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The role of inorganic polymer technology in the development of 'green concrete'

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Abstract

The potential position of and drivers for inorganic polymers ("geopolymers") as an element of the push for a sustainable concrete industry are discussed. These materials are alkali-activated aluminosilicates, with a much smaller CO_2 footprint than traditional Portland cements, and display very good strength and chemical resistance properties as well as a variety of other potentially valuable characteristics. It is widely known that the widespread uptake of geopolymer technology is hindered by a number of factors, in particular issues to do with a lack of long-term (20+ years) durability data in this relatively young research field. There are also difficulties in compliance with some regulatory standards in Europe and North America, specifically those defining minimum clinker content levels or chemical compositions in cements. Work on resolving these issues is ongoing, with accelerated durability testing showing highly promising results with regard to salt scaling and freeze–thaw cycling. Geopolymer concrete compliance with performance-based standards is comparable to that of most other high-strength concretes. Issues to do with the distinction between geopolymers synthesised for cement replacement applications and those tailored for niche ceramic applications are also discussed. Particular attention is paid to the role of free alkali and silicate in poorly-formulated systems and its deleterious effects on concrete performance, which necessitates a more complete understanding of the chemistry of geopolymerisation for the technology to be successfully applied. The relationship between CO_2 footprint and composition in comparison with Portland-based cements is quantified.

Keywords: Geopolymer; Fly ash; Cement manufacture; Alkali activated cement

1. Introduction

Inorganic polymer concretes, or 'geopolymers,' have emerged as novel engineering materials with the potential to form a substantial element of an environmentally sustainable construction and building products industry [1,2]. These materials are commonly formed by alkali activation of industrial aluminosilicate waste materials such as coal ash and blast furnace slag, and, as will be discussed in detail in this paper, have a very small Greenhouse footprint when compared to traditional concretes. Given correct mix design and formulation development, geopolymeric materials derived from coal ash (Class F and/or Class C) can exhibit superior chemical and mechanical properties to ordinary Portland cement (OPC) [1], and be highly cost effective. A key attribute of geopolymer technology is the robustness and versatility of the manufacturing process; it enables products to be tailor-made from a range of coal ash sources and other aluminosilicate raw materials so that they have specific properties for a given application at a competitive cost. Applications of particular interest at present include low or high strength concretes with good resistance to chloride penetration, fire and/or acid resistant coatings, and waste immobilization solutions for the chemical and nuclear industries. The specific properties of geopolymers which lead to particular suitability in each of these applications will be outlined briefly in this paper.

Despite these key technological attributes, and environmental and cost savings compared to OPC, the main drivers for the uptake of the technology by existing players in the cement and concrete products industry may not form a compelling business case for geopolymer production by these organizations at this time. This is particularly so for large cement companies, where the low profit margins and high financial risk involved with the introduction of a revolutionary (rather than evolutionary) technology in low- and high-strength concrete applications respectively must be taken into account. The successful adoption

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of geopolymer technology in the future will be governed by a host of factors to be discussed here, including the ability to add significant value to coal ash and/or slag waste streams, wider understanding of the benefits of the technology, as well as the potential to significantly reduce carbon dioxide emissions compared to OPC manufacture. This paper discusses the practical technical, environmental, and commercial drivers in more detail, as well as how geopolymer technology may form part of an overall 'Green Concrete' industry. Later in the article, the commercial drivers for adoption of geopolymer technology are explored in a broader context that takes into account not just the desirable application of the material, but also the market reality.

2. Performance, properties and applications

There is now a significant yet still modest amount of scientific literature exploring the properties of geopolymeric materials on the laboratory scale. However, more significantly, there is a growing understanding of the real world-scale capabilities of the technologies being developed through plant trials and commercial rollouts, most of which are naturally protected by confidentiality agreements. Nonetheless, it is clear that materials exhibiting the following performance properties can be made with both technological and commercial confidence:

- high compressive strength gain [3]
- good abrasion resistance, particularly when mixed with PTFE filler [4]
- rapid controllable setting and hardening [3]
- fire resistance (up to 1000 °C) and no emission of toxic fumes when heated — either in the form of a carbon fibre/ geopolymer composite [5] or as a pure geopolymer (e.g. a geopolymeric coating on an exposed surface) [6]
- high level of resistance to a range of different acids and salt solutions [7]
- not subject to deleterious alkali–aggregate reactions [8]
- low shrinkage and low thermal conductivity [9]
- adhesion to fresh and old concrete substrates, steel, glass, ceramics [10]
- high surface definition that replicates mould patterns [6]
- inherent protection of steel reinforcing due to high residual pH and low chloride diffusion rates [11,12].

It is important to note that not all geopolymer products will possess all of these properties, i.e. there is no single all-encompassing formulation that can optimize all the properties listed above. Like all technologies, recipes and formulations are ultimately tailored to achieve required specifications at a minimum cost. With sufficient knowledge and understanding of raw material reactivity and chemistry, it is possible to tailor the material to attain combinations of the above properties to optimize both cost and technical performance. Some properties (in general not those related to concrete applications) are best achieved by the use of metakaolin [13] or synthetic aluminosilicate precursors [14] rather than fly ash, and so the exploitation of these properties will depend on the development of niche applications in which the relatively high cost of these precursors compared to fly ash is not a driving consideration.

It must be remembered that notions of 'cheap' and 'expensive' in structural and non-structural construction applications are very different from those in the context of high-tech ceramics or other niche, low volume/high performance applications. The commercial uptake of geopolymer technology therefore provides the opportunity to create value in a large number of disparate markets, from construction to aerospace, using essentially the same technology. These different markets have vastly different needs: some may utilize bulk amounts of coal ash to form a variety of value-added products, whereas others involve production of inexpensive ceramic-like materials from purer precursor materials. This is not to say, however, that geopolymer technology is the most suitable or most competitive technology available for all of the applications noted above. Along with traditional OPC systems, other new or alternative cementing systems [15] will continue to be utilized in the market where most applicable, and often in hybrid or blended products. In blended systems, knowledge of the chemistry and science of each component, as well as their interactions with each other, is vital.

Fly ash-based geopolymerisation has only become the subject of intense research interest within the past decade [1,16], however there are currently a number of well-established academic and industrial research centers worldwide that are investing significantly in developments in this field. While development of products is not difficult to achieve on a laboratory scale simply by empirical mix formulation, the ability to understand and control the setting process and repeatability using variable material sources have always proven to be issues in large-scale production. These issues have been the primary industrial research focus, although the nature of the work is largely outside of the public domain. Significant academic knowledge has also been generated in this vein, including extensive studies on developments of different characterization techniques [9,17–25], the effects of different chemical additives and/or contaminants [3,26–30], and the influence of curing conditions (humidity, time and temperature) [9,31,32]. Production of geopolymer concrete on a full manufacturing scale can now be achieved for high-strength ready-mix concrete, which represents the successful implementation of a technically very challenging product. This is not to say that academic research in this field will not continue to deliver substantial technological benefits, but rather that this effort will complement the push for a material that is already proven to be technically viable to be rolled-out as a commercially attractive proposition also.

The other area in which significant research has been conducted is in the study of the durability of geopolymers exposed to various aggressive scenarios, generally in the format of accelerated leaching tests. In laboratory and industrial testing, geopolymers have displayed excellent resistance to chemical attack by chloride (including sea water), various acids, alkali and sulphate [7,33–35]. These properties present significant technological benefits in comparison to OPC where such resistance is required. It must be noted that most concrete structures in the world will never be exposed to potentially damaging levels of any of these aggressive agents. However, there are some emerging markets in the world, namely in the Middle East [36], where traditional OPC suffers from technological challenges such as these that may be overcome at least to some extent by use of geopolymer concrete.

The thermal resistance properties of geopolymers significantly exceed those of OPC, with very little structural damage observed up to 700–800 °C in many instances [6,37,38]. The pseudo- or proto-zeolitic nature of the geopolymeric binder phase has led to its use as an encapsulant for radioactive waste, in particular cesium and strontium which are able to be strongly chemically bound into and effectively immobilized by the matrix, rather than the simple physical or weak chemical encapsulation achievable with traditional cement encapsulation technology [27,39,40]. Freeze–thaw resistance is also an issue of significant interest in many parts of the world, and testing of geopolymers under repeated freeze–thaw cycling shows that very little deterioration is observable [41]. Combined with a very high resistance to chloride penetration [12], this shows that geopolymer technology has great potential for use in, for example, highway applications in cold areas, where a combination of freeze–thaw cycling and de-icer salt scaling often leads to rapid deterioration of OPC [42].

The chemistry of the geopolymeric binder system lends itself ideally to rapid strength development. However, unlike in most traditional cementitious binder systems, this does not always come at the cost of reduced long-term properties. Geopolymers that set very rapidly do not necessarily show deterioration in performance over a period of years to decades, and prolonged exposure to aggressive (particularly moist) conditions may in some instances even lead to a gradual increase in strength over a very extended period of time [43,44].

Given that geopolymers are a highly complex and as yet relatively poorly understood material, there are clearly many areas in which further work is required. This does not, however, mean that geopolymer technology is insufficiently developed for some applications. This is particularly the case for non-load-bearing applications in the construction industry and niche fire-resistance and refractory applications, where durability issues are more easily proven. Fig. 1 provides an outline of the areas in which research into physicochemical aspects of geopolymeric binders is currently focused. It must be noted that this diagram does not represent in detail the role of or problems related to the aggregate in determining geopolymer properties, or the interrelationship

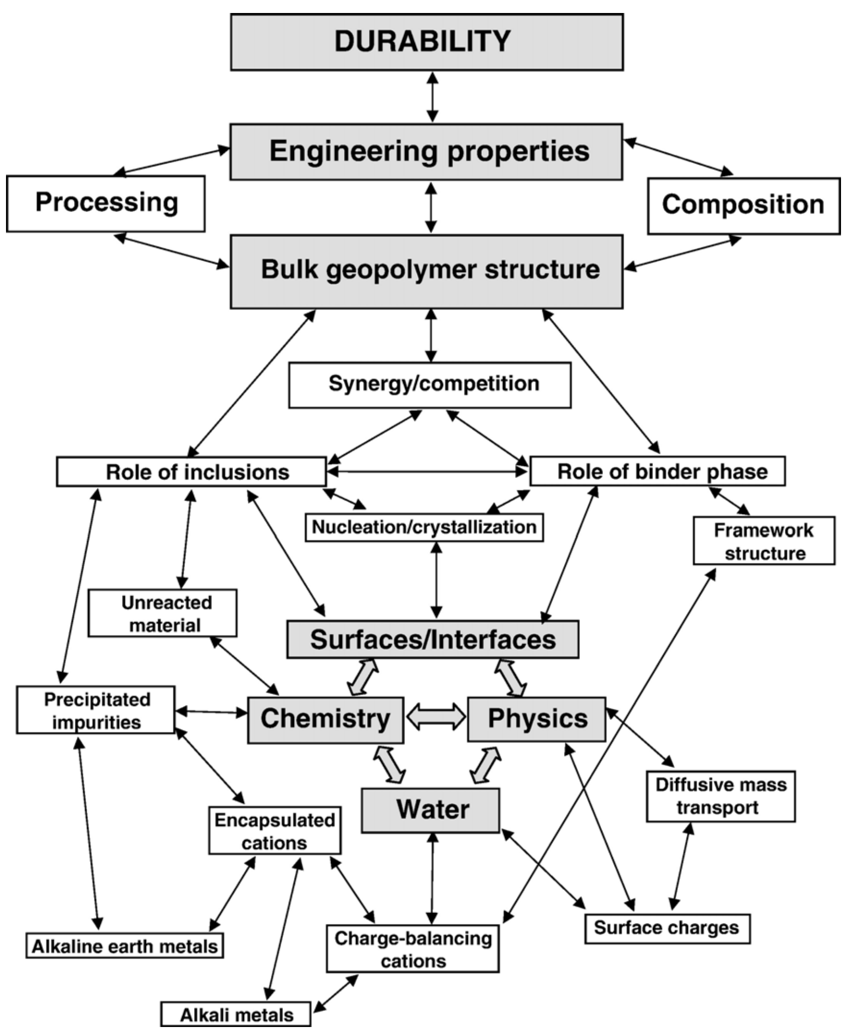

Fig. 1. Schematic diagram showing some of the interrelationships between different technical and scientific aspects of geopolymer binder technology. Research in each of these areas is currently required and/or ongoing.

between aggregate and binder properties. The choice of aggregate, and its relationship to the binder, will clearly play a critical role in determining the properties of any inorganic polymer concrete, and so will be expected to be linked – directly or indirectly – with every aspect of geopolymer binder chemistry depicted in Fig. 1.

The position of the “Durability” box at the top of Fig. 1 is by no means an accident. More than any other technological aspect or engineering property, durability will be the factor that overrides all other technological drivers in determining the success or failure of geopolymer technology in the construction industry. At this point in time, and given the relatively short history of geopolymer research, all that can be stated is that preliminary accelerated testing shows very promising results indeed, and that work is intensively ongoing.

The dry shrinkage of fly ash-based geopolymer concrete is, due to the inherently lower water demand and the gel nature of the binder, greatly improved compared to that of OPC. The significantly lower rate of heat evolution during setting of fly ash geopolymers compared to OPC hydration [45] means that the driving force for water expulsion from the partially-cured concrete is also significantly reduced. Thus, larger sections of concrete can be placed without need for specialty chemicals and admixtures. Additionally, because mix-water is not chemically bound to the geopolymer matrix (in contrast to its role as an integral component of C–S–H structures), any water loss that does occur is much less likely to cause damage to the integral matrix structure. Field-scale testing has shown that it is possible to pour, without need for shrinkage cuts, a 12 m length of ready-mix inorganic polymer concrete footpath using exactly the same batching, transportation, pouring and forming techniques as are used for OPC.

3. Technical challenges

The greatest challenge for any technology looking to be adopted in the construction industry is fundamentally two-fold. The key technological and engineering aspect of this challenge relates to product certification in each market. As geopolymers are made from ashes and/or metallurgical slags, these raw materials vary from source to source, requiring a large investment in formulation and certification from each source. However, it must be noted that this issue is largely the same as that faced in the supply of these materials for cement production. This results in a significant financial and temporal barrier to implementation, despite the fact that raw material variation is accounted for in proper mix design (also similar to cement manufacture). Published studies have independently verified the favorable material properties of geopolymers synthesised from a wide variety of ashes and slags generated worldwide [1,46–52]. However, due predominantly to these barriers, the technology has not yet been adopted on a routine commercial scale for such applications. Despite the above-mentioned drivers for the further development and commercialization of geopolymer technology, there are a number of barriers that remain, in particular:

- the lack of uniform nomenclature for geopolymer/inorganic polymer systems,
- entrenched attitudes in the cement industry (e.g. that alkali is bad for all systems, and that fly ash-containing cements have poor freeze–thaw resistance in the presence of salt),
- adherence to compositionally-based building codes and standards (i.e. geopolymers do not contain OPC, and so will not meet standards specifying a maximum allowable supplementary cementitious material content),
- the lack of quantitative data on durability due to the relatively recent popularization of research in this field, and
- the understandably conservative nature of the construction and building products industry with regard to new products (i.e. if a product fails, there is a likelihood of human loss).

From a more practical standpoint, geopolymer technology is yet to establish itself as a recognized, viable, and proven technology solution for the construction industry. This lack of practical acceptance of the technology is rooted in the necessarily conservative nature of the construction industry, coupled with the very different chemistry of geopolymers when compared to OPC and related binders. The bulk of literature in the public domain is focused on creating a “cement replacement” material, as this is perceived as the most pervasive, profitable, but also ‘green’ application for geopolymers. However, inherent in this is the assumption that the existing cement industry is actively seeking to replace a century or more of knowledge and experience with an unproven material. This proposition does not therefore take into account the large economic and commercial barriers that must be overcome for a technology to develop a successful market presence. This primary barrier is the highly developed and stable nature of the global construction industry, with the exception of rapidly expanding markets such as China and India.

As mentioned above, the technological issues relating to geopolymer technology are essentially not the bottle-neck in the application of the material, and no ‘silver-bullet’ academic study will hasten the commercialization of the technology. New technological barriers can be created by a disinterested industry more easily than they can be rigorously solved in an academic sense. The technological, commercial and environmental aspects of the technology are sufficiently proven such that the timing of the market deployment of geopolymers in the construction industry is largely in the hands of industry, rather than in research and development. As such, the most critical driver for geopolymer technology uptake, desire for change, is not a priority at this time, although this is likely to be subject to ever-changing market forces.

However, the inherent fire resistance/thermal stability, workability, adhesive properties and acid resistance of geopolymer technology have naturally led to the development of many other products with advantageous market potential. These niche applications do not necessarily compete with existing OPC technology, or need to overcome the same barriers to entry in terms of regulatory requirements, decades of durability data, or market access. In all likelihood, it is in these applications, and in the more progressively regulated and less stably segmented markets of China, the Middle East and India, that geopolymer technology will become a commercial reality. In less dynamic economies, where technological innovation, and market growth and competitiveness are less critical in the construction industry, the uptake of this technology will be driven only by consumer demand, government regulation or global competition.

4. Environmental benefits

One of the primary advantages of geopolymers over traditional cements from an environmental perspective is the much lower CO_2 emission rate from geopolymer manufacture compared to OPC production. This is mainly due to the absence of a high-temperature calcination step in geopolymer synthesis from ashes and/or slags, whereas the calcination of cement clinker not only consumes a large amount of fossil fuel-derived energy, but also releases CO_2 as a reaction product. While the use of an alkaline hydroxide or silicate activating solution rather than water for cement hydration does reintroduce some Greenhouse cost, the overall CO_2 saving due to widespread geopolymer utilization is expected to be highly significant. The use of metakaolin in geopolymers would also increase the CO_2 emissions per tonne of product, however the high cost of metakaolin and the high water demand of metakaolin geopolymers means that this is not considered a viable possibility for large-scale geopolymer production in construction applications.

A recent article exploring the CO_2 emissions related with cement clinker production estimated the amount of CO_2 released per tonne of binder, including blending with ashes and slags, to be approximately 0.815 tonnes [15]. Although this article did not consider the environmental aspects of admixtures required for high-performance applications setting control, this figure is adopted as a guide for comparison with geopolymer technology. In comparison, the CO_2 emission of geopolymers is generally considered to be very low, although this is subject to formulation variations specific to each application. Therefore, it is helpful to express the CO_2 emission of geopolymers in terms of composition. Fig. 2 shows the total calculated CO_2 emission of geopolymer binders taken from literature publications as a function of the dissolved solids (Na_2O+SiO_2) content of the activating solution, which are the principal emitting components. The estimated amounts of CO_2 evolved during the production of Na_2O (as $2NaOH+Cl_2$ in the chlor-alkali process) and SiO_2 as aqueous sodium silicate (a general figure for concentrated waterglass solutions) are each approximately 1 tonne/tonne (personal communication, PQ Corporation). As an absolute worst-case scenario, one may assume that all emissions related with the chlor-alkali process for production of sodium hydroxide and chlorine are attributed to sodium hydroxide. It is then possible to represent the reductions in CO_2 emission of geopolymer binder compared to OPC as simply a function of the proportion of the total geopolymer binder phase that is derived from dissolved sodium and silica. Fig. 2 shows such a comparison, made on the basis of this value of 1 tonne/tonne, for geopolymer compositions – derived from both fly ash and metakaolin precursors – obtained from the literature [11,17,18,28,33,53–56].

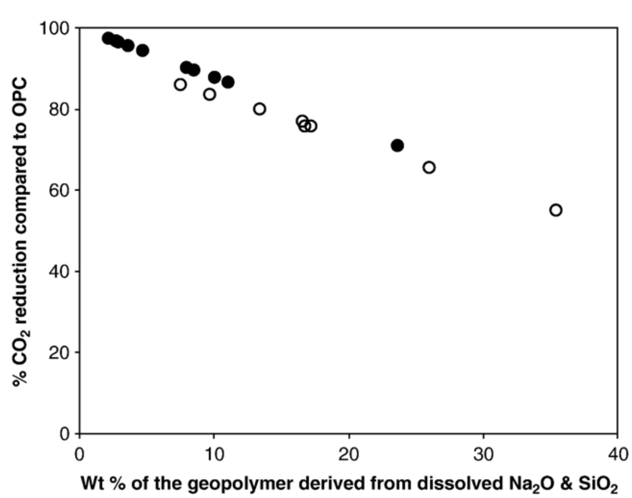

Fig. 2. Total estimated CO_2 emission of geopolymer binders as a function of dissolved component content. Compositions are taken from the literature [11,17,18,28,33,53–56], for fly ash (solid points) and metakaolin (open circles) geopolymers. Calculations include 72 kg CO_2/tonne metakaolin production [57].

While the formulations vary substantially to fulfill application requirements, Fig. 2 provides evidence that geopolymer binders can in general deliver an 80% or greater reduction in CO_2 emission compared to OPC. In addition to this, it is generally accepted that geopolymer-type concretes have a far lower water demand due to high fly ash content. This means that geopolymer concretes possess two further environmental benefits: water reduction (which is of particular interest in naturally dry environments including Australia, the Middle East and parts of India and China), and no requirement of superplasticising chemical additives (which are expensive relative to the price of concrete, and also contribute more to CO_2 emissions). Further, one could consider that the primary material produced from the chlor-alkali process is chlorine (for use in the production of plastics, and evidenced by the reciprocal relationship between chlorine demand and NaOH price on commodity markets). Thus, at best the vast majority, but at worst at least 50% of all emissions related with this process should be attributed to chlorine, further significantly reducing the emissions of geopolymer concrete. Therefore, the CO_2 emissions need to be distributed in some way between the NaOH and Cl_2 products. Indeed, one could argue (although possibly successfully only while the infant geopolymer industry does not alter the demand for NaOH in a substantive manner) that the CO_2 emissions related with the chlor-alkali process should be largely attributed to the primary product of chlorine, as is the case in fly ash 'manufacture' during power generation. This has not been done here, meaning that the CO_2 savings shown in Fig. 2 may be considered a somewhat conservative estimate dependent on the accounting methodology and CO_2 attribution scheme for the chlor-alkali process. It is clear that a full life-cycle analysis is required in the near future to consider in full the detail of such calculations, and potentially incorporate the added durability of geopolymer concrete.

While at this time an environmental driver may not in itself be enough to induce widespread adoption of geopolymer technology, anticipated increases in the financial cost of CO_2 emission via any carbon credits trading scheme, and increases in the cost of potable water, would render these factors commercial drivers which may take on some significance in the construction products industry. However, many other alternative approaches to reducing the CO_2 output of cement usage are making significant headway [15]. Methods for fly ash and slag utilization also provide environmental benefits by removing these materials from landfill, and geopolymers are able to incorporate a much higher fraction of waste material than is possible using blended cements or other existing or evolutionary technologies. Therefore, based on Fig. 2, geopolymers still represent a competitive technology when considering these 'environmentally friendly' OPC incorporating systems.

In addition to Greenhouse benefits, geopolymer technology also provides the opportunity for the utilization of waste streams that may not be of any benefit in OPC-blending applications. For example, work on magnesia-iron slags [52], ferronickel [48] slags, and tungsten mine waste [58], has shown that these materials can be effectively geopolymerised, while they are of little or no benefit in OPC. Immobilization of toxic and/or radioactive wastes, as mentioned in Section 2, also provides significant environmental benefit in the long term when compared to current disposal regimes. These may turn out to be minor niche applications for geopolymer technology, but they do provide additional environmental drivers for these materials in certain scenarios and in certain regions where these wastes are available and/or problematic.

5. Regulatory issues

Probably the single greatest hurdle facing the emerging geopolymer industry in terms of application in the construction industry as a load-bearing material is not technological, but rather regulatory. In the developed world, there are very specific standards for what is considered 'acceptable' performance for a cementitious binder. These have clearly been developed over many years, with input from cement manufacturing companies with the behavior of OPC-based concretes specifically in mind. Despite this, standards containing restraints such as 'minimum cement content' are beginning to be seen as prohibitive, even for cement-based systems. High cement content essentially allows and encourages mix-design favoring poor quality aggregates and high water content. Therefore, a product such as geopolymer concrete may perform entirely acceptably but without conforming exactly to the established regulatory standards, particularly with regard to rheology and chemical composition. This may prove to be a significant hindrance to the acceptance of geopolymer technology in these markets.

It must also be noted that similar issues arise in the use of other non-OPC binders, or even high-performance OPC-based systems, which may not simply be an evolution of existing OPC technology but instead require a different chemical paradigm. However, the developing world does not have the same entrenched standards, and is generally more willing to accept an innovative solution to a problem such as concrete replacement as market demand will greatly exceed supply in the coming years. These markets, particularly China where fly ash is available due to the wide use of coal power generation, where CO_2 emission is likely to become an increasingly significant political issue and where freeze–thaw resistance is an issue in many regions, may prove to be the primary areas in which geopolymer technology becomes accepted on a regulatory level.

However, having said that, geopolymer concrete is entirely capable of meeting or exceeding the vast majority of existing performance-based standards in construction applications, especially where acid, chemical and fire resistance is required. Work on compliance with concrete strength standards has been carried out by various investigators [59,60]. It must be noted that due to the generally high compressive strengths achieved by geopolymer concretes, these materials are subject to the same difficulties with regard to compliance with elastic modulus standards [60] as are widely observed in high-performance concretes [61]. In real terms, issues relating to standards of concretes used in construction excluding geopolymer technology only exist due to the lack of commercial push for the technology from major industry and regulatory stakeholders. If and when geopolymers become a favorable (economic and/or environmental) value proposition, there must exist sufficient data proving the durability of the material. The development of appropriate standards for these materials must therefore become a priority. Naturally, the nature and push of the economic and environmental drivers will determine the rate and nature of the changes in this respect.

6. Concretes or ceramics?

One of the primary decisions facing the geopolymers research community at the current point in time is that the applications for inorganic polymer technology are effectively divided between two distinct fields — cement replacement, or utilization as a low-cost alternative ceramic. While the product can be tailored to be ideally suited to one or the other of these fields of application, it is a challenge for the research community as a whole to make clear the distinction between the specific product formulations that are best suited to each specific application. For example, work has recently been published stating that it is possible to form 'geopolymer' products over a compositional range from $0.5 < Si/Al < 300$ [62]. Some of the compounds formed over this entire compositional range may indeed have interesting properties in limited ceramic applications, where resistance to aggressive environments is not important. However, the products formed at the Si-poor ($Si/Al < 1$) or Si-rich ($Si/Al > 5$) ends of this 'potential' compositional range will be entirely inappropriate for cement replacement applications due to their low strength, low thermal stability, generally low to negligible chemical resistance, and tendency to dissolve in water due to having excessive Na/Al ratios and/or observable carbonate crystals formed within the 'geopolymer' matrix, indicative of very large amounts of free alkali within the product.

In defining the role of inorganic polymer technology in the development of "Green concrete", as is the key aim of the current paper, the composition range of interest must therefore be narrowed to include essentially the range from $1 < Si/Al < 5$, and with Na/Al ratios not too dissimilar from 1. Probably the most useful definition of what exactly constitutes a geopolymer has recently been published by Rees et al., [19] and entails the formation of a solid aluminosilicate product that retains its integrity when agitated gently in water once hardened. The exact locations of the endpoints of the range of interest will of course depend on the solid aluminosilicate source chosen — slags and class C fly ashes will often have a low Al content while making quite an acceptable geopolymer concrete, metakaolin has a high Al content, and class F fly ashes are roughly intermediate. However, the requirement for the geopolymeric binder phase to have Na/Al ∼1 for optimal mechanical and durability performance is unavoidable, as was discussed in some detail in a recent review of the field [2]. A clear division in research focus between geopolymer-like products of wildly varying composition and displaying very few of the properties desirable in a geopolymer concrete, and those that are of commercial value as cement replacement materials – or even in ceramic-type applications but still displaying the chemical resistance and strength performance characteristic of geopolymeric binder – is therefore required. This is not by any means to say that the study of metakaolin- or synthetic precursor-based geopolymers is of limited benefit in the development of useful geopolymer concretes — in fact quite the opposite, as these products do display the strength and durability properties of interest, and form a very valuable model system whereby the structure–property relationships of the highly complex fly ash/slag systems may be better understood [1,63]. However, care must be taken when defining what is and what is not a geopolymer, as negative durability results obtained from poorly-formulated and/or poorly-characterized systems are likely to have a deleterious impact on perceptions of geopolymeric materials as a viable alternative to existing cement technologies.

7. Summary — Current challenges and obstacles

In order to develop a geopolymer industry, it is necessary to gain the greater acceptance of the technology by potential manufacturers and end-users, i.e. the technical virtues need to be "de-risked" and the commercial and environmental value of the technology quantified so that this can be accurately incorporated into the value proposition. This can be achieved through a more open-dialogue approach between academia and industry, and also the wider dissemination of basic knowledge. The current challenge, which is currently being addressed through intensive research efforts worldwide, is to create a knowledge base that can be accessed in order to produce tailor-made geopolymeric matrices derived from waste materials for specific industrial applications, and on a cost-competitive basis.

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