COMMERCIALISATION OF GEOPOLYMER CONCRETE IN AUSTRALIA

D.G. BRICE; J.S.J. VAN DEVENTER

Department of Chemical & Biomolecular Engineering, University of Melbourne, Victoria 3010

Zeobond Pty Ltd, P.O. Box 23450, Docklands VIC 8012, Australia

ABSTRACT

Alkali-activated 'geopolymer' concrete under the trade name E-Crete^{TM} has been commercialised in Australia. Interest and market demand for the technology continue to grow rapidly, with the increasing engagement and environmental awareness of manufacturers, end-users as well as government. E-Crete^{TM} is not based on Ordinary Portland Cement (OPC) and is instead made from fly ash and blast furnace slag with an alkaline activator. Life cycle analysis of the binder shows an 80% reduction in CO_2 emissions when compared to OPC; this remains the main driver for commercial growth.E-Crete^{TM} is achieving approval from regulatory authorities. VicRoads, the roads authority of the State of Victoria in Australia, has included E-Crete^{TM} in its specification for general concrete paving and non-structural use in footpaths, kerbs and guttering. Progress has also been made through a RILEM Technical Committee to establish the framework for a performance standard for alkali-activated concrete. This paper outlines the CO_2 emissions challenge for OPC and the reasons why geopolymers offer an alternative. The process employed in the commercialisation of E-Crete^{TM} is discussed with particular attention given to the initial market challenges, strategies implemented to overcome them and considerations for future growth.

KEYWORDS:

Alkali-activated; Geopolymer; Commercialisation

INTRODUCTION

As a result of many years of research into its reaction mechanisms, property development and durability, OPC has become accepted technically as the only principal binder with which to make concrete (Scrivener and Kirkpatrick, 2008). This combined with attributes of low use cost, established infrastructure and widespread availability of raw materials, have led to the market dominance of OPC.

OPC based concrete is the most widely used construction material and is second only to water as the most used commodity by mankind today (Aïtcin, 2000). Global cement production is an estimated 2.6 billion tonnes (Freedonia Group, 2009) and contributes between 5-8% of global man made CO_2 emissions (WWF-Lafarge Conservation Partnership, 2008; Scrivener and Kirkpatrick, 2008). Forecasts undertaken in 2006 predicted that cement production will grow to 5 billion tonnes by 2030 (WWF-Lafarge Conservation Partnership, 2008). This projected growth is driven by rapidly increasing demand for advanced civil infrastructure in China, India, the Middle East and the developing world (Taylor et al., 2006).

In 2005 cement production (total cementitious sales including OPC and OPC blends) had an average emission intensity of 0.89 with a range of 0.65 to 0.92 tonnes CO_2 per tonne of cement (International Energy Agency, 2007). Emissions are released primarily during clinker manufacture, in which limestone is calcined according to the reaction $CaCO_3 \Rightarrow CaO + CO_2$, releasing carbon dioxide. The reaction also requires kiln temperatures over 1,400^{o}C, which releases CO_2 from the combustion of fossil fuels for energy. There is somewhat limited scope for improvement, with adoption of best practice (increased energy efficiency in production, improved use of blended cements and introduction of carbon capture systems etc.) estimated to be able to reduce average emissions to 0.53 tonnes CO_2 per tonne of cement by 2050 ((WWF-Lafarge Conservation Partnership, 2008; Scrivener and Kirkpatrick, 2008).

The increasing focus on global warming, changing public and consumer preferences for "green" products, and the associated markets in carbon credits, have made a strong case for the use of alternative cements. These binding systems provide the only viable direct opportunity for near term and substantial CO_2 emissions reduction. Calcium aluminate cements, calcium sulpho aluminate cements, super sulphated cements, magnesium oxy carbonate and calcium carbonate cements, all represent binder systems that deliver a significant departure from the traditional chemistry of OPC (Juenger et al., 2011). Most have merit at a laboratory scale, but in one way or another have been demonstrated to be problematic at an industrial scale and remain largely unproven over sufficient length of in-service application. Typically, they are constrained from full scale application by one or more of the following: (a) long term durability data; (b) regulatory standards; (c) industrial and commercial experience; (d) raw material supply chain.

Alkali activated materials (AAM) or 'geopolymers' face similar hurdles, but have a much longer in-service track record (Shi et al., 2006; Van Deventer et al., 2010a;Xu et al., 2008) and are made using predominantly high-volume, widely available industrial wastes, therefore delivering significant reduction in CO_2 emissions (Duxson et al., 2007a). Fly ash and blast furnace slag appear the most promising precursors for large-scale industrial production (Provis et al., 2010). At a laboratory scale it is possible to use volcanic ash, natural pozzolans and calcined clays as source materials, but cost and supply chain constraints make these difficult to implement at an industrial scale (Van Deventer et al., 2012a).

The chemical reaction pathways, microstructure and engineering properties of geopolymer concrete have been reviewed extensively (Davidovits, 2009; Duxson et al., 2007b; Komnitsas and Zaharaki, 2007; Pacheco-Torgal et al., 2008a,b; Provis and Van Deventer, 2009) and it is not the aim of this paper to duplicate such work. It is worth noting however, that geopolymer concrete hardens through a process of dissolution, gelation and polymerisation stages between the alkali and the Al and Si complexes (Duxson et al., 2007b; Xu et al., 2001). The resulting concrete has performance properties similar to those made with OPC (Roy, 1999;Shi et al., 2006).

The fundamental technology of AAM as the reaction between an alkaline source and an aluminosilicate containing precursor was first described by Purdon (1940). Following his initial assessment, the former Soviet Union and China developed alkali activated slags as a way of supplementing shortages in OPC. In the 1960s, Prof Victor Glukhovsky of Kiev, Ukraine was involved in the construction of apartment buildings, railway sleepers, road sections, pipes, drainage and irrigation channels, flooring for dairy farms, pre-cast slabs and blocks, using alkali activated blast furnace slag (Shi et al., 2006;Rostoyskaya et al., 2007). Subsequent studies have shown that these structures have high durability (Xu et al., 2008).

In the 1980s, Joseph Davidovits in France, patented many formulations for niche applications (Davidovits, 1982), and first proposed the name 'geopolymer' (Davidovits, 2009).AAM based materials have been used in applications in Europe, the Americas and the Asia pacific region (Juenger et al., 2011). Despite the exponential growth of research papers in this field over recent years, there are few examples of translating this investment at a laboratory scale into commercialisation (Van Deventer et al., 2012a).

Geopolymers (Davidovits, 1991) in this review are classified as a subset of AAMs (Figure 1) where the binding phase is almost exclusively aluminosilicate based and very highly co-ordinated (Duxson et al., 2005, Provis et al., 2009). AAM more broadly refers to any binder system derived by the reaction of an alkaline salt (solid or dissolved) with a solid silicate precursor material (Buchwald et al., 2003; Shi et al., 2006). For example, AAM includes binder systems such as alkali activated slags and lime pozzolan/slag cements, while geopolymers are more specifically alkali activated pozzolan cements (Shi et al., 2011).

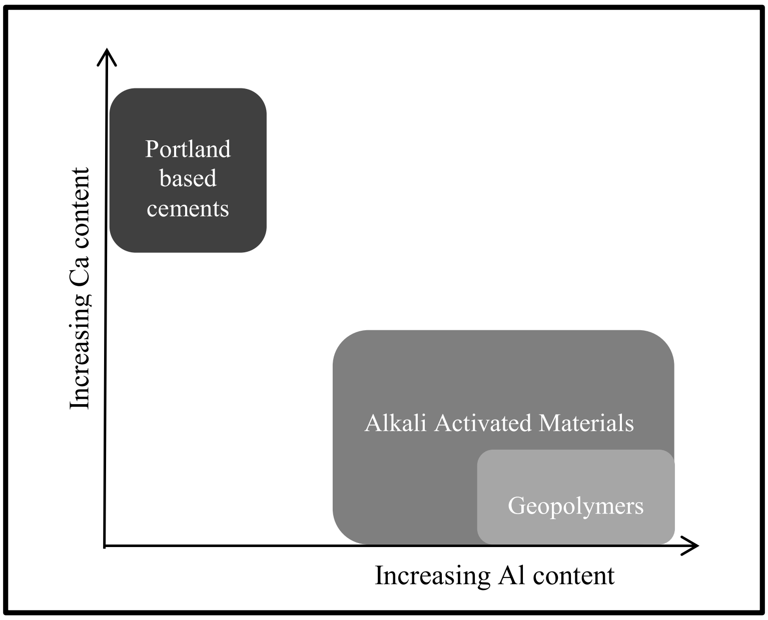

Figure 1 – Classification of different subsets of AAMs, with comparisons to OPC - Adapted from Van Deventer et al. (2010a)

The global commercial uptake of alkali activated 'geopolymer' technology has been limited to date. This paper will outline the recent product development and market validation of E-Crete^{TM} using case studies with specific focus on how key technical, regulatory and industry barriers have been overcome during commercialisation of AAM concrete in Australia.

COMMERCIALISATION OF AAM CONCRETE

Zeobond, a Melbourne-based company, has built production facilities and is supplying AAM concrete, E-Crete^{TM} to the local market. E-Crete^{TM} utilises for its binder a blend of fly ash and blast furnace slag, with combinations of commercially available, alkaline activating components including silicates, carbonates, hydroxides and aluminates. Combinations of activators are selected according to the desired performance properties of the product.

A commercial life cycle analysis comparing E-Crete^{TM} binder with OPC blends available in Australia was conducted by the NetBalance Foundation, Australia, in 2007. The binder-to-binder comparison showed an 80% reduction in CO_2 emissions. A 60% reduction was achieved for E-Crete^{TM} compared to Portland cement based concrete, as the energy cost of aggregate production and transport was equivalent for the two materials (NetBalance Foundation, 2007).

The use and application of OPC based products have been advanced and refined over many decades. This provides the construction industry with a high degree of confidence that the product is fit for purpose. AAM concrete, as a product that is intended to commercially compete with OPC concrete, must prove that it can perform equivalently in terms of cost, form and function, while delivering significant reductions in CO_2 emissions. Figure 2 depicts the process of translating research and development (R&D) to project delivery, end market and commercial use, and is intended to highlight the interdependency of the stages involved.

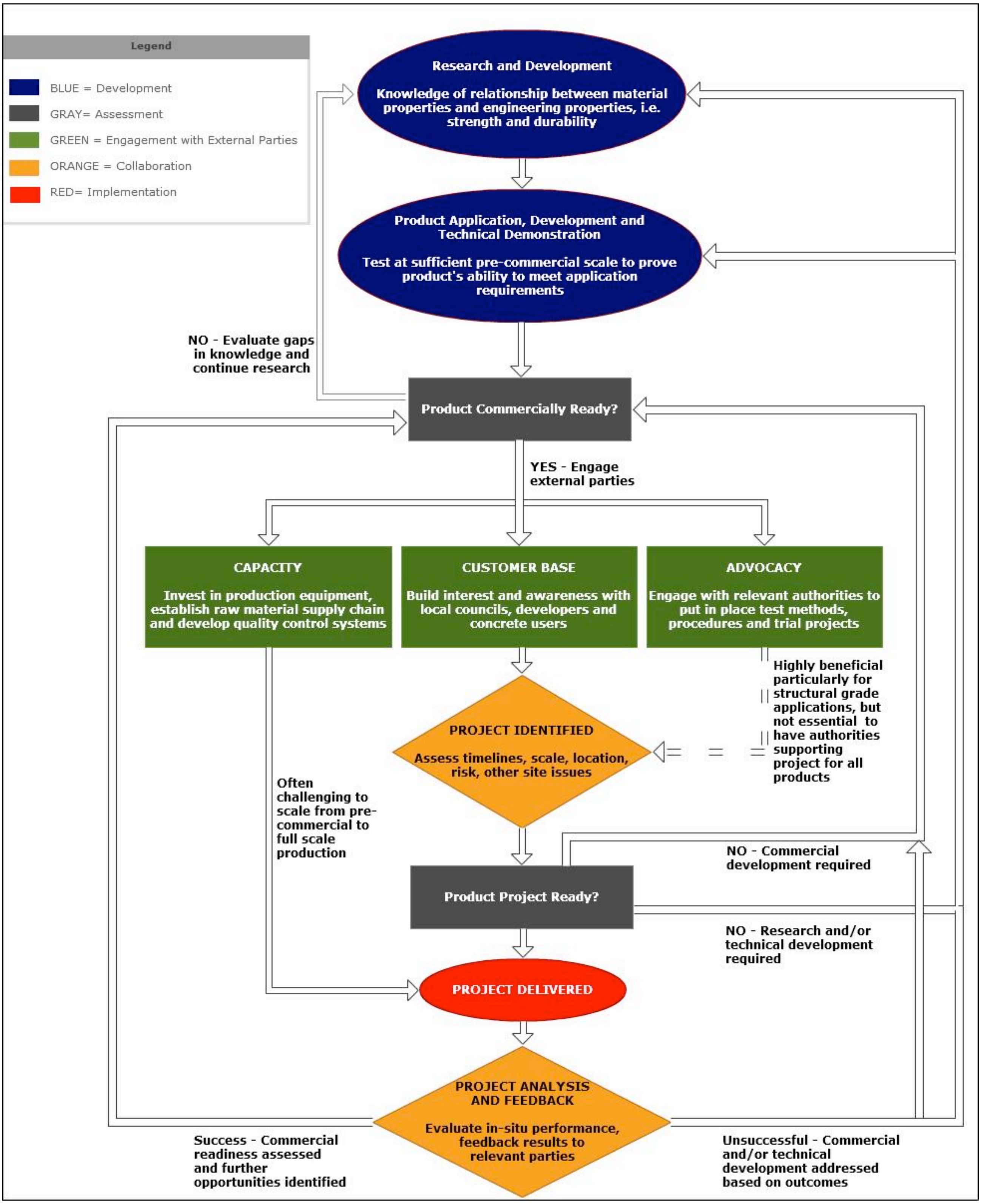

Figure 2 – Flow diagram for commercialisation of geopolymer cement and concrete (Van Deventer et al., 2012a)

R&D is often closely tied to commercial development in the field of AAM (Figure 2, Development). Leading-edge scientific research remains critical to enhancing the performance and utility of AAM concretes. It provides fundamental understanding of reaction mechanisms, gel chemistry, phase formation, reaction kinetics and microstructure of the binder. This knowledge then feeds the practical advancement of the rheological, engineering and durability properties of the building material.

The combination of R&D and access to industrial scale, production equipment provide a starting platform for the development and control of the system in 'real world' applications. In 2007, Zeobond built the world's first concrete batch plant dedicated solely to the demonstration and production of AAM concrete in Campbellfield, Melbourne. At this scale, many additional factors such as placement conditions, raw material quality control, product robustness and end user satisfaction, become critical.

Zeobond has deemed it essential to sign license agreements with large independent concrete manufacturers, with the aim of broadening E-Crete^{TM} distribution, thus maximising the use of products in different applications and locations. Concrete manufacturers typically first engage with the technology via in-house field trials driven by a specific application (Figure 2, Assessment).The initial trials enable an assessment of handling parameters including workability, finish ability, curing requirements as well as early strength. Visual and tactile engagement with the product at this stage is notably important. This interaction builds confidence that AAM concrete 'behaves' similarly to OPC concrete and that typical end-user requirements can be met. E-Crete^{TM} has been demonstrated at industrial scale in the USA, United Arab Emirates, China and Australia in applications such as blocks, pits, pipes, panels, tunnel segments and beams.

Pre-commercial, independent accredited testing has proven critical to demonstration of product performance to the market. For non-structural concrete (footpath, driveways, kerb and channel etc.), assessment typically includes density, yield, air content, slump, set time, compressive strength (early and ultimate) and shrinkage. Additionally, for higher strength and structural grade concretes (beams, tunnel segments, pipes etc.),tests may include flexural and tensile strength, acid, chemical and fire resistance, water permeability, carbonation, sorptivity, creep, steel protection and numerous others. Knowledge and insight gained from this advanced testing are continuously fed back into the product development cycle and stimulate further research.

Transforming successful product trials into project delivery requires the establishment of a customer base, the scale up of capacity and engagement from relevant regulatory authorities (Figure 2, Engagement with External Parties). Customers prior to purchase require a level of surety that concrete alternatives are able to perform under the prevailing environmental conditions. This includes the ability to handle the loads for which they are specified, and continue to perform for the life of the asset. In most cases, the customer will seek compatibility with existing market practices, process and handling requirements as well as test results from externally verified sources.

The preference of many customers is to first use AAM concrete in low risk applications. Risk is defined by the level of perceived consequence in financial, reputational and operational terms. Preferred projects have flexible project timelines, are readily accessible and consequences of failing to meet performance targets, such as compressive strength, have low impact. Progression to higher risk applications requires the engagement of regulatory authorities, engineers and specifiers. These parties typically prefer to take a step-wise approach towards the development of standards and commercial adoption, as outlined by Van Deventer et al. (2012b).

E-Crete^{TM} has generated interest through tightly focused education of local councils, government authorities, corporations, project developers and architects (Figure 2, Collaboration). The consistent strategy of this process has been to highlight the CO_2 benefit and alleviate concerns or potential misconceptions of the market stakeholders. Successful product education builds confidence in product performance and in turn, creates project and technology advocates who further raise awareness.

Demonstration coupled with independent evaluation by regulatory authorities can provide substantial confidence to the market and moreover, become an enabler for progress. E-Crete^{TM} for example, has been used by VicRoads, the Victorian government organisation responsible for managing Victoria's road network (Figure 2, Implementation). Projects conducted include 55 MPa pre-cast panels, 40 MPa retaining walls, 32 MPa concrete pavement works and 25 MPa footpath. VicRoads is now actively involved in developing durability standards for E-Crete^{TM} to be used in VicRoads' own specifications, including structural applications and recently approved E-Crete^{TM} grades 20, 25 and 32 MPa in the specification for general concrete paving and non-structural use in footpaths and kerb and guttering (VicRoads, 2010).

Zeobond also continues to work closely with the RILEM (International Union of Laboratories and Experts in Construction, Materials, Systems and Structures) Technical Committee on Alkali-Activated Materials (TC

224-AAM) providing advice about the structure of performance based standards for AAM and the associated testing methods for durability. As outlined by Provis (2012), a global framework for performance based standards for AAM binder and concrete has been developed recently.

With stronger levels of market endorsement and regulatory support, the focus for project delivery shifts substantially away from technical requirements to operational elements of quality control, raw materials supply and delivery. E-Crete^{TM} is currently produced by combining fly ash, slag and alkaline activators together at the concrete batching plant. This requires installation of storage silos and materials handling equipment, site by site quality control to compensate for variations of raw material and a high level of skill from the operators, all of which restrict the scalability and growth capacity of the product. The geographical distribution constraints of E-Crete^{TM} currently affect the scale and location of the projects that can be targeted.

Zeobond has developed an advanced AAM binder where all components are processed into a dry cement powder, similar to that of OPC (Van Deventer et al., 2010b). The centralised production of a single component is highly advantageous as many of the quality control, distribution and supply chain challenges of the existing process can be directly addressed. Constructing such facilities is however, capital intensive and requires significant market drivers for AAM concretes (synthesised via the existing process) to justify investment.

TESTING FOR DURABILITY

Proving the durability of AAM concretes in 'real world' applications remains the most significant obstacle to recognition in standards for structural grade concretes and hence, commercial adoption of the technology. Despite use of AAM concretes since the 1940's, the availability of high quality in-service data and detailed investigation to prove durability and long-term stability is limited.

Accelerated concrete durability tests usually involve exposure of small samples to aggressive conditions for short periods of time, with examples including chloride and sulphate exposure, freeze-thaw cycling and carbonation testing. The data obtained from these types of tests are then applied to a predictive model based on historical observations of OPC based concrete and/or engineering principles and used to predict the service life of the concrete. The deficiency of applying tests and models designed for OPC concrete to an alternative binder system is that excellent or poor results may or may not be relevant for prediction of in-service life. Identifying methods to accurately estimate durability performance of AAM concrete remains an area open to active academic research by the authors and co-workers.

Historically, adoption of new binder materials in the construction industry has been a slow process. Fly ash, slag and silica fume are now widely accepted as quality supplementary cementitious materials for OPC concrete but took several decades to truly establish market presence. For more rapid acceptance, AAM concretes require a combination of: (a)broad scale, field experience in low risk applications;(b) advanced trial experience in structural applications;(c) international engagement on performance standards and (d) quality research focused on innovative methods to analyse and predict long term in-service performance based on accelerated durability test methods.

CONCLUSIONS

The main commercial driver for AAM concrete in Australia continues to be the reduction in CO_2 emissions when compared to OPC. The progress from research and development through to full scale project delivery is technically challenging but proven achievable. Expansive future growth of the technology is reliant upon increased regulatory and industry participation and the development of methods for predicting service life based on accelerated tests.

High profile application projects in Australia have demonstrated the need for a broad range of stakeholder engagement to enable commercialisation of AAM. Most notably, such stakeholders include manufacturers, regulatory bodies, government, end users, architects, developers and engineers.Barriers remain with respect to the establishment of enduring market access to a supply chain for key raw materials (i.e. fly ash, slag, alkaline activators). Delivering a wider distribution network for supply of AAM concrete requires further capital investment and political support.

ACKNOWLEDGMENTS

This work has been funded by Zeobond Pty Ltd and the Australian Research Council (ARC) through an ARC Linkage Project grant awarded jointly with John Provis. Authors JSJvD and DGB hold financial interest in Zeobond Pty. Ltd., a producer of alkali-activated cements and concretes.

REFERENCES

Aïtcin, P.C. 2000. "Cements of yesterday and today; Concrete of tomorrow". Cement and Concrete Research 30 1349-1359.

Buchwald, A., Kaps, C. and Hohmann, M. 2003. "Alkali-activated binders and pozzolan cement binders - complete binder reaction or two sides of the same story?". In: Proceedings of the 11th International Conference on the Chemistry of Cement, pp. 1238–1246. Durban, South Africa.

Davidovits J. 1982. "Mineral polymers and methods of making them".U.S. Patent 4,349,386.

Davidovits, J. 1991. "Geopolymers - inorganic polymeric new materials". Journal of Thermal Analysis 37(8) 1633–1656.

Davidovits, J. 2009. "Geopolymer Chemistry and Applications". 2^{nd}Ed.InstitutGéopolymère, Saint-Quentin, France.

Duxson, P., Provis, J.L., Lukey, G.C., Separovic, F. and Van Deventer, J.S.J. 2005."^{29}Si NMR study of structural ordering in aluminosilicate geopolymer gels". Langmuir 21(7) 3028–3036.

Duxson, P., Provis, J.L., Lukey, G.C. and Van Deventer, J.S.J. 2007a. "The role of inorganic polymer technology in the development of 'Green concrete'". Cement and Concrete Research 37(12) 1590-1597.

Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A. and Van Deventer, J.S.J., 2007b. "Geopolymer technology: The current state of the art". Journal of Materials Science 42(9) 2917-2933.

Freedonia Group. 2009. "World Cement to 2012".http://www.freedoniagroup.com/World-Cement.html.

International Energy Agency.2007. "Tracking industrial energy efficiency and CO_2emissions - Executive Summary". Retrieved at http://www.iea.org/Textbase/npsum/tracking2007SUM.pdf

Juenger, M.C.G., Winnefeld, F., Provis, J.L. and Ideker, J. 2011. "Advances in alternative cementitious binders". Cement and Concrete Research 41(12) 1232-1243.

Komnitsas, K. andZaharaki, D. 2007. "Geopolymerisation: A review and prospects for the minerals industry". Minerals Engineering 20(14) 1261-1277.

NetBalance Foundation. 2007. "Carbon emission life cycle assessment of geopolymer concrete". Melbourne, Australia.

Pacheco-Torgal, F., Castro-Gomes, J. and Jalali, S. 2008a."Alkali-activated binders: A review. Part 1.Historical background, terminology, reaction mechanisms and hydration products". Construction and Building Materials 22(7) 1305-1314.

Pacheco-Torgal, F., Castro-Gomes, J. and Jalali, S., 2008b."Alkali-activated binders: A review. Part 2.About materials and binders manufacture". Construction and Building Materials 22(7) 1315-1322.

Purdon, A.O. 1940. "The action of alkalis on blast-furnace slag". J SocChemInd- Trans Commun 59 191-202.

Provis, J.L. and Van Deventer, J.S.J. (eds). 2009. "Geopolymers: Structures, Processing, Properties and Industrial Applications".Woodhead Publishing, CRC Press, Cambridge U.K., 454 pp.

Provis, J.L., Rose, V., Bernal, S.A. and Van Deventer, J.S.J. 2009. "High resolution nanoprobe X-ray fluorescence characterization of heterogeneous calcium and heavy metal distributions in alkali activated fly ash". Langmuir 25(19) 11897–11904.

Provis, J.L., Duxson, P. and Van Deventer, J.S.J. 2010. "The role of particle technology in developing sustainable construction materials". Advanced Powder Technology 21(1) 2-7.

Provis, J.L. 2012. "Alkali-activated binders and concretes: The path to standardization".ASTM Symposium on Geopolymer Binder Systems, San Diego, CA.

Rostovskaya, G., Illyin, V. And Blazhis, A. 2007. The service properties of alkaline concretes. Alkali Activated Materials – Research, Production, and Utilisation.ČeskáRozvojováAgenturao.p.s., Prague. 593-610 pp.

Roy, D.M. 1999. "Alkali-activated cements: Opportunities and challenges". Cement and Concrete Research 29 249–254.

Scrivener, K.L. and Kirkpatrick, R.J. 2008."Innovation in use and research on cementitious material". Cement and Concrete Research 38(2) 128-136.

Shi, C., Krivenko, P.V. and Roy, D.M. 2006."Alkali-activated cements and concretes". Taylor & Francis, Abingdon, UK, 376 pp.

Shi, C., Fernández Jiménez, A. and Palomo, A. 2011."New cements for the 21st century: The pursuit of an alternative to Portland cement". Cement and Concrete Research 41 750–763.

Taylor, M., Tam, C. and Gielen, D. 2006."Energy efficiency and CO_2 emissions from the global cement industry". International Energy Agency.

Van Deventer, J.S.J., Duxson, P., Brice, D.G. and Provis, J.L. 2010a."Chemical research and climate change as drivers in commercial adoption of alkali activated materials". Waste& Biomass Valorization 1(1) 145–155.

Van Deventer, J.S.J., Feng, D. and Duxson, P. 2010b."Dry mix cement composition, methods and systems involving same". US Patent 7,691,198 B2.

Van Deventer, J.S.J., Brice, D.G., Kilcullen A.R., Provis, J.L. and Bernal, S.A. 2012a."Development, standardization and applications of alkali-activated concretes".ASTM Symposium on Geopolymer Binder Systems, San Diego, CA.

Van Deventer, J.S.J., Provis, J.L. and Duxson, P. 2012b."Technical and commercial progress in the adoption of geopolymer cement". Minerals Engineering 29 89-104.

VicRoads. 2010. Standard Specification Section 703, General Concrete Paving.
http://www.vicroads.vic.gov.au/Home/Moreinfoandservices/TendersAndSuppliers/StandardDocuments.htm

WWF-Lafarge Conservation Partnership. 2008. A blueprint for a climate friendly cement industry: How to turn around the trend of cement related emissions.
http://assets.panda.org/downloads/cement_blueprint_climate_fullenglrep_lr.pdf

Xu, X., Provis, J.L., Van Deventer, J.S.J. and Krivenko, P.V. 2008. "Characterization of aged slag concretes". ACI Materials Journal 105(2) 131-139.