How to overcome technical and commercial barriers to the adoption of alkali activated concrete

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ABSTRACT: Life Cycle Analysis has shown that Alkali Activated Material (AAM) binder can reduce carbon emissions, compared to OPC cement, by at least 80%. One of the main barriers to adoption of AAM is the lack of control over the supply chain of source materials such as fly ash and blast furnace slag. An understanding of market dynamics and the industry value chain is required to push AAM into the well established and conservative construction market. Another barrier is the fact that most concrete standards have been developed on the basic premise that OPC cement will be used. A related issue is the testing protocols for durability, which may or may not suit AAM concrete. Unlike OPC, a long in-service track record of AAM is absent. Consequently, research and theoretical insight must be used instead to justify the validity of applying existing or modified durability testing methodology to AAM concrete.

1. INTRODUCTION

Concrete made from Ordinary Portland cement (OPC), including its blends with mineral admixtures, is second only to water as the commodity most used by mankind today. Global OPC production in 2008 was around 2.6 billion tonnes (Fredonia Group, 2009), corresponding to around 11 billion tonnes per annum of concrete (Mehta and Monteiro, 2006). The cement industry contributes conservatively 5-8% of global carbon dioxide (CO₂) emissions (WWF-LaFarge Conservation Partnership, 2008; Scrivener and Kirkpatrick, 2008), mainly through decomposition of limestone and combustion of fossil fuels during cement production. Grinding and transport are lesser, but also significant, contributors to the environmental footprint of the cement industry. The rapidly increasing demand for advanced civil infrastructure in China, India, the Middle East and the developing world is expected to expand the cement and concrete industries significantly (Taylor et al., 2006).

With increasing global focus on climate change, the cement industry is gradually coming to acknowledge the fact that meaningful production of alternative binders will form part of a carbon constrained industry, aiding in significantly reducing CO₂ emissions and providing some advantages in performance only offered by these alternative binding systems (Damtoft et al., 2008) Usually the driver for competition in the construction materials industry has been cost reduction, in which case alternative materials starting from a low volume basis can never compete against large scale OPC production. Abatement of CO₂ and technical features are now playing a major role in growth of alternative binder systems.

There are various possible alternatives to OPC technology which have attracted attention in different parts of
the world. Juenger et al. (2011) review the chemistry, characteristics, advantages and disadvantages of these alternative systems in more detail. Calcium sulphoaluminate cements are increasingly being used and studied, and contain binding phases based mainly on hydration products of Klein’s compound (ye’elimite) (Glasser and Zhang, 2001). In addition, there are two major types of alternative binders that have not been commercialised widely, being the alkali activated material (AAM) system, and also magnesium-based systems.

In AAM chemistry, the reactive aluminosilicate phases present in materials such as fly ash, slag, calcined clay or volcanic ash are reacted with alkaline reagents including alkali metal silicates, hydroxides, carbonates, and/or sodium aluminate (Provis, 2009), to form zeolite-like aluminosilicate gel phases of varying (but generally low) degrees of crystallinity. AAM concrete has been shown to be quite resistant to attack by acids and by fire, and does not produce the high reaction heat associated with OPC concrete, which reduces cost and potential cracking issues when the material is placed in large volumes.

Magnesium-based cements (including oxide, phosphate, oxychloride and other specific types of phase assemblage) have been used in niche applications and can also give superior fire resistance, with much lower CO₂ emissions than OPC. Phosphate cements have not been used commercially and require more R&D, but in general the magnesium phosphate system has technical and economic limitations compared with AAMs. The focus of this paper will be on the commercial and technical barriers that must be overcome in the establishment of an AAM industry, with particular reference to Zeobond’s development of E-Crete™ technology in Australia.

2. ROLE OF RESEARCH IN THE COMMERCIALISATION OF AAM

The commercial implementation of AAM technology in Australia is currently being driven by multiple teams operating in different parts of the country. The Centre for Sustainable Resource Processing, based in Perth, has been making advances in this area over the past decade and conducted a number of trial pours in recent years. The Melbourne-based company, Zeobond, developed its own pilot-scale production facilities in 2007 and now supplies its concrete, E-Crete™, to major civil infrastructure projects including freeway expansion works and bridge construction and repairs through license. E-Crete™ utilises for its binder a blend of fly ash and ground blast furnace slag, with combinations of proprietary alkaline activating components which are tailored for specific raw materials and products.

There are numerous technical and commercial factors driving the commercial adoption of AAM technology. It is clear that the development of an understanding of the chemistry and mechanisms of geopolymer synthesis is pivotal to the optimal mix design of “green” concretes for large-scale applications in industry. Demand pull, led by a carbon-conscious consumer market, continues to be the key driver for the short term adoption of geopolymer concrete. Counter-balancing this demand driver is the inherent resistance of the civil construction industry to new products, where time and demonstration on relevant industrial scales are prerequisites for practical credibility, as well as the cost implications of non-equitable economies of scale.

A detailed chemical understanding of the properties of AAM binders, in particular in the study of areas such as setting time, workability and durability, plays an enabling role in the commercialisation process. There is now a growing amount of scientific literature exploring the properties of geopolymeric materials on the
laboratory scale. Unfortunately, a large proportion of this information has limited direct value in commercial adoption; geopolymer concrete that performs adequately according to all standards can be synthesised easily in a laboratory, while it is much more difficult to reproduce such performance in a commercially and practically feasible form in real-world applications. Indeed, closing this apparent disparity and gap between the laboratory and the real-world has been the focus of much research conducted by Zeobond. Being able to achieve this has unlocked the commercial value of geopolymer technology.

3. TECHNICAL BARRIERS

One of the reasons for the rapid development of E-Crete™ technology is that key Zeobond staff come from a background in mineral processing, which is directly applicable to the technology of cement and concrete. For example, the phase chemistry of cement and other mineral components (particularly fly ash and slag) is critical in controlling reactivity, and so the accurate understanding of the different glass phases present in AAM raw materials is required to determine the optimal processing method and composition of binder components to be applied to manipulate concrete properties. This is particularly the case for AAM systems, as they rely heavily on reactions involving fly ash and slag particles, which are relatively less reactive than OPC, and more mineralogically diverse. This introduces the need for alkali activation (i.e., an initially high pH in the solution phase, as opposed to the later, autogenous generation of alkaline pore solutions in hydrated OPC) to catalyse the reaction process whereby the precursor particles are partially dissolved to provide nutrients for the binder-forming reactions. Classified fly ash and ground slag available through the cement supply chain are not able to be used straightforwardly with existing alkaline activators to prepare optimal AAM binders, so special preparation of alkaline activators may be warranted. In addition, fly ash and slag (being waste materials) are subject to far more variability, especially when they are obtained from a range of sources, than OPC as a quality controlled product. Therefore, online monitoring and optimisation of activator types and binder components is necessary in the production of consistent, high-quality AAM concretes.

It is important to control the rheology of fresh concrete to enable it to be placed and finished, and the ability to do this without adversely affecting the final properties of the hardened concrete depends primarily on the manipulation of colloidal interactions by the use of chemical admixtures such as superplasticisers. The range of currently commercially available superplasticisers have been developed specifically to suit the complex series of chemical reactions which take place in the OPC system, and so are usually not effective in the AAM system. Moreover, most of the various admixtures used to control slump, surface hydration, air dispersion, water retention, and other properties of the OPC system are less effective in the AAM system. Consequently, there is a need to develop a whole set of new admixtures for the AAM system, which presents a significant challenge for an emerging industry with a lack of scale, but which is still required to compete with the well established OPC industry.

Ground granulated blast furnace slag is widely used to replace part of the binder component in OPC concretes in many parts of the world, giving performance and durability advantages in addition to environmental and (usually) cost benefits. Slow-cooled slags, which tend to be more crystalline and less reactive, are also used as aggregates in some applications. Direct alkali activation of vitreous slags produces “alkali-activated slag binders” (Shi et al., 2006), which are related to geopolymers in terms of the processing
route (alkali activation) used, but which generate a binder which more closely resembles the hydration products of OPC, in that it is comprised of calcium silicate hydrate phases rather than an alkali aluminosilicate gel as is found in geopolymers. Alkali activation also provides the potential for the utilisation of non-blast furnace slags; alternative materials such as ferronickel, steel and phosphorus slags have also been alkali-activated to form usable concretes, at least on a laboratory scale (Shi et al., 2006). The leaching of toxic metal components from some of these slags during activation may prove to be a cause for some concern, but - as is the case for fly ashes - the selection of appropriate waste materials for use as AAM precursors is both important and possible.

At present, AAM concrete is most commonly produced by blending coal ash, slag and alkali activators together in a concrete batching plant. This requires a high level of skill from the operators of the batching plant, which is rarely available in the premix concrete industry. Ash and slag are waste materials of variable composition, so that the concrete mix designs and the added alkanes need to be varied to compensate for these variations in the ash and slag. Such a technology, where the quality control is mainly at the batching plant level, is not scalable on an industry-wide level and has limited appeal in the market, despite the growing market pull for “green” construction materials.

In contrast with this situation, Zeobond has developed a process whereby the various solid materials and activators are processed together to produce a dry cement binder that behaves in a similar way to OPC (Van Deventer et al., 2010). Independent Life Cycle Analysis has shown that the carbon emissions associated with Zeobond’s binder are at least 80% lower than that of OPC. The quality control is hence centralised in the cement binder plant, so that the dry powder can be distributed to various concrete batching plants, as is the case with Portland cement. To a large extent this addresses the supply chain challenges and difficulties in price competition which are inherent when sourcing materials from OPC-related suppliers. The process of establishing such dry binder processing facilities is capital intensive and requires a significant existing market for AAM concretes (synthesised via the existing process) to justify investment.

4. STANDARDS FRAMEWORK

The regulatory framework governing concrete to be utilised in various applications relies on a typical cascade of standards, with application standards referring to concrete standards, and concrete standards referring to standards covering cement and other raw materials. Hence, when considering the regulatory framework for a concrete binder system such as AAM cement or concrete, most of the attention to regulatory aspects should be focused on the cement standards, although some aspects of concrete standards also need to be considered. In general, all of the world’s concrete application, concrete and cement standards are based on two “super” standards, i.e., European Union EN 197 and United States ASTM C150/C595/C1157. For instance, Chinese cement and concrete standards are based heavily on European Union Standards, while Australian standards are based heavily on the American standards.

These standards have been developed over many years, and in collaboration with input from OPC manufacturing companies, with the chemistry and behaviour of Portland-based concretes intrinsically in mind. However, prescriptive standards containing constraints such as “minimum cement content” are increasingly being viewed as excessively prohibitive, even for OPC-based systems. Products such as geopolymer or AAM concrete may not simply be an evolution of existing OPC technology, but instead may
require an entirely different chemical paradigm to understand their behaviour, and may perform entirely acceptably but without conforming exactly to the established regulatory standards – particularly with regard to rheology and chemical composition (Hooton, 2008). This is a significant hindrance to the acceptance of AAM technology. However, by working with all stakeholders, these barriers can be overcome, provided that the intent of regulatory standards is met.

VicRoads, the state roads authority in Victoria, Australia, recently recognised geopolymer concrete as being equivalent to OPC for non-structural applications in a 2010 update to their design specification Section 703. Zeobond is working with VicRoads to also recognise geopolymer concrete for structural applications in Section 620. Zeobond’s E-Crete is already used in VicRoads structural projects, and by local councils and housing developers in sub-divisional works and slabs; applications which represent approximately 70% of all concrete usage. These large scale applications are pivotal to the process of gradually convincing standards authorities to accept AAM concrete.

5. TESTING FOR DURABILITY

The question of whether geopolymer or AAM concretes are durable remains the major obstacle to recognition in standards for structural concrete, and hence commercial adoption. A material such as AAM, which has been subjected to detailed investigation only recently, cannot possibly have the availability of decades of in-service testing and durability data to prove its long-term stability. Most standard methods of testing cement and concrete durability involve exposing small samples to very extreme conditions – in particular highly concentrated acid or salt solutions - for short periods of time. These results are then used to predict how the material will perform under normal environmental conditions over a period of decades or more. In some of these predictive models, engineering concepts including mass transport through porous media, reaction kinetics and particle packing are used. However, the key shortcoming of this approach to “proving” durability is that it can only provide indications of the expected performance, rather than definitive proof. Therefore, there has been a very slow process of adoption of new materials, as one may need to wait up to 20-30 years for real-world verification. Adoption of fly ash and slag in OPC concretes is the prime example, where the use of these supplementary materials was resisted for decades. It is the authors’ experience that asset owners and their insurance companies are willing to use AAM or geopolymer based concrete in low risk applications based on accelerated durability testing. In contrast, higher risk applications such as high rise buildings, which constitute a smaller fraction of the total concrete market, will follow only when the market is comfortable with the real world track record of the material in low risk applications.

Zeobond works closely with various roads authorities in monitoring the performance of in-situ AAM concrete structures and also in developing appropriate test methods for durability. The work conducted by RILEM Technical Committee 224 on AAM provides essential advice to standards authorities about the structure of performance based standards for AAM and the associated testing methods for durability (http://www.rilem.net/tcDetails.php?tc=224-AAM).

As outlined by Provis et al. (2011), there have been a number of studies of chloride diffusion in alkali-activated slag concretes, with the performance of these materials in accelerated chloride penetration tests generally observed to be at least comparable to that of OPC. Zeobond’s E-Crete has been shown repeatedly to have significantly lower chloride diffusion and acceptable freeze-thaw performance compared
with OPC concrete. This excellent performance of AAM concrete is related to the highly refined pore network forming a dense low-calcium C-A-S-H phase (Provis et al., 2011). It is envisaged that advanced techniques such as synchrotron-based nanotomography will ultimately be used to compute transport properties of the AAM gel generated from various mix designs (such as water/binder ratio), and hence changes in durability performance.

6. SUPPLY CHAIN RISKS

Involvement of a competitive and efficient supply chain is essential for the successful scale-up of AAM technology. For instance, granulated blast furnace slag (GBFS) is produced during the production of pig-iron. Although there is a risk that production methods for pig-iron will change and reduce the availability of GBFS, this is not currently viewed as a substantial risk. As demand for GBFS increases, blast furnace operators will invest in rapid cooling slag handling equipment in order to increase the production of GBFS. The further development and industrial adoption of the new CSIRO air-cooled slag granulation method (Jianshani et al, 2010) is important in regions with a shortage of clean water, which is the standard chilling medium. The main risk facing GBFS supply for AAM use is preferential utilisation of GBFS in OPC blends rather than in AAM.

There is a risk that a substantial reduction in world-wide carbon emissions will result in reduced coal fired energy production, and hence reduced availability of coal ash. While there is a global determination to reduce energy dependency on thermal coal, it is more likely that coal combustion will continue to increase in the coming decades, but with some level of carbon capture through sequestration or mineralisation. In any event, only a very small fraction of coal ash is currently used in concrete. A more substantial risk is the well-intended control of coal ash as a hazardous material by, for example the US EPA, which leads to uncertainty in investment in the supply chain of all supplementary cementitious materials.

In economically developed and structurally segmented markets for cementitious materials, distribution networks for slag and fly ash are established, making it uncompetitive or practically impossible to invest in new channels to market. In some cases, even voluminous by-product streams like slag and fly ash are largely utilised or earmarked via long-term option contracts. Due to the rapid increase in demand and production in markets such as China and India, new opportunities for both OPC and AAM supply channels are foreseeable. However, in established markets such as the UK, where fly ash production does not exceed its consumption in cement, the existing market for OPC utilises all of the available fly ash. Despite the increasing number of research papers on AAM, there has been little development of the supply chain channels necessary for scale production, which will continue to limit the wider adoption of AAM technology until this bottleneck is resolved.

7. THE PATH OF COMMERCIALISATION

Figure 1a shows a small section of E-Crete paving completed as part of the Victorian Government upgrade of the Westgate Freeway in Port Melbourne. While small in volume, this project required that the concrete meet all of the technical specifications of the local road authority, VicRoads, the ultimate asset owner, the Port Melbourne City Council, and was approved for use by the construction consortium that included numerous national and multi-national construction companies and engineering firms. This small project demonstrates
the entire process of commercialisation of geopolymer concrete.

Figure 1b shows the installation of 55MPa E-Crete precast panels for VicRoads. This concrete was required to meet the structural concrete code (VicRoads Section 610), unlike the non-structural grade concrete in Figure 1a. Here the level of concrete specification and scrutiny was consistent with bridge design, with the aim of using the highest grade concrete specified by VicRoads as a “stretch target” for trial purposes.

As opposed to focusing on the technical detail of these projects, attention is drawn to the fact that these case studies demonstrate something that is rarely seen in AAM technology, i.e. the vast regulatory, asset management, liability and industry stakeholder engagement process that has been undertaken by Zeobond to commercialise its E-Crete. The shift from the laboratory to the real-world is not a process of scale-up of technology alone. While such technical challenges are sufficient to be insurmountable to many, it is the ability to manage the scale-up of industry participation and acceptance of AAM concrete that provides the core challenge to the future world of an AAM concrete industry.

8. CONCLUSIONS

The fact that all premixed and precast concrete standards are based on an assumption of the use of OPC remains a major obstacle to the commercial adoption of AAM concrete. Even when asset owners and specifiers such as government, architects and design engineers accept the results of durability testing of AAM concrete, the main barrier to entry of AAM into an established market is access to a suitable supply of source materials including fly ash, granulated blast furnace slag and alkaline activators. Significant development of supply chains to accommodate AAM, predominantly in developing markets, is essential to overcome this barrier. This crucial aspect of commercialisation is seldom appreciated by the research community, governments or the ultimate users of concrete. It is important for commercial AAM concrete producers to work closely with research partners to develop testing methods for accelerated durability, especially as longer term in-service testing data become available. Substantial progress has been made in Australia, where the local road authority has recognised AAM concrete for non-structural applications.
9. REFERENCES


