Pathways and barriers for acceptance and usage of geopolymer concrete in mainstream construction

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ABSTRACT

Geopolymer [low carbon] concrete offers potential advantages such as structural performance, reduced greenhouse gas emissions, and acid and fire resistance. However, despite these advantages widespread commercial use of geopolymer concrete in the construction industry has encountered numerous technical, economic and institutional barriers. With increasing concerns regarding climate change, designers are keen to use alternatives to ordinary Portland cement-based concrete, but face uncertainties regarding properties, performance and lack of compliance with AS 3600 and related standards.

This paper describes ongoing work performed under the Cooperative Research Centre for Low Carbon Living and $3.1 million funded project to identify pathways and barriers for the acceptance and usage of geopolymer concrete in mainstream construction.

Current definitions of concrete and the ways in which concrete is commonly specified are examined in order to find potential modifications to include geopolymer concrete. An industry survey was performed and this identified barriers specific to geopolymers and potential actions to overcome raised issues. Lessons from successful introduction of other alternative materials to the construction industry are also considered.

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 (http://www.lowcarbonlivingcrc.com.au/) 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 adoption of low CO2 emission concrete and contribute to reduction of emissions in the built environment. The objectives to this paper 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 CO2 concrete, specifically geopolymer concrete, can be surmounted.

CURRENT DEFINITIONS AND REQUIREMENTS OF CONCRETE IN STANDARDS AND SPECIFICATIONS

Alternatives to Portland cement concrete are being explored as a means of reducing CO2 emissions associated with construction (1). These alternatives include alkali-activated slag and fly ash to form aluminosilicate based binders or "geopolymers". In order to better understand how alternative concretes such as geopolymer materials may be integrated into existing standards and practices, it is useful to examine the conventional definitions of concrete. Traditionally, the term "concrete" is used in the engineering field to describe material using Portland cement as the binder. The definitions of concrete in commonly used standards and guides are summarised in Table 1.

Organisation/Standard/Document	Definition
AS 3600 – 2009 "Concrete Structures", AS 1379 – 1997 "Specification and Supply of Concrete", AS 5100.5 – 2004 "Bridge Design Part 5: Concrete" and AS 3735- 2001 "Concrete Structures for Retaining Liquids"	Mixture of cement, aggregates and water, with or without the addition of chemical admixtures.
CCAA/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 CT-13 "ACI Concrete Terminology" 2013	Concrete: mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials.
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.

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 CT-13 Standard on Concrete Terminology produced in January 2013 uses the term “hydraulic cement”. Hence, there has been a change in definition from ACI 116R-00
- ACI CT-13 has 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. 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.

In addition to the standards considered above, construction projects within Australia may follow state authority specific requirements. This is particularly the case for transportation infrastructure. Most Australian State specifications refer to AS 1379 for the definition of concrete and require that cement complies with AS 3972. For example VicRoads (State of Victoria Road Transport Authority)

- 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.

Details of the experiences of VicRoads with geopolymer concrete have been described (2). 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 more widespread use of geopolymer concrete.

Specification of concrete for a construction project typically calls for a mix design and/or particular properties. State transportation authority specifications designate mix design limits and required properties for different grades of concrete. Engineers are, therefore, familiar with specifying parameters such as minimum cementitious content, maximum water/cementitious material ratio and minimum 28 day compressive strength. Thus, transition to alternative concretes would be facilitated by use of similar and appropriately modified terminology.

PROPERTY REQUIREMENTS

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. Mechanical and physical properties for conventional concrete are well-established. Therefore, adoption of geopolymer concrete for structural applications will necessitate understanding of behaviour and identification of any substantial differences from current design assumptions. Furthermore, durability properties such as chloride diffusion coefficient, carbonation coefficient and sulphate resistance require consideration in order to comply with AS 3600 durability design.

CURRENT DEVELOPMENTS IN RECOMMENDED PRACTICES AND STANDARDS FOR GEOPOLYMER CONCRETE

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 (3). This document provides background information on geopolymer chemistry and materials and properties of geopolymer concrete. Recommendations on modification to current standards are given in the document.

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 fly 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 program.

ASTM Committees C01 (Cement) and C09 (Concrete and Concrete Aggregates) have been 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 CO2 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 typically associated with regulatory or institutional issues, risk-averse decision makers or lack of flexibility in standards and specifications rather than technical barriers.

PRIOR ASSESSMENTS

Several authors have highlighted technical, regulatory, economic and supply chain barriers specific to widespread use of geopolymer concrete. Examples include (4):

- 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

It has also been stated that (5) “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 has also been considered (6). 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 were identified as impediments to acceptance of geopolymers (6).

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 (7). 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 required

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

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 associated greenhouse gas emissions. There is also variability in published greenhouse gas data depending on the raw materials, transportation, curing and calculation methodology (8, 9). Conflicting emission data is regarded as detrimental to adoption of geopolymer concrete.

INDUSTRY SURVEY ON BARRIERS

A survey consisting of six questions was undertaken to obtain input from representatives of the concrete and affiliated industries within Australia. Participants were asked to identify barriers to the implementation of geopolymer concrete and provide opinion on potential pathways for overcoming these barriers. There were 42 total respondents to the survey and 40-42 responses to each question. The results for the first section of the survey are presented in the figures below. Full details of the survey, including the additional written comments, will be presented in a final report for the CRC (http://www.lowcarbonlivingcrc.com.au/).

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.

Respondents 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.

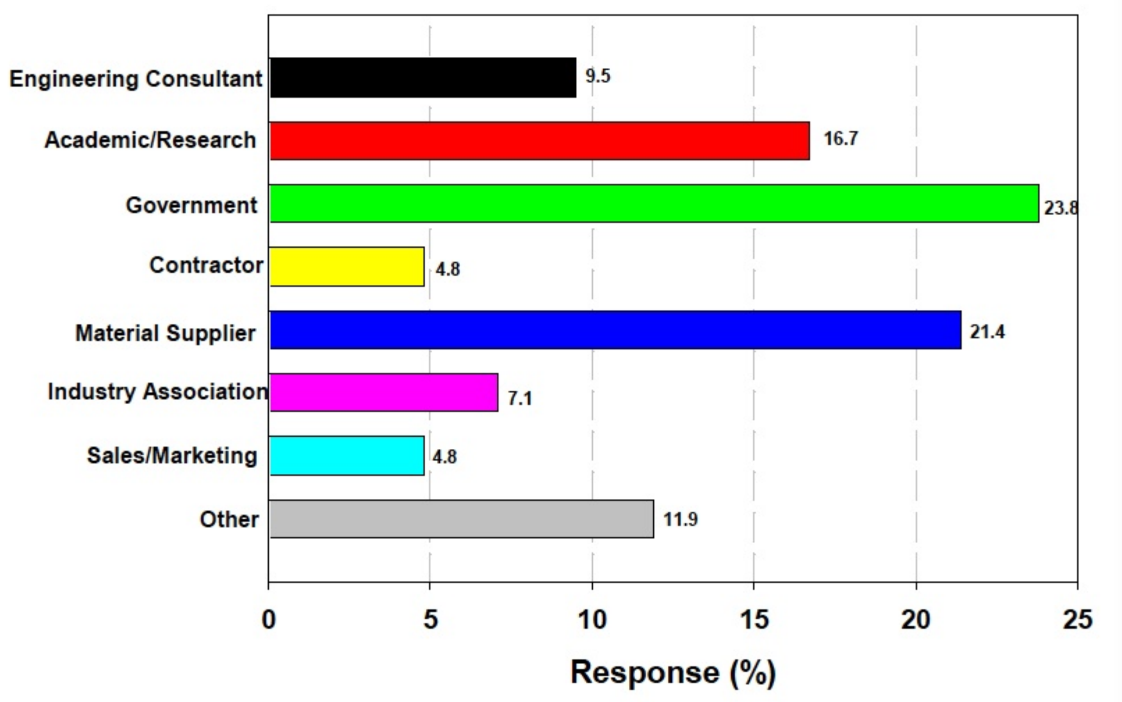

Figure 1. Responses to “What is your primary role? (Tick one only)”.

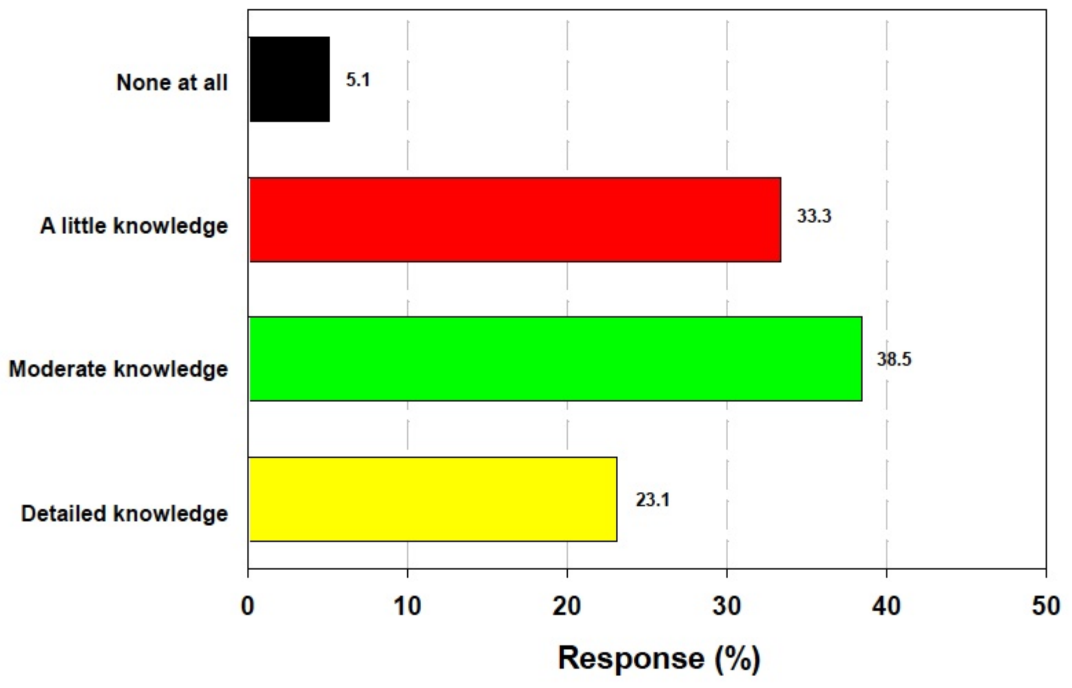

Figure 2. Responses to “What is your familiarity with geopolymer concrete? (Tick one only)”

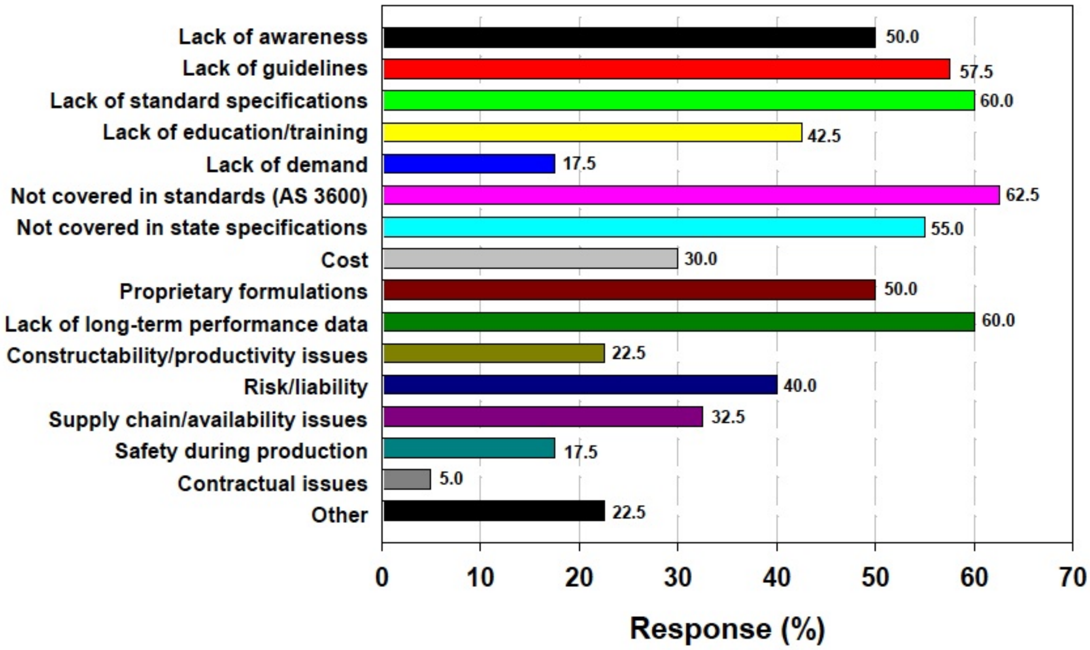

Figure 3. Responses to "What do you think are the barriers to widespread implementation of geopolymer concrete? (Tick all that apply)".

POSSIBLE PATHWAYS FOR GEOPOLYMER CONCRETE

Greater acceptance of geopolymer concrete requires that concerns and issues are addressed in a thorough and acceptable manner. In summarising the future of low CO2 cements, the following was stated (1): *"Clearly, if any alternative cementing system is ultimately to have a real impact on global CO2 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.

Specific to geopolymer concrete, strategic development of standards, particularly cement and concrete standards, has been identified as being pivotal to commercialization (4). Working with relevant stakeholders was proposed as a means of achieving this. Other strategies included securing supply chain of materials, large scale demonstration and industry projects and development of specific durability tests (4). 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 (4).

Other authors (5) recommended the development of performance-based standards for greater acceptance of low CO2 concrete, along with acceptance by consulting engineers. 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. 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. Inclusion of geopolymers in VicRoads standards represents significant progress in this regard.

INDUSTRY SURVEY ON PATHWAYS AND APPLICATIONS

The industry survey performed as part of the CRC work 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.

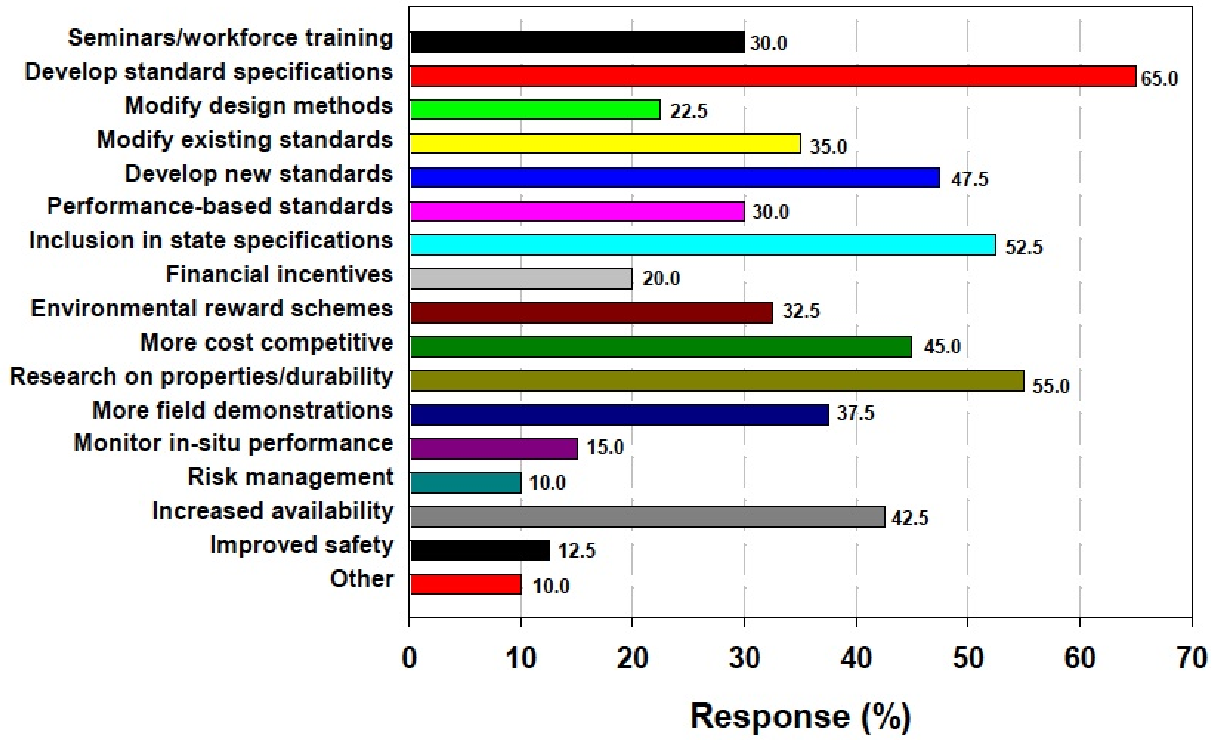

Figure 4. Responses to "What actions do you think should be taken to overcome the barriers to implementation of geopolymer concrete? (Tick all that apply)"

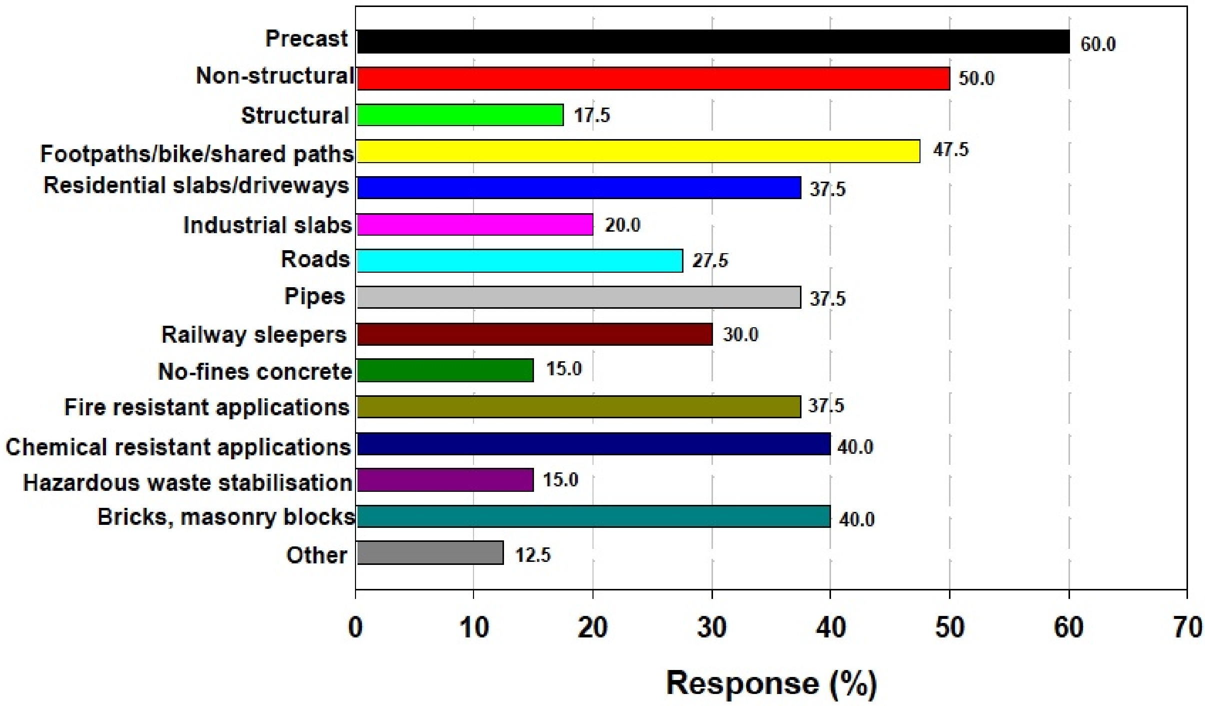

Figure 5. Responses to "What applications do you think offer the highest volume use of geopolymer concrete in the near future? (Tick all that apply)".

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 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 (30.0-37.5%). 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

These actions should be accompanied by ongoing education and training, field demonstrations, cost reductions and greater availability. Issues relating to product variability, intellectual property, conflicting greenhouse gas data, and control by cement and concrete suppliers also need to be addressed.

In the near-term, 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.

EXAMPLES OF PATHWAYS FOR OTHER MATERIALS

New and innovative materials tend to have a long period of gestation (typically around 20 years) before widespread acceptance and substitution are achieved (10). For materials proposed for substitution into a particular application, performance and cost are key factors. Materials with enhanced performance but higher cost can benefit from information on how the market values that performance (10). In the case of geopolymer concrete, costs are predicted to be higher than conventional concrete under current availability (8). Therefore, overcoming the costs in terms of performance requires analysis of the importance of superior properties (e.g., fire or acid resistance) and greenhouse gas reduction to the construction industry and greater dissemination of potential benefits to end users.

The TRB research agenda (11) proposed actions to address specific barriers to implementation of new and innovative materials and technologies in the transportation industry. Many of these actions are similar to those recommended for geopolymer concrete and include outreach to raise awareness, education and workforce training, development of new or modified standards and specifications, development of performance-based standards and specifications and dissemination of best practices.

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 the US Department of Energy's 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 versatility.

BNL's work on polymer concrete comprised:

- 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.

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, particularly from ACI Committee 440. 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.

CONCLUSIONS

Alternative, low CO2 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 geopolymers 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.

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