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Review Paper

Perspectives on research directions in cement and concrete

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Abstract: This paper marks the 20th anniversary of the Asian Concrete Federation by taking a perspective-style overview of current research directions in cementitious materials, and the concretes made from them. Despite a (sometimes well-earned) reputation for conservatism, the cement and concrete sector is a hotbed of innovation and creativity, and there are many opportunities to better leverage these innovative and creative processes through collaborations between specialists in fields including (but not limited to) chemical, materials, process, concrete technology, structural engineering, and engineering design. Many routes are currently being investigated for "green cement" or "green concrete" production, and it is important to carefully consider and assess which of these are likely to give the most feasible (and most rapid), pathways to deep carbon emissions reductions. To achieve sustainability, we need to make better cements, to make better concretes, and to use these concretes better in practical engineering applications. This paper provides some thoughts about how this may be able to be achieved, with the intention of sparking future discussions and developments.

Keywords: Sustainability; Cement; Concrete; Multiscale; Carbonation

1. Introduction

This paper is intended to contribute to the celebration of the 20th anniversary of the Asian Concrete Federation (ACF), which is an organisation with an essential role to play in guiding, nurturing and disseminating knowledge generation, linking countries with the world's highest market demands (in terms of both volume and technical innovation), and most extensive skills bases, in the production and use of construction materials. The paper will attempt to do this by looking at the current state of this field worldwide, particularly focusing on advancements in cement research, and projecting some thoughts about what may come in the next 20 years in which the ACF will continue to play an important role in framing discussions and developments.

The opening premise of this discussion is that the global (and Asian) cement and concrete sector is facing immense challenges related to the sustainability of its operations. The sheer scale at which these essential materials are produced means that various local and global systems are placed under significant stress, and this is increasingly (and rightly) gaining attention as we seek to limit the damage caused to our planet by human actions. The cement industry is classified as "difficult to decarbonise" in technical and techno-economic assessments [1], and the reasons for this are both complex and deep-seated.

Areas that have been raised as important points for attention include:

- CO_2 emissions, as the most prominent pathway to environmental damage in ongoing international discussions [2]
- Environmental emissions footprint in aspects other than CO_2 – for example, pollution by dust, acid gas, or heavy metal emissions, among others [3-6]
- Raw materials (aggregate and/or limestone)

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supply from natural sources [7-10]

- Raw materials supply from secondary sources [11]
- Water usage [12, 13]
- Transportation and logistics [6, 14]

As with any paper that is intended to make predictions about the future, it is necessarily a mixture of personal opinions and speculation, and so it is almost certain that some of the predictions here will be proven incorrect in coming years – but this should be viewed with optimism, and as a challenge to the community regarding the need to overcome some of the barriers that are mentioned.

This is intended to be a brief discussion piece rather than an extensive literature review, although it is intentionally rather rich in literature citations, which it is hoped will spark the interest of the reader. The basis of the discussion broadly follows the "value chain" concept elaborated by Habert et al. [15], which highlights the need for inter-connected improvements at every level from "one bag of cement" to "the building stock". The terminology used in that paper is somewhat reworded here, but a similar four-fold classification can be applied to identify the necessary action levels:

1. Making better cement
2. Making better concrete
3. Making concrete better
4. Using concrete better

The main focus here will be on advances at the cement level, corresponding to the main interests of the author, but with some brief comments also provided regarding efficiency in the specification, production, and use of concrete. The paper will mainly give brief examples of how research can, and should, contribute to improving the environmental and societal performance – and therefore also the key economic role – of the cement and concrete sector within the next 20 years.

2. Making better cement – Reducing or absorbing CO_2?

Portland cement manufacturing, in a modern process plant with the extensive pollution control measures that are in place in such facilities, is a highly efficient process when considered in realistic thermodynamic terms [16], and also in the benefit that it provides to society by generating the materials that are needed to support a modern lifestyle and high quality of life. Nonetheless, it is widely acknowledged that significant gains must be sought, in terms of the environmental footprint per tonne of cementitious material produced, if the global cement sector is to be allowed (by regulators and by society in general) to continue operating at the scale that it currently does.

There are numerous avenues of research and development currently under investigation as the cement sector seeks to improve its environmental performance; these range from the relatively straightforward to the very highly creative, and provide a wealth of opportunities (and at different risk levels, which may appeal to different types of investors, from industry incumbents to national research funders to venture capitalists) by which ideas can be brought into practice. Some of the types of materials and processes under development are discussed below.

2.1 New cement chemistries

Higher-volume blended cements are continuing to receive high levels of interest, including the validation of new supplementary cementitious materials (SCMs) [17, 18], and more extensive use of conventional SCMs such as the national roll-out of Type IL limestone blends in the USA [19] and ternary blends (particularly including calcined clays) in Europe and elsewhere [20, 21]. These processes and materials are clearly attractive as an essential step in the process toward net-zero production of construction materials; this is contingent of course on securing a viable and large-volume supply of SCMs in each particular geographic location [11], and this brings heterogeneity in defining which is the "ideal" solution or material to use in each case. It is therefore also essential to have appropriate standards in place to accommodate the increasing diversity of SCMs – and potentially also continuing up the scale of replacement levels to include cements The increasing importance of non-Portland cements is also being reflected – maybe initially at a symbolic level, but also in practice – by professional bodies who have historically represented Portland cement producers. For

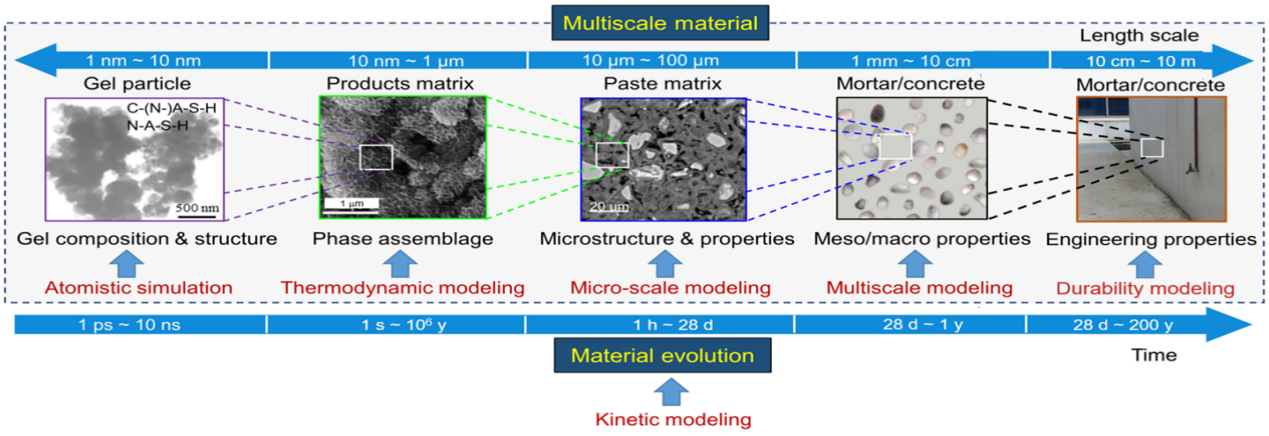

Fig. 1 Schematic illustration of some of the length and time scales that are commonly described when modelling cementitious materials. Adapted from [37] by permission of Dr Y. Zuo.

example, the Portland Cement Association (USA) has in May 2025 been renamed to the American Cement Association, saying that "The name 'Portland Cement Association' no longer accurately reflects the modern mindset of today's manufacturers, or the materials they currently produce" [46]. The American Concrete Institute has also incorporated scope for alternative cements (defined as "an inorganic cement that can be used as a complete replacement for portland cement or blended hydraulic cement") into the flagship ACI Code 318-19 [47] subject to approval by the "licenced design professional and the building official" and following demonstration of appropriate performance. The same organisation also published an important Task Group report describing the scope and some opportunities for alternative cements [48].

In the UK, the industry-led Green Construction Board, and the Institution of Civil Engineers, published a Roadmap which relies heavily on alkali-activated cements in both the medium and longer-term as a way to approach net zero emissions [49], and in Australia, the Concrete Institute of Australia in 2023 presented a "National Roadshow on Lower Carbon Alternative Binder Concrete" [50] to highlight advances in non-Portland (particularly alkali-activated) concretes in conjunction with the release of a new national standard describing those materials [51]. ASTM International and the British Standards Institute have released specifications that either explicitly or implicitly specify alkali-activation as a pathway to production of cements and concretes with potentially significant reductions in CO_2 emissions [32-35]. When such prominent participants in the lifecycle of Portland cement and concrete are now moving toward full recognition of non-Portland cements in general construction applications, following the experience of regional specifying bodies in other nations [52-55], and considering also the re-launch of a European standard for supersulfated cement [56], it is increasingly clear that diversification in cement types in national and international markets is proceeding at speed, providing strong support for ongoing and future developments in the available "toolkit" of cement types [57].

2.2 Alternative routes to Portland clinker

Decarbonisation of Portland cement clinker production is also under active investigation; belitic [58] and iron-rich [59] clinker types offer some opportunities for reduced emissions footprints (and increased use of waste-derived raw materials in the kiln feed) while performing largely similarly to conventional clinkers, although often with some delay to the reaction process; this is in many ways an appealing possibility to evolve from current compositions, although may offer rather a limited extent of emissions reduction. Alternative non-fossil-fuelled processes for the initial removal of CO_2 from limestone (yielding CaO that is potentially suitable for further conversion to clinker) have been proposed using electrical, solar, and chemical routes, as reviewed by [60, 61], and direct electrochemical production of Portland clinker phases in conjunction with steel production has also been described [62]. This type of process tends to gain a lot of publicity and media attention when a new opportunity is announced, which is both a benefit

(for attracting further investment) and a challenge (for appropriate management of expectations) when it happens [63, 64].

However, as with all technologies discussed in this article but particularly relevant to radically new process routes - it is both difficult and essential to generate independent third-party assessments of the technical and environmental claims made by the proponents of a new technology. This was discussed in detail recently by Driver et al. [65] for the case of CO_2 mineralisation, and is particularly important when considering the very high capital costs associated with establishing a new process at million-tonne per year scale [61].

2.3 Uptake of carbon dioxide in cements

Carbon capture and storage in cementitious materials has also been highlighted as an avenue for decarbonisation [66], and features particularly prominently in industry roadmaps for emissions reduction; it has also been highlighted as the greatest risk factor in actually implementing those roadmaps, due to uncertainties around both technical and economic feasibility [67]. Success in the full-scale industrial roll-out of carbon capture projects in the energy sector in general has been very elusive in the past decades [68]. To meet the necessary emissions reduction levels attributed to this technology by global and various national cement and concrete sector net-zero roadmaps, the rate of deployment of carbon capture units on cement kilns needs to increase (very rapidly) from approximately one (pilot-scale) unit every few years, to one or more units per day. This presents a critical challenge to the sector overall, if carbon capture is to play its intended role in the search for carbon emissions reductions. So, in the context of assessing future research directions in this paper, it is difficult to avoid the suggestion that additional emphasis should be placed on other routes to decarbonisation, to mitigate the uncertainty in availability of carbon capture facilities in the short to medium term.

The enforced carbonation of alkaline materials – whether in powder form prior to use in cementitious blends, or to induce/accelerate setting of Portland-based or non-Portland cements, or after a concrete block has hardened – is now a very prominent pathway to production of "low-carbon" construction elements. This is not specifically new technology, as the historical lime-based mortars used in Asia, Europe, Africa, and elsewhere have for many centuries hardened through atmospheric CO_2 uptake [69, 70], and technique for incorporating CO_2 at different stages of the production of various types of cement and concrete are well established. However, it is essential to note that in applying CO_2 treatment to either cementitious powders or concrete elements, the careful control of the CO_2 in this process is imperative. The CO_2 uptake values, and thus the overall environmental balance figures, that are calculated for such processes sometimes assume that all of the CO_2 applied to the powders or concretes is taken up effectively, without any direct losses to atmosphere from opening a process vessel or curing chamber to remove the product at the completion of a batch-mode carbonation cycle, or via leakage from a continuous process. Such an assumption does not appear realistic under many scenarios.

As an illustration of what appears to be a correct accounting for these losses in describing a proposed process: a process involving carbonation of cement suspensions prior to hardening [71] showed an uptake efficiency between 26-45%, which means that the other 55-74% of the CO_2 that was injected into the cement must either be recaptured (and probably re-purified, with associated energy costs) or calculated as being emitted from the process (as it had previously been captured, and so may otherwise have been sequestered in another manner). The authors of that study did find that their process had a net emissions benefit even with these losses taken into consideration, meaning that it was overall a beneficial thing to be doing.

However, when considering different processes in the context of correctly-scoped lifecycle assessments, it is very possible that the advertised savings promoted in a technical publication (or commercial press release) by the inventors or promotors of a process may not necessarily be realistic [65]. So, the ability to actually achieve both economic and technical viability while mineralising CO_2 should be considered carefully when designing and assessing processes.

Also, pilot processes that are currently being developed and implemented are largely based on industrially-produced CO_2 – resulting from the

intentional conversion of hydrocarbons to CO_2 for use as an industrial feedstock – rather than CO_2 captured from industrial processes to reduce their emissions. This can (and probably should) presently be viewed as an "emissions investment", which will be paid back when the processes are transitioned to full-scale operation using captured CO_2. However, the nature of the source of CO_2 used in such processes should be considered; if the CO_2 that is used to carbonate a concrete element has been produced specifically for that purpose, it is correct to ask whether the carbonation uptake is actually a net saving in a global sense. For induced-carbonation processes to bring a genuine benefit, it is imperative that they operate solely using captured CO_2 which would otherwise require another form of sequestration, and this requires careful thought about industrial synergies and co-location of concrete production facilities with large CO_2 capture infrastructure. The direct use of cement kiln flue gas as a source of CO_2 has been discussed [72, 73], but the relatively low concentrations involved in this process mean that the process tends to be rather slow for practical application.

When considering uptake of CO_2 via carbonation of cementitious materials, it is also important to consider when this uptake is actually achieved. Figure 2 shows a schematic view of this situation, illustrating the difference in climate change-related impacts between avoiding CO_2 emissions entirely (or mitigating them at the time of production), and allowing the CO_2 to be emitted but then re-absorbed via carbonation in service. The shaded portion of Figure 2 represents the additional climate effects due to the extra CO_2 remaining in the atmosphere for a longer period of time; this is only a conceptual depiction, but is intended to highlight the urgency of achieving deep carbon emission reductions rather than giving full credit to slow natural carbonation processes for CO_2 uptake.

The direct benefits of accelerated emissions reductions have been calculated under different sets of boundary conditions and assumptions; the details of such work are beyond the scope of the current discussion. However, the importance of urgency in reducing emissions is highlighted by figures such as a calculated reduction by 153 million in the number of worldwide premature deaths by the end of the 21st century, comparing a 2°C warming reference scenario to a 1.5°C warming scenario based on achieving emissions cuts more rapidly up to 2050 [75]. The urgency of the decarbonisation of cementitious materials production must therefore be strongly emphasised. We cannot afford to wait for the availability of new technologies that will only become scaleable close to 2050 before taking action, even if those may enable specific 2050-timed targets to be reached, because the cumulative damage to the global environment during the intervening years will not be acceptable to society.

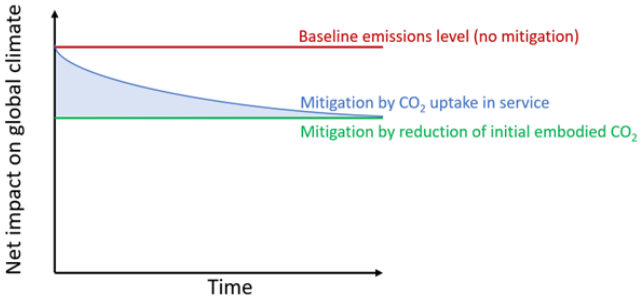

Fig. 2 Schematic illustration of the climate benefits of initial, rather than delayed, mitigation of CO_2 emissions.

The shaded area (between the blue and green curves) represents the difference in net terms, on a timescale of multiple years, gained by preventing or mitigating emissions immediately upon material production, compared to relying on gradual CO_2 uptake in service. The timescale indicated is a period of several decades, corresponding to a good-quality concrete reaching its near-final extent of natural carbonation; the residence time of CO_2 in the atmosphere is subject to significant uncertainty but is likely to be measured in centuries rather than decades [74], so the impact levels per unit CO_2 emission are sketched as being constant over time.

2.4 Making better concrete, and making concrete better – From low–tech to high–tech and back again?

There has sometimes in history been rather a disconnect between those focused on "science" of cements and those who discuss "engineering" of concretes. Fortunately this division seems to be reduced in current practice, as researchers recognise the value and power of interdisciplinary and multiscale studies,

and connect chemical behaviour to macroscopic engineering properties. Recognition of the essential role of chemical admixtures [76] – which are obviously acting at the nanoscale to improve rheology and other engineering-scale properties, and are essential to modern advanced concrete practice – has been a significant part of this process.

However, this is not necessarily a new thing; a quote from Blount in 1915 [77] is particularly of interest in this context:

"Thanks to the fact that for some forty years the regulation of the composition [of Portland cement] has been in the hands of the chemist, little is left to be desired in the modern commercial product".

This rather enlightened view from the past compares very favourably with more recent commentaries, e.g. the following text which is quoted from Neville [78]:

"…I am not concerned with what is sometimes called pure scientific research, which aims at improving understanding [of] the various basic phenomena involved in the behaviour of concrete. That kind of research is valuable in scientific – I am tempted to say, cultural – terms but it is not part and parcel of the construction industry."

As the current article is presented in the context of a research journal, published by a research and innovation-focused society such as ACF, whose main aim is the dissemination of important and useful information to key stakeholders (which would certainly include the "construction industry" as defined by Neville in the quote above), it probably suffices to say that it is fortunate that key decision-makers in the sector hold views more closely resembling those of Blount than those of Neville. This then brings additional opportunities for advancement in "every-day" (conventional) concretes, by application of the science developed for much more "advanced" types of materials – for example, the increased use of chemical admixtures as mentioned above, to offer cost-effective concretes of higher strength and durability for routine applications via reduced water content [76, 79]. Similarly, research into 3D printing of concretes, which should be considered a high-tech application of these materials, has brought new insight into fundamental concrete rheology, stiffening and setting mechanisms as a function of binder chemistry, cold joint formation, non-destructive materials characterisation, and early-age hydration under non-ideal (low relative humidity) conditions, among other factors which are relevant and important also in the successful and efficient design and use of conventional castable concretes [80].

With this more advanced knowledge of both materials design and materials performance at hand, it is then possible to choose a more nuanced view of the selection of the most appropriate material (and process) for a particular application. For example, Müller [81] has illustrated how a concrete designed with increased compressive strength can readily offer lower specific CO_2 emissions, measured in kg CO_2 e/(m3·MPa), and Purnell [82] also discussed differences in specific CO_2 emissions metrics that may be relevant for material to be used in columns or in beams, which can motivate different materials choices depending on the exact application scenario that is envisaged. In the end, it is essential to carefully and correctly frame the specific questions when asking more broadly, "how can I minimise the environmental footprint of this construction" [83], as this requires a many-faceted assessment involving skills sets in materials chemistry, materials engineering, concrete technology, structural engineering, design and architecture, and construction logistics, as well as specific expertise in life cycle assessment [84]. It is only once a question is properly defined that a meaningful answer can be found – and this remains an open (and expensive) challenge when considering cement and concrete materials design, specification and use.

It is also essential, as part of this type of discussion, to mention the key role of standards in both enabling and restricting selection of the most appropriate materials. Conventionally, prescriptive standards for concrete mix design assume (explicitly or implicitly) that stronger concrete should also be more durable concrete, and so specific minimum 28-day strength grades are specified for different types of environmental exposure. While this is clearly logical in the case of physical mechanisms such as freeze-thaw action, and for chemical mechanisms such as alkali-silica reaction that can cause failure by cracking [85], it cannot necessarily be assumed that is this true for materials of very different chemistry, and/or where 28-day strength is not a good representation of the

capabilities of the material in the longer term. It is true that it is difficult to use conventional Portland cement to make highly durable low 28-day strength concretes, but it is less clear whether this is necessarily true for other cements. It is quite possible that there are lessons to learn here from historical concrete formulation and usage practices, where there are numerous examples (e.g. [86, 87] and other literature) of decades-old or centuries-old materials giving – for various reasons – better durability than their modern equivalents which are generally formulated for high flowability and rapid early strength development.

Similarly, the question of whether standards should specify a minimum cement (or paste) content per cubic metre of concrete, or alternatively a maximum total water content, remains open even for Portland cement-based materials [88]. Even the definition of parameters as fundamental as "water/cementitious materials ratio" in higher-volume Portland blends remains contentious [89], and this places challenges in the way of deployment of such materials in various countries.

The standardisation of alternative non-Portland binder systems is in most countries following a performance-based approach rather than the prescriptive approaches applied to Portland cement concrete design [23], and so there is a fundamental need to better define (in both philosophical and practical senses) what is meant by "performance" in this context. There is a very strong temptation to default back to established reliance on 28-day compressive strength, or basic highly-accelerated tests that are intended to approximate "real" behaviour under attack by chloride, or carbonation, or other important durability considerations. Whether these parameters (and test methods) are meaningful and/or representative for non-conventional cement or concrete types is under open and highly active investigation [90-94].

There is also increasing interest – and significant potential benefit – related to alternative forms of reinforcement of concretes; the use of non-metallic (continuous or fibre) reinforcement is the subject of a large American Concrete Institute initiative at present [95], and can be connected to the discussion in the previous section regarding alternative binder chemistries. At present, cements are designed more-or-less universally to enable the passivation of mild steel, with a high pH, low permeability, and minimised chloride content. However, where reinforcement types other than mild steel are used, this requirement may potentially be relaxed. This may bring into consideration cement types (or admixture types) which are currently not able to be used in structural concrete due to high chloride content (e.g. alinite cement [96] or Sorel-type oxychloride cements [97]), or which have near-neutral or only slightly alkaline pH values (e.g many types of Mg-based binder [98], or cements using an acid-phosphate constituent [99, 100]).

3. Concluding remarks: Making better use of better concrete – Putting the pieces together

The title of this concluding section is intended to mirror the final bullet point from the Introduction section ("using concrete better"), but also with a shift in emphasis to also incorporate the innovations at material and process levels that have been described in the previous sections. Simply stating that concrete needs to be "used better" puts the onus on a designer, structural engineer, or constructor to make improvements in their own sphere of influence – and this is absolutely necessary (particularly when discussing workmanship in construction), yet also not in itself sufficient to reach the essential end-point of sustainable construction. Rather, the responsibility for improvements in the use of materials in engineering works must be shared between those who specialise in the design aspects, and those who specialise in materials. Improvements at a material level can support (and potentially enable) innovation in design and structural domains, as opportunities are unlocked by advances in material properties and performance, supported by the necessary codes and standards to enable practical application. It is essential to build more efficiently, in both material production and material usage domains, while achieving the necessary structural safety and reliability – and this is fundamentally a cross-disciplinary question requiring collaboration across experts who specialise in different length scales and different time scales. This requires connectivity across specialisations – and here professional societies such as ACF and its regional and global counterparts have a potentially enormous role to play, along with initiatives such as the

GLOBE Consensus (https://globe-consensus.com/) and others.

Looking forward to the next 20 years of the ACF, it is therefore highlighted that in a time of increased global uncertainty and severe climate challenges, the power of connections between people – as enabled by organisations such as ACF – is what will enable a sustainable future for construction to be unlocked. The future of global concrete innovation and production will certainly continue to take on an ever more Asian-influenced character, as the resources (both intellectual and technical) that are building rapidly in many Asian nations will be brought to bear more and more strongly to address challenges at a global scale. This leadership and influence can be focused and leveraged through organisations such as ACF, which will therefore continue to hold a major role in the global professional landscape in coming years.

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