, pp. 211-216, 2002.

Bakharev, T., Sanjayan, J.G. and Cheng, Y-B., Resistance of Alkali-Activated Slag Concrete to Acid Attack, Cement and Concrete Research, Vol. 33, No. 10, pp. 1607-1611, 2003.

Bickley, J., Hooton, R.D. and Hover, K.C., Preparation of a Performance-Based Specification for Cast-in-Place Concrete, RMC Research Foundation, 2006a.

Bickley, J., Hooton, R.D. and Hover, K.C., Performance Specifications for Durable Concrete, Concrete International, Vol. 28, No. 9, pp. 51-57, 2006b.

Cement Sustainability Initiative (CSI) and European Cement Research Academy (ECRA), Development of State-of-the-Art Techniques in Cement Manufacturing: Trying to Look Ahead, Dusseldorf, Geneva, 2009.

Centre for Sustainability at TRL, The $CO_2$ Emissions Estimator Tool for the use of Aggregates in Construction -User Guide V 1.0, Waste Resources and Action Programme (WRAP), Report AGG079-007, 2006.

Chen, C., Habert, G., Bouzidi, Y. and Jullien, A., Environmental Impact of Cement Production: Detail of the Different Processes and Cement Plant Variability Evaluation, Journal of Cleaner Production, Vol. 18, No. 5, pp. 478-485, 2010.

Concrete Institute of Australia, Recommended Practice for Geopolymer Concrete, Z16, 2011.

Damtoft, J.S., Lukasik, J., Herfort, D., Sorrentino, D. and Gartner, E.M., Sustainable Development and Climate Change Initiatives, Cement and Concrete Research, Vol. 38, No. 1, pp. 115-127, 2008.

Diaz-Loya, E.I., Alluche, E.N. and Vaidya, S., Mechanical Properties of Fly-Ash-Based Geopolymer Concrete, ACI Materials Journal, Vol. 108, No. 3, pp. 300-306, 2011.

Duxson, P. and Provis, J., Low $CO_2$ Concrete: Are We Making Any Progress?, BEDP Environment Design Guide, November 2008.

Duxson, P., Provis, J.L., Lukey, G.C., and van Deventer, J.S.J., The Role of Inorganic Polymer Technology in the Development of 'Green Concrete', Cement and Concrete Research, Vol. 37, No. 12, pp. 1590-1597, 2007.

Fernández-Jiménez, A.M, Palomo, A. and López-Hombrados, C., Engineering Properties of Alkali-Activated Fly Ash Concrete, ACI Materials Journal, Vol. 103, No. 2, pp. 106-112, 2006.

Fernández-Jiménez, A.M, Palomo, A. and Puertas, F., Alkali-Activated Slag Mortars Mechanical Strength Behaviour, Cement and Concrete Research, Vol. 29, No. 8, pp. 1313-1321, 1999.

Fernández-Jiménez and Puertas, F., The Alkali-Silica Reaction in Alkali-Activated Granulated Slag Mortars with Reactive Aggregate, Cement and Concrete Research, Vol. 32, No. 7, pp. 1019-1024, 2002.

FHWA, Geopolymer Concrete, CPTP TechBrief, FHWA-HIF-10-014, March 2010.

Flower, D.J.M., and Sanjayan, J.G., Greenhouse Gas Emissions due to Concrete Manufacture, International Journal of Life Cycle Assessment, Vol. 12, No 5, pp. 282-288, 2007.

García-Lodeiro, I., Palomo, A., and Fernández-Jiménez, A., Alkali–Aggregate Reaction in Activated Fly Ash Systems, Cement and Concrete Research, Vol. 37, No. 2, pp.175–183, 2007.

Gartner, E., Industrially Interesting Approaches to “Low- $CO_2$” Cements, Cement and Concrete Research, Vol. 34, No. 9, pp. 1489-1498, 2004.

Gartner, E.M. and Macphee, D.E., A Physico-Chemical Basis for Novel Cementitious Binders, Cement and Concrete Research, Vol. 41, pp. 736-749, 2011.

Hasanbeigi, A., Price, L., and Lin, E., Emerging Energy-Efficiency and $CO_2$ Emission-Reduction Technologies for Cement and Concrete Production: A Technical Review, Renewable and Sustainable Energy Reviews, Vol. 16, No. 8, pp. 6220-6238, 2012.

Henry, M. and Kato, Y., Perspectives on Sustainable Practice and Materials in the Japanese Concrete Industry, Journal of Materials in Civil Engineering, Vol. 24, No. 3, pp. 275-288, 2012.

Josa, A., Aguado, A., Heino, A., Byars E., and Cardim, A., Comparative Analysis of Available Life Cycle Inventories of Cement in the EU, Cement and Concrete Research, Vol. 34, No. 8, pp. 1313-1320, 2004.

Kupwade-Patil, K. and Allouche, E.N., Impact of Alkali Silica Reaction on Fly Ash-Based Geopolymer Concrete, Journal of Materials in Civil Engineering, Vol. 25, No. 1, pp. 131-139, 2013.

Kupwade-Patil, K. and Allouche, E.N., Examination of Chloride Induced Corrosion in Reinforced Geopolymer Concretes, Journal of Materials in Civil Engineering, in press, 2013.

Law, D.W., Adam, A.A., Molyneaux, T. K. and Patnaikuni, I., Durability Assessment of Alkali Activated Slag (AAS) Concrete), Materials and Structures, Vol. 45, No. 1425-1437, 2012.

LinkedIn, http://www.linkedin.com/groups/Will-Geopolymer-Binders-be-next-1516127.S.107056377, accessed 17 April 2013.

Maine, E., Probert, D. and Ashby, M., Investing in New Materials: A Tool for Technology Managers, Technovation, Vol. 25, pp. 25-23, 2005.

Marceau, M.L., Nisbet, M.A., VanGeem, M.G., Life Cycle Inventory of Portland Cement Manufacture, PCA R&D Serial No. 2095b, Portland Cement Association, 2006.

Masanet E., Price, L., de la Rue du Can, S., Brown, R. and Worrell E., Optimization of Product Life Cycles to Reduce Greenhouse Gas Emissions in California. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-110-F, 2005.

McLellan, B.C., Williams, R.P., Lay, J., van Riessen, A. and Corder, G.D., Costs and Carbon Emissions for Geopolymer Pastes in Comparison to Ordinary Portland Cement, Journal of Cleaner Production, Vol. 19, No. 9-10, pp. 1080-1090, 2011.

Miranda, J.M, Fernández-Jiménez, A., González, J.A. and Palomo, A., Corrosion Resistance in Activated Fly Ash Mortars, Cement and Concrete Resaerch, Vol. 35, pp. 1210-1217, 2005.

Neville, A.M., Properties of Concrete, Fourth Edition, John Wiley and Sons, New York, 1996.

Pacheco-Torgal, F., Abdollahnejad, Z., Camões, A.G., Jashidi, M. and Ding, Y., Durability of Alkali-Activated Binders: A Clear Advantage over Portland Cement or an Unproven Issues?, Construction and Building Materials, Vol. 30, pp. 400-405, 2012.

Pan, Z., Sanjayan, J.G. and Rangan, B.V., Fracture Properties of Geopolymer Paste and Concrete, Magazine of Concrete Reaserch, Vol. 63, No. 10, pp. 763-771, 2011.

Perera, D.S., Geopolymers: Low Energy and Environmentally Sound Materials, in Global Roadmap for Ceramic and Glass Technology, S. Friedman (ed) American Ceramic Society, pp. 623-634, 2007.

Petermann, J.C., Saeed, A. and Hammons, M.I., Alkali-Activated Geopolymers: A Literature Review, Air Force Research Laboratory, AFRL-RX-TY-TR-2010-0097, 2010.

Reddy, D.V., Edouard, J.B. and Sobhan, K., Durability of Fly Ash-Based Geopolymer Structural Concrete in the Marine Environment, Journal of Materials in Civil Engineering, Vol. 25, No. 6, pp. 781-787, 2013.

Reid, J. M., Recycling in Transport Infrastructure, Proceedings of the Institution of Civil Engineers, Transport, Vol. 153, No. 4, pp. 255–262, 2002.

Russell, J.S., Anderson, S.D., Trejo, D. and Hanna, A.S., Construction Engineering and Management Research Program, NCHRP Web Document 51, November 2002.

Sagoe-Crentsil, K., Brown, T. and Taylor, A., Creep Behaviour and Drying Shrinkage Performance of Steam-Cured Geopolymer Concrete, Concrete in Australia, Vol. 38, No. 3, pp. 28-32, 2012.

Sarker, P.K., Bond Strength of Reinforcing Steel Embedded in Fly Ash-Based Geopolymer Concrete, Materials and Structures, Vol. 44, pp. 1021-1030, 2011.

Shayan, A. Specification and Use of Geopolymer Concrete in the Manufacture of Structural and Non-Structural Components, Austroads Report, Austroads Project No. TS1835, 2013.

Stengel, T., Reger, J. and Heinz, D., Life Cycle Assessment of Geopolymer Concrete – What is the Environmental Benefit?, Concrete Institute of Australia Conference, 2009.

Transportation Research Board, Research Agenda for Transportation Infrastructure Preservation and Renewal, Reports from a Conference, Washington, D.C., November 12–13, 2009.

Turner, L. and Collins, F., Geopolymers: A greener alternative to Portland cement?, Concrete in Australia, Vol. 40, No. 1, pp. 49-56, 2012.

Van Deventer, J.S.J., Provis, J.L. and Duxson, P., Technical and Commercial Progress in the Adoption of Geopolymer Cement, Minerals Engineering, Vol. 29, pp. 82-104, 2012.

Yang, K-H, Song, J-K., and Song, K-L., Assessment of $CO_2$ Reduction of Alkali-Activated Concrete, Journal of Cleaner Production, Vol. 39, No. 1, pp. 265-272, 2013.

Weil, M., Dombrowski, K., Buchwald, A., Life-Cycle Analysis of Geopolymers, in Provis, J.L., Van Deventer, J.S.J. (Eds.), Geopolymers: Structures, Processing, Properties and Industrial Applications. Woodhead Publishing Limited, Cambridge, England, pp. 194-210, 2009.

Witherspoon, R., Wang, H., Aravinthan, T. and Omar, T., Energy and Emission Analysis of Fly Ash Based Geopolymers, Proceedings of SSEE International Conference, Society for Sustainable and Environmental Engineering, Melbourne, 2009.

Worrell, E., Galitsky, C. and Price, L., Energy Efficiency Improvement Opportunities for the Cement Industry, LBNL-72E, January 2008

Zhao, R. and Sanjayan, J.G., Geopolymer and Portland Cement Concretes in Simulated Fire, Magazine of Concrete Research, Vol. 63, No. 3, pp. 163-173, 2011.