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Innovation in cements – can we meet future construction needs sustainably?

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Abstract. There has been an enormous growth in the volume and scope of technical analysis of alternative cements, accompanied by claims of "sustainability", during the past decade. Some of this growth has been accompanied by real-world actions in terms of commercialization, trials, and deployment. However, there are a very large number of lines of investigation – some of which appear extremely promising from environmental and technical perspectives – that have not yet been translated into reality. This presentation will address some of the key drivers for a sustainable future in cement technology, with a particular focus on alkali-activated materials, including comments on the pathways by which some of the evident potential of these materials can be unlocked for the benefit of society.

Keywords: Cement, Concrete, Sustainability.

1 Introduction

For over a century, the global use of concrete in construction has been dominated by materials based on Portland cement as the primary binder. Evolving from developments in western Europe in the early 19th century [1-4], and spreading worldwide first through exports and later through development of distributed production capacity in every region of the globe [5-9], Portland cement has become ubiquitous worldwide. It is available and widely used in every country, with largely similar performance characteristics governed by similar standardization regimes in each country [10], and has been used in such enormous quantities worldwide that the hydration products of Portland cement are considered to be one of the key markers for the geological era of the "Anthropocene", corresponding to the time period in which the Earth's crust has been most markedly influenced by human activities.

However, Portland cement has to some degree become a victim of its own success, in terms of the identified environmental footprint – raw materials extraction, energy usage, and emission of pollution – that is attributed to the cement industry. When considering cement on a per-unit basis it is actually a relatively low-emissions material compared to other engineering materials, particularly metals [11]. However, the fact that more than 4 Gt of cement is produced worldwide per annum means that the overall sectoral emissions footprint is considered extremely problematic as global society seeks to reduce its detrimental impact on the planet Earth as a whole, and the Earth's atmosphere in particular.

The criticality of the need to reduce the environmental footprint of cement production, and the difficulties (on many levels) associated with achieving the necessary reductions to approach net-zero emissions status, have been highlighted by Increasingly prominent messaging from policy-makers and sectors of society which for decades had not even considered public discussion of what had been considered by most a relatively uninteresting commodity material. For example, the World Economic Forum has in 2020 listed "low-carbon cements" among the Top 10 Emerging Technologies for global society [12], among such other entries as quantum sensing and digital medicine; it has been very rare within recent history that construction materials are given such prominence in discussions of technological development priorities. Certainly the research and development funding committed by governments and other funders to construction materials has long fallen many orders of magnitude below that which is committed to most of the other entries in such lists. As a sector aiming to improve performance in this regard, it is evidently time for the research community to ensure that policymakers and science agencies are aware that the identified importance of construction materials – including, but not limited to, cements – needs to be matched by commensurate provision of funding support for research and development activities.

In seeking to decarbonize – or at least greatly reduce the emissions of – the cement and concrete sector, there are many stages of the value chain that can and must be addressed. The situation has been discussed in detail in a recent review paper [13], and the arguments and perspective put forward in that paper will not be repeated in detail here. It is clear that savings must be made in the design of cements, in the use of cements to produce concretes, in the use of concretes to produce elements or structures, and in the design and continuing operation of those structures, if deep decarbonization is to be achieved as needed to limit global temperature rise and restrict the degree of irreversible ecosystem damage that is incurred. Governments and industry bodies in several countries have produced roadmaps for the decarbonization of construction materials production and use, which generally share an emphasis on the reduction of clinker content in Portland cement blends, increased use of non-Portland cements, carbon capture by process retrofitting and/or by materials in service, and improvements in the specification and design of concretes and concrete structures.

The main focus of this paper is at the cement level, and specifically on the use of alkali-activated cements as a way to achieve concretes with good engineering performance in desired applications, with the potential for greatly reduced emissions profiles compared to conventional solutions. This is not in any way to indicate that this is the only way in which emissions savings can or should be achieved – actually, it is quite the opposite. It is essential to develop and deploy a toolkit of environmentally responsible approaches to the provision of construction materials, each of which is appropriate and economically viable to use in given scenarios (and potentially less so in other scenarios). Diversification of the suite of available materials, processes and technology options is essential, and the available options then need to be assessed and used accordingly, to ensure that the desired outcomes are met in engineering, environmental, and economic senses. The materials to be discussed in more detail in the following section are an example of a part of this toolkit, and potentially one with a very high potential for impact if deployed at scale in appropriate engineering applications, and so it is essential to understand both strengths and potential weaknesses of a class of materials in the context of this type of discussion.

2 Factors influencing the use, and potential use, of alkali-activated cements

This section will address briefly some of the key factors that influence whether alkali-activation is a potential pathway to the beneficial and useful production of construction materials in a given location and context.

2.1 Materials availability

The first pre-requisite for the production and use of alkali-activated materials at scale is that the necessary materials are available in sufficient quantities – and will remain so for a sufficiently long timeframe to make the development work worthwhile in terms of a return on investment. This is a particular challenge in a lot of work related to valorization of waste materials by alkali activation [14, 15]; the quantities of waste generation which may be considered very problematically large to many industries, on the order of hundreds to thousands of tonnes per year, are far below the usual throughput of a Portland cement production facility and may therefore be challenging to operate in competition due to factors related to economy of scale and material quality control. There are also questions related to alkali-activator supply, but these are generally an order of magnitude less pressing than the questions of powder supply, due to the relative fractions of the mix designs which are filled by each constituent.

The most widely used precursors in alkali-activated binders are ground granulated blast furnace slag and coal fly ash. Both of these are facing supply restrictions in some parts of the world, as iron extraction from ores is diminishing and the use of coal in electrical power generation is being phased out. However, some parts of the world do still have ample un-valorized slag and ash supplies, including materials that have been stockpiled or landfilled over the past decades – and so it is eminently logical that where these materials are available, they should be used to the greatest extent possible. Arguments have been made that the cements research community should shift its sole focus to the blending of high-volume natural resources such as limestone, clays (calcined or otherwise activated), and natural pozzolanic materials [16], as these are available in larger quantities worldwide, whereas slags and coal ashes are produced in smaller quantities than Portland cement and with an already reducing supply. However, this one-size-fits-all perspective entirely neglects the very heterogeneous distribution of ash and slag resources worldwide; if the global scenario is taken to be the average of every locality, then it would be true that cements based on the use of geological resources would be more logical than those which rely on industrial by-products. However, the global scenario is not the average of every locality – it is actually the sum of every locality. From this perspective it is essential to consider the regions and nations which have high and continuing availability of materials that are suitable for alkali-activation – both industrially sourced and those based on clays – as prime opportunities to gain benefit from these materials.

It is also worthwhile to comment on the use of alkali-activation compared to the use of high-volume supplementary cementitious materials (SCMs) in Portland blends. When the blending fraction of an SCM is sufficiently high (and noting that standards such as EN 197-1 allow blending of up to 95% ground granulated blast furnace slag with Portland cement), the reaction process and products of the cement as a whole will be dominated by the SCM rather than by the Portland cement. This means that the key purpose of whatever constituent is blended with the SCM (whether that is Portland cement or an alkali activator) will be to optimize the reaction of the SCM, rather than to take on a primary cementing role in and of itself.

The question must therefore be asked: if the main purpose of the non-SCM constituent(s) of a cement is to activate the SCM, why should it be assumed that Portland cement is necessarily the best material to take on this role? Of course, there may be cases in which this is true, and high-volume SCM blends with Portland cement have been shown to give excellent performance in many applications. However, it is equally possible that the best SCM performance can be gained either by alkaline activation of the SCM, or potentially through a hybrid approach in which both Portland cement and an alkali activator are used, gaining synergies from the presence of both of these reactive constituents in enhancing the overall binder performance [17, 18]. It is only by questioning the fundamental assumption that cements must contain Portland cement that the true potential of the reactive silicates used as SCMs in blended cements and as precursors for alkali-activation can be properly assessed and used.

2.2 Demonstrating and validating technical performance

As the global standardization environment increasingly moves from a prescriptive basis (defining compositions, and assuming that sufficient performance will be reached) to a performance basis (defining the outcomes that must be achieved, and giving flexibility in how this is done) [19-21], it is becoming increasingly important that performance assessment is linked to suitably validated and standardized test methods. Initiatives focused on the testing of Portland cement-based materials, including via very large interlaboratory test programs [22], are providing new levels of insight into the intrinsic variability of tests conducted within and between laboratories, and the uncertainty bounds that are therefore associated with specific test methods [23]. This is equally true, and potentially even more critically important, for alkali-activated materials and other classes of non-Portland cements for which prescriptive standards do not exist. Efforts such as the work of RILEM Technical Committee 247-DTA on durability testing [24-26], RILEM Technical Committees 238-SCM and 267-TRM on SCM reactivity testing [27, 28], and others, are providing valuable insight that is being used actively in the development of new standards for materials and tests [29, 30]. The current American Concrete Institute code ACI 318-19 permits the use of “alternative cementitious materials”, which must be approved by both the designer and the building official. This approval depends on the responsibility of the material supplier and the concrete producer to test the material in sufficient depth and breadth to demonstrate that it will perform as needed, in conditions resembling the intended application.

Obviously such testing requires further (and ongoing) validation of test methods; this is not a challenge that is isolated to the field of alternative cements, as the same type of validation is also needed for testing of conventional cements and concretes under performance-based standardization. However, the additional question that must be asked when assessing test methods for application to non-Portland cements is whether there are intrinsic assumptions in the test method that link to the chemistry or other characteristics specifically of Portland cement – for example, curing immersed in limewater, or degradation mechanisms that relate solely to constituents of Portland cement. Conversely, in testing and validation of concretes based on alternative cements, it is essential to demonstrate that there are no unexpected detrimental surprises or mechanisms of performance loss that would not be captured by testing for the common degradation mechanisms of Portland cement. A primary example here is the conversion phenomenon in calcium aluminate cements, which must be used as a cautionary tale as any new types of cements are being deployed at scale [31, 32]. Fundamentally, a risk calculation needs to be made regarding the applications into which a new material is placed – in the unlikely case that a surprising loss of performance is experienced, what would be the consequences of this, in terms of safety and financial loss? This calculation depends on the level of confidence in material performance that has been gained through field applications, and at least in the case of alkali-activated cements this is continuing to increase rapidly as the number of demonstration projects, and the age of the demonstration structures that have been constructed and monitored over the past decades, both increase in parallel. In the end, this validation of laboratory testing through comparison with field results is essential, and is the only way that full acceptance of new materials can be reached at an industrial and practical level.

3 Concluding remarks

This paper has provided a brief discussion of some key aspects related to the development, use and testing of alkali-activated concretes, with a view toward their use at full scale as a construction material. Many of the points raised are also applicable to many other elements of the ever-growing toolkit of non-Portland, hybrid, and blended cements that are increasingly being identified as offering attractive technical, cost, and environmental profiles in the construction industry. Innovation in construction materials is necessarily a slow process due to the very high levels of confidence that are required related to material performance and durability in service, and although accelerated testing can provide some answers, the degree and impact of the acceleration of degradation remain sources of uncertainty in the application of many such methods. In the end, performance of a material needs to be proven and tested, to support agreement between all participants in the value chain that the necessary extent of this "proof" has been reached for the application in question. This is obviously material-specific and application-specific – and similarly, calculations of the relative environmental and economic benefits of innovative construction materials compared to established baseline materials are also material-specific and application-specific. The pathway to future sustainability in construction materials supply requires a validated toolkit of options, assessed locally for materials availability, engineering performance, and economic and environmental viability. This level of local detailed assessment is clearly labor-intensive and intellectually much more demanding than simple compliance with prescriptive standards, but this is a fundamental and necessary condition for a sustainable global construction sector.

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