Introduction

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1.1 Climate emergency, resource efficiency and circular economy

In 2018, Professor Bendell authored a dramatic piece warning about the probable social collapse articulating the perspective that it is now too late to stop a future collapse of our societies because of the current climate emergency, and that we must now explore ways to reduce harm (Bendell, 2018). His warning was taken seriously by the European Commission who invited him for a presentation in 2019 (Bendell, 2019). Also, on November 5, 2019, Ripple et al. (2019) warned that "clearly and unequivocally planet Earth is facing a climate emergency" which was tacit support for Bendell's views. This emergency helps to explain why this chapters does not start with a classic review of the recent developments of alkali-activated concretes but instead by reviewing crucial facts about climate emergency, resource efficiency, and the circular economy as a way to provide a context for the contribution of alkali-activated concrete. The rate of warming of the Arctic temperature has more than doubled the rate of in recent decades (Xiao et al., 2020). As a consequence, the replacement of ice by water will lead to a higher absorption of solar radiation that makes oceans warmer, causing basal ice melting (Tabone, Robinson, Alvarez-Solas, & Montoya, 2019) and a warmer atmosphere. This constitutes positive feedback that aggravates the aforementioned problem. The latest data on rates of melting combined with new models suggest that an ice-free Arctic summer could occur by 2030 (Screen & Deser, 2019). The warming of the Earth will also result in extensive permafrost thaw in the Northern Hemisphere. With thaw, large amounts of organic carbon are mobilized, where some are converted and released into the atmosphere as greenhouse gases. In turn, this facilitates positive permafrost carbon feedback and further warming (Tanski, Wagner, Fritz, Sachs, & Lantuit, 2018). In 2019, Turetsky reported that permafrost thawing could release between 60 billion and 100 billion tons of carbon. This, in addition to the 200 billion tons of carbon expected to be released in other regions, lead to more thawing. Vicious cycles of drought leading to fire leading to more drought constitute more positive feedback, thereby aggravating carbon dioxide emissions and global warming. Kareiva and Carranza (2018) stated that positive feedback loops represent the

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gravest existential risks, and the risks society is least likely to foresee. Recently, Bamber, Oppenheimer, Kopp, Aspinall, and Cooke (2019) concluded that future sea level rise with the inclusion of thermal expansion and glacier contributions results for 2100 will exceed 2 m, which is more than twice the upper value put forward by the Intergovernmental Panel on Climate Change in the Fifth Assessment Report. This is especially worrisome because 90% of urban areas are situated on coastlines, making the majority of the world's population increasingly vulnerable to the current climate emergency (Elmqvist et al., 2019). At the same time, the United Nations estimates that by 2030, 700 million people will be forced to leave their homes because of drought. Drought and heat waves associated with this climate emergency are responsible for damaging crop yields, deepening farmers' debt burdens and inducing some to commit suicide. No wonder that Wallace-Wells (2017) wrote about catastrophic scenarios that include starvation, disease, civil conflict, and war. To make things worse, the current climate emergency is also impacting microorganisms not only exacerbating the impact of pathogens and the increase of diseases but also having a positive feedback on climate change (Cavicchioli et al., 2019). It is no surprise that some (Harper, 2020; Gills, 2020) believe that Covid-19 is the pandemic that humanity deserves. Still some researchers believe that that the disruptive forces of Covid-19 could serve as a way to accelerate the decline of carbon-intensive industries, technologies, and practices, thus helping to drive low-carbon innovation (Markard & Rosenbloom, 2020). As it is, climate change policy should not only focus the reduction of GHG emissions from energy, but should also limit the quantity of raw materials used in manufacturing processes based on fossil fuels, as they represent 45% of the total current GHG emissions (Durán-Romero et al., 2020). An interesting picture in the March 2020 issue of National Geographic magazine showed that, annually, the world economy uses more than 100,000 million tons of natural resources (an average of 13 tons per person). Of that consumption, 67,000 million tons are transformed into atmospheric pollution like carbon dioxide or become solid waste like the plastics that enter the oceans each year. Of the remaining 35,000 million tons, only 8400 million tons are reused. The project population growth in 2050 is expected to reach 9.7 billion (UN, 2019), which would mean an increase of natural resources to 126,000 million tons per year. That means we need to increase the reuse of those resources by an additional 26,000 million tons per year just to tackle the consumption associated with population growth. Deetman et al. (2020) recently modeled global building stock and construction materials and showed that the demand for construction materials will continue to increase in most regions, even in developed countries. For instance, the global demand for steel and cement for the building sector is estimated to be 769 MT/year and 11.9 GT/year, respectively. With respect to building materials, the European Union has assumed a leading role for a sustainable future. The Europe 2020 Strategy and its flagship initiative on "A Resource Efficient Europe" (COM, 2011b) set the EU on this path towards transformation. The flagship called for a roadmap "to define medium and long term objectives and the means needed for achieving them." The Roadmap to a resource efficient Europe (COM, 2011a) proposes a new pathway to action on resource efficiency involving all key stakeholders, sets several milestones to 2030 and provides a framework explaining how policies interrelate and build on each other in which future actions can be designed and implemented coherently. An important concept inserted in the Europe 2020 Strategy for smart, sustainable, and inclusive growth is the circular economy (COM, 2014). The concept of Circular Economy (CE) emerged as a way to increase resource use efficiency and minimize resource inputs, waste, and emissions generation. The definition of the circular economy concept encompasses: "open production systems—in which resources are extracted, used to make products and become waste after the product is consumed—should be replaced by systems that reuse and recycle resources and conserve energy," (Huysman, De Schaepmeester, Ragaert, Dewulf, and De Meester (2017)). Recently, some authors have suggested a Circular Economy model (Durán-Romero et al., 2020). Nevertheless, other authors have warned about problems associated with recycling high waste content. Lee, Pedersen, and Thomsen (2014) warned that full implementation of European waste legislation will increase unwanted micro-pollutant recycling. The studies of Knapp, Allesch, Müller, and Bockreis (2017) confirmed this problem by showing certain contaminants can be critical. These authors state that regulations for material recycling are required to ensure adequate quality control measures. Also, although the concept of circular economy is already being enforced by several countries, some authors showed that there are still several limits and challenges to be addressed. One reason concerns the fact that countries are not interested in allowing hazardous materials (even with just trace amounts) to cross borders (Service, 2020). In 2015, a tailings dam in Brazil collapsed, killing 19 people and contaminating 668 kilometers of river. In 2018, a dam failed at a major mine in Australia. Last year, a dam disintegrated at a decommissioned Brazilian iron mine, releasing 21 million cubic meters of mine wastes and killing 270 people (Cornawall, 2020a,b). Also, what about the billions of tons of red mud piling up, where only 3% is currently recycled? Nevertheless, and since alkali-activated materials have shown to be more apt to reuse industrial wastes (van Deventer, Provis, & Duxson, 2010; Pacheco-Torgal, Labrincha, Leonelli, Palomo, & Chindaprasit, 2014; Bernal, Rodríguez, Kirchheim, & Provis, 2016; Wan et al., 2018; Abdulkareem, Havukainen, Nuortila-Jokinen, & Horttanainen, 2021), the contribution of alkali-activated concrete would be especially important in that context. However, there are pessimistic views (Habert, Miller, & John, 2020) claiming that the monopoly of concrete based on OPC will not be overthrown due to the risk aversion of the construction industry. Still, the authors of this chapter believe that it is unlikely that risk aversion is the real reason, and, instead, the construction industry is focused on minimizing up-front build costs. So when global governments decide to place a high tax on the extraction of virgin raw materials, thus benefiting materials that can recycle a high waste content, alkali-activated concrete mixtures could finally gain a cost-competitive edge over Portland cement concrete-based mixtures. Its worth noting that the extraction of virgin raw materials have already existed in Nordic countries since the 1990 s and that environmental taxation is becoming an important component to enforce a circular economy (Vence & López Pérez, 2021). Even more important, one must remember that it was the shortage of Portland cement in the former Soviet Union that was responsible for the construction of many infrastructures using alkali-activated slag-based concrete (Provis & Van Deventer, 2013). That shortage may occur again in the not so distant future in countries that do not decide to ban the extraction of nonessential virgin raw materials to prevent the polluting consequences of the extraction process such as the loss of biodiversity and the contamination of groundwater and surface water.

1.2 Brief overview on alkali-activated materials concrete

The first edition of the Handbook of Alkali-Activated Cements, Mortars and Concrete that was published in 2014 was later selected to be indexed in Scopus database where it has already received more than one hundred citations, and, as consequence, is in the top 1% most-cited publications in the field of alkali-activated binder based materials published since 2014. The structure of the first edition had much to do with the fact that back then the investigations made in this field of research were mainly by chemistry and materials science experts. Only few researchers from civil engineering were involved in this area, which helps to explain why the first edition had a low number of chapters about concrete formulations and concrete performance and many chapters had nothing to do with concrete at all. For instance, the chapters regarding coatings, geotechnical or thermal insulation applications, photocatalytic degradation of pollutants or even about efflorescence. In what concerns the important issue of efflorescences in alkali-activated materials although the first publication referenced on Scopus database about alkali-activated materials is from the year 1979 it took 30 years so researchers in that field start writing on the problem of efflorescences. Hundreds of researchers prefer to highlight the positive aspects of alkali-activated materials, sometimes exaggerating them and choosing to hide negative aspects. More than a decade ago, senior scientist Frantisek Skvara told the first author of this chapter that over many years when he went to conferences and mentioned the problem of efflorescence no one would discuss it. Of course, it was much more interesting to report positive and exciting findings but that may help the advancement of science. This shortcoming also helps to understand why this area has been incapable of scratching the industrial importance of Portland cement. Fortunately, in recent years, a Scopus survey shows that many researchers have dedicated their efforts to solving this problem. Going back to the alkali-activated concrete topic, it is worth remembering that since the aforementioned publication of the Handbook many researchers from civil engineering have studied alkali-activated concrete mixtures. A Scopus survey for the papers published since 2014 having the words “alkali-activated concrete” or “geopolymer concrete “in the title retrieved 540 documents for the former and 1458 documents for the latter. One comment regarding the statistics concerns the fact that many of those geopolymer-related publications could have used the term geopolymer more for marketing purposes than for scientific reasons, as suggested by Provis & Van Deventer (2013). This means that the alkali-activated terminology is not gaining traction against the commercial terminology "geopolymer," which does not help the market acceptance of these materials. Contrary to what Pacheco-Torgal, 2015 wrote in the first edition of this book, the authors of this chapter agree that a new terminology is indeed needed, and since the authors of these chapters believe that waste recycling (and not carbon dioxide performance) is the most important feature of these material, a new terminology that promoting its high recycling ability is essential for its future widespread application in the construction industry.

The aforementioned Scopus survey also shows that in 2014, less than 90 publications were written with respect to these concretes, but those numbers have been growing, and in the last two years more than 200 publications were published each year regarding alkali-activated concrete. These are mostly journal articles (70%), where Construction and Building Materials is the most-cited journal for the results of their studies. As a consequence, it is important that this knowledge must be digested/curated to avoid duplicated investigations for which the present proposal intends to make a substantial contribution. This curating task is important because the publication deluge in all scientific fields is a serious problem as recognized by Pan, Petersen, Pammolli, and Fortunato (2018). Studies on alkali-activated concrete published since 2014 include several reviews that can be summarized as follows. In 2016, Ding et al. reviewed the mechanical properties of alkali-activated concretes mostly based on slag-based, fly ash-based, and fly ash/slag-based types. They reported that a combination of slag and fly ash allows alkali-activated concretes to achieve a reasonable early age compressive strength without heat curing. They also concluded that the slag/fly ash ratio is a very influential factor to the mechanical properties of AAC. Zhang, Shi, Zhang, and Ou (2017) reviewed the durability of alkali-activated materials including factors influencing water absorption and permeability of AAMs, effect of gel composition and exposure environments on carbonation, chloride penetration and chloride migration test methods, and sulfate resistance in high-calcium and low-calcium alkali-activated systems. The review carried out by Ma, Awang, and Omar (2018) sorted six groups of alkali-activated concrete according to the aluminosilicate sources. Fly ash FA-based, metakaolin MK-based, slag SG-based, rice husk ash RHA-based, high-calcium wood ash HCWA-based and a combination of either two of the earlier mentioned aluminosilicates. Zhang, Wang, Li, Wang, and Ling (2020) reviewed 173 papers on alkali-activated concrete (still only 160 had concrete in the title) focusing on source materials, alkaline activator requirements, curing conditions, compressive strength, elastic performance, tensile strength, flexural strength, fracture performance, bonding strength between geopolymer/alkali-activated concrete and steel bars, high temperature resistance, abrasion resistance, porosity and water absorption, frost resistance, chemical attack resistance, drying shrinkage, and carbonation resistance. The authors concluded that the current research status reveals that more investigations related to feasible and economical mix proportions, with which the geopolymer/alkali-activated concrete could exhibit the best engineering properties, are required. Elahi, Hossain, Karim, Zain, and Shearer (2020) reviewed 229 papers on alkali-activated materials focusing on raw materials and fresh properties. They reported a decrease in workability when high-calcium materials are used and when an increased molar ratio of sodium silicate to sodium hydroxide is used. Hassan, Arif, and Shariq (2020) reviewed the performance of reinforced geopolymer concrete structural elements. This paper has some conflicting statements like when they mention in the introduction that the initial price of GPC has been one of its main drawbacks compared to OPC concrete; however, they are expected to even up in the long run as the price of carbon dioxide emissions during the clinker production will be incorporated in the future costing of OPC concrete, but in the conclusions, they stated the opposite claiming that since the essential component of GPC is an industrial byproduct (FA), GPC is comparatively low cost to produce. This information neglected that the costliest part of alkali-activated materials are the activators. The same incorrect considerations on cost were made in a recent literature review by Amran, Alyousef, Alabduljabbar, and El-Zeadani (2020). Also, in the introduction, they refer to the sialate terminology, thereby neglecting what was written by Provis and Van Deventer (2009) who mentioned that the sialate nomenclature "implies certain aspects of the geopolymer gel structure which do not correspond to reality." Chowdhury et al. (2020) carried out a light review (based on less than forty references) on some properties without extracting relevant knowledge. In fact, the paper has some weaknesses like when the authors mention that "The term geopolymer was first introduced by Davidovits in 1979" forgetting that geopolymer is just a commercial name for the alkali-activation of kaolinite/limestone/dolomite (Palomo et al., 2014) and also that a 1908 patent of Kuhl was recognized as the first on the alkali activation of aluminosilicate precursors to obtain an ordinary Portland cement (OPC) alternative material (Provis, 2014). Not to mention that they also fail to understand that the claims of Davidovits concerning the fact the geopolymers had 80% less carbon emissions than Portland cement were not scientifically valid and never been submitted to a peer review process. Also, since Habert, De Lacaillerie, and Roussel (2011) have proven beyond any doubt that the production of most standard types of geopolymer concrete has just a slightly lower impact on global warming than standard Ordinary Portland Cement (OPC) concrete and on the other hand they have higher environmental impact regarding other impact categories than global warming. Furthermore, Turner and Collins (2013) showed that the CO_2 footprint of a 40 MPa alkali-activated concrete was approximately 9% less than comparable concrete containing 100% OPC binder, and the OPC concrete mixture used in this study could have a much lower carbon footprint even below the geopolymer concrete mixture if fly ash had been used as a partial replacement of Portland cement as its current practice in the construction industry. The bottom line is that several reviews have been carried out in the field of alkali-activated concrete, but they fail to capture the essential knowledge already produced in the field of alkali-activated concretes, which is the motivation for this book.

1.3 Outline of the book

This book provides an updated state of the art on the field of alkali-activated concrete.

The first part reviews the mix design, rheology, and curing of alkali-activated concrete mixtures (Chapters 2–8).

Chapter 2, A Mix Design Procedure for Alkali-Activated Concrete Based on the Concept of Reactive Modulus presents a unified mix design procedure for alkali-activated concrete. Using the concept of the reactive index, which is formulated by five major oxides in the reactive ingredients in AAC (CaO, Na_2O, SiO_2, Al_2O_3 and Fe_2O_3) together with other key mixing factors for an AAC mix (i.e., water-to-geo-solids ratio, paste-to-aggregate volume ratio, and coarse-to-fine aggregate volume ratio), a unified model for predicting the compressive strength of AAC at each given temperature interval is successfully developed. Examples of the application of such a procedure are provided and validated using recently-published experiments.

Chapter 3, Mix Design of Fly Ash Based Alkali Activated Concrete concerns the mix design of fly ash-based alkali-activated concrete. It uses Artificial Neural Network and Multivariate Adaptive Regression Spline techniques to compare the 28-day compressive strength predictions against the actual values. Targeted compressive strengths ranging from 30 to 55 MPa at 28 days were achieved with laboratory testing using the proposed mix design methodology.

Chapter 4, Alkali-Activated Dry-Mix Concretes reviews alkali-activated dry-mix concrete in terms of mix designs and proportioning, fresh and hardened properties, micro and nanostructure, and environmental and cost evaluation.

Chapter 5, Optimization of Production Parameters of Alkali-Activated Concrete provides a brief review about important parameters for the production of alkali-activated concrete.

Chapter 6, Influence of Precursors on Rheology of Alkali-Activated Material categorizes alkali-activated materials based on the type of aluminosilicate precursors and discusses the effects of the aforementioned parameters on the rheology of alkali-activated materials.

Chapter 7, Alkali-Activated Concrete via Oven and Microwave Radiation Curing presents a comprehensive review on alkali-activated concrete via oven and microwave radiation curing, where the influences of oven and microwave radiation curing on the alkali-activated concrete were investigated with respect to their physical, mechanical, and chemical properties.

Chapter 8, Oven-Cured Alkali-Activated Concrete presents the current state of research on the effect of these parameters on the mechanical (under compression, flexure, and tension load), durability (water absorption and sorptivity, sulfate resistance, carbonation, and freeze-thaw resistance), time-dependent (creep and shrinkage), and ultrasonic pulse velocity properties of oven-cured alkali-activated concrete.

The properties of alkali-activated concrete are the subjects of Part II (Chapter 9 – Chapter 14).

Chapter 9, Nonconventional Alkaline Activating Solutions for Alkali-Activated Mortars and Concretes presents an overview of the production, characterization, application, and environmental aspects of alkali-activated concretes produced using non-conventional alkaline activating solutions

Chapter 10, Ambient-Cured Geopolymer Concrete With Single-Alkali Activator analyzes the mechanical properties and microstructure of mixtures based on fly ash, ground granulated blast furnace slag, and silica fume that were activated using a single-alkali activator

Chapter 11, Alkali-Activated Concrete Versus Ordinary Portland Cement Concrete and Roman Concrete When Using Sea Sand and Seawater compares the performance of alkali-activated concrete versus OPC concrete when using sea sand and seawater.

Chapter 12, One-Part Alkali-Activated Concrete With Seawater discusses recent investigations on one-part alkali-activated materials with seawater in terms of binder composition, reaction products, physical properties and durability, as well as current research limits and potential opportunities.

Chapter 13, Properties of Lightweight Fiber Reinforced Alkali-Activated Concrete covers the performance of acoustic panels made with fiber-reinforced alkali-activated slag foam concrete containing lightweight recycled aggregates produced using an industrial side stream

Chapter 14, Properties of Alkali-Activated Lightweight Concrete presents a brief overview of the properties of alkali-activated lightweight concrete. The strengths of lightweight concrete were examined by considering the aggregate type and density, the alkali activator type and concentration, the type of fiber reinforcements and foaming agents, which are the factors that have the most impact on strength. Thermal conductivity, fire resistance, acoustic performance, and durability properties have been explained considering the key points in the literature.

Chapter 15, Structural Performance of Waste-Based Reinforced Alkali-Activated Concrete reviews the structural performance of reinforced alkali-activated waste-based concretes used in the production of beams, columns, walls, tunnel panels and railway sleepers

Part III (Chapter 16-Chapter 22) deals with the durability and Life cycle analysis (LCA) of alkali-activated concrete

Chapter 16, Alkali-Aggregate Reaction in Alkali-Activated Cement Concretes summarizes the problems of alkali-aggregate reaction in alkali-aggregate concretes.

High-calcium and low-calcium alkaline activated cement concrete have been separately summarized, and the effects of AAR on these two systems were compared. The effects of the activator modulus, sodium oxide content, the percentage of calcium, silica, and aluminum, and the content of aggregates on the expansion of alkali-activated concrete were discussed.

Chapter 17, Chloride Penetration in Alkali-Activated Concrete reviews various aspects associated with chloride penetration on alkali-activated concrete. It covers the influence of precursors, activators, and curing on chloride transport mechanisms.

Chapter 18, Seawater Resistance of Alkali-Activated Concrete discusses the durability of different alkali-activated concretes in the marine environment. Aggressive ion compositions of the marine environment in several regions are summarized, and the chemical attacks and deterioration mechanisms of geopolymer concretes are investigated in detail

Chapter 19, Acid Resistance of Alkali-Activated Concrete discusses the resistance of alkali-activated concrete against acid attack. It reviews the deteriorating effect of acid on alkali-activated concretes, the characteristics of the acid environments, and the standards used to determine the acid resistance of alkali-activated concretes. Effects of acid attack on the mechanical, physical, and microstructural properties of alkali-activated concrete are also reviewed.

Chapter 20, Fire Resistance of Recycled Aggregate Alkali-Activated Concrete reviews aspects related to thermal characteristics and response to exposure to the elevated temperatures of alkali-activated concrete containing recycled aggregates.

Chapter 21, Lifecycle Assessment of Lightweight Alkali-Activated Concrete looks at the life cycle assessment of lightweight alkali-activated concrete.

Chapter 22, Lifecycle Assessment of Fiber-Reinforced Alkali-Activated Concrete closes Part IV by assessing the environmental performance of several fiber reinforcements of alkali-activated mixtures used to build sewer pipes for hydraulic engineering

References

Abdulkareem, M., Havukainen, J., Nuortila-Jokinen, J., & Horttanainen, M. (2021). Environmental and economic perspective of waste-derived activators on alkali-activated mortars. *Journal of Cleaner Production*, *280*, 124651.

Amran, Y. M., Alyousef, R., Alabduljabbar, H., & El-Zeadani, M. (2020). Clean production and properties of geopolymer concrete; A review. *Journal of Cleaner Production*, *251*, 119679.

Bamber, Jonathan L., Oppenheimer, Michael, Kopp, Robert E., Aspinall, Willy P., & Cooke, Roger M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences*, *116*(23), 11195−11200.

Bendell, Jem (2018). Deep adaptation: a map for navigating climate tragedy. Institute for Leadership and Sustainability (IFLAS) Occasional Papers Volume 2. University of Cumbria, Ambleside, UK. http://insight.cumbria.ac.uk/id/eprint/4166/1/Bendell_DeepAdaptation.pdf.

Bendell, Jem (2019). Because it's not a drill: technologies for deep adaptation to climate chaos. In: Connect University Conference on Climate Change, 13 May 2019, DG Connect, European Commission, Brussels, Belgium. http://insight.cumbria.ac.uk/id/eprint/4776/.

Bernal, S. A., Rodríguez, E. D., Kirchheim, A. P., & Provis, J. L. (2016). Management and valorisation of wastes through use in producing alkali-activated cement materials. *Journal of Chemical Technology & Biotechnology*, *91*(9), 2365−2388.

Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., … Crowther, T. W. (2019). Scientists' warning to humanity: Microorganisms and climate change. *Nature Reviews. Microbiology*, 1.

Chowdhury et al (2020). Study of various properties of geopolymer concrete − A review.

COM. (2011a). *571. Roadmap to a resource efficient Europe*. Brussels: European Commission.

COM. (2011b). *21. A resource efficient Europe*. Brussels: European Commission.

Cornwall, W. (2020a). A dam big problem. https://science.sciencemag.org/content/369/6506/906.summary.

Cornwall, W. (2020b). Catastrophic failures raise alarm about dams containing muddy mine wastes. https://www.sciencemag.org/news/2020/08/catastrophic-failures-raise-alarm-about-dams-containing-muddy-mine-wastes.

COM. (2014). *398 Final. Towards a circular economy: A zero waste programme for Europe*. Brussels: European Commission.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, 118658.

Durán-Romero, G., López, A. M., Beliaeva, T., Ferasso, M., Garonne, C., & Jones, P. (2020). Bridging the gap between circular economy and climate change mitigation policies through eco-innovations and Quintuple Helix Model. *Technological Forecasting and Social Change*, *160*, 120246.

Elahi, M. M. A., Hossain, M. M., Karim, M. R., Zain, M. F. M., & Shearer, C. (2020). A review on alkali-activated binders: Materials composition and fresh properties of concrete. *Construction and Building Materials*, *260*, 119788.

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., ... Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability*, *2*(4), 267.

Gills, B. (2020). Deep restoration: From the great implosion to the great awakening. *Globalizations*, *17*(4), 577−579.

Habert, G., De Lacaillerie, J. D. E., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: Reviewing current research trends. *Journal of Cleaner Production*, *19*(11), 1229−1238.

Habert, G., Miller, S. A., John, V. M., et al. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat Rev Earth Environ*.

Harper, K. (2020) The coronavirus is accelerating history past the breaking point. https://foreignpolicy.com/2020/04/06/coronavirus-is-accelerating-history-past-the-breaking-point/.

Hassan, A., Arif, M., & Shariq, M. (2020). A review of properties and behaviour of reinforced geopolymer concrete structural elements-A clean technology option for sustainable development. *Journal of Cleaner Production*, *245*, 118762.

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, Conservation and Recycling*, *120*, 46−54.

Kareiva, P., & Carranza, V. (2018). Existential risk due to ecosystem collapse: Nature strikes back. *Futures*, *102*, 39−50.

Knapp, J., Allesch, A., Müller, W., & Bockreis, A. (2017). Methods to estimate the transfer of contaminants into recycling products−A case study from Austria. *Waste Management*, *69*, 88−100.

Lee, J., Pedersen, A. B., & Thomsen, M. (2014). Are the resource strategies for sustainable development sustainable? Downside of a zero waste society with circular resource flows. *Environ. Technol. Innov.*, *1*(2), 46−54.

Ma, C. K., Awang, A. Z., & Omar, W. (2018). Structural and material performance of geopolymer concrete: A review. *Construction and Building Materials*, *186*, 90−102.

Markard, J., & Rosenbloom, D. (2020). A tale of two crises: COVID-19 and climate. *Sustainability: Science, Practice and Policy*, *16*(1), 53−60.

Pacheco-Torgal, F. (2015). *Introduction to handbook of alkali-activated cements, mortars and concretes. Handbook of alkali-activated cements, mortars and concretes* (pp. 1−16). Woodhead Publishing.

Pacheco-Torgal, F., Labrincha, J., Leonelli, C., Palomo, A., & Chindaprasit, P. (Eds.), (2014). *Handbook of alkali-activated cements, mortars and concretes*. Elsevier.

Palomo, A., Krivenko, P., Garcia-Lodeiro, I., Kavalerova, E., Maltseva, O., & Fernández-Jiménez, A. (2014). A review on alkaline activation: New analytical perspectives. *Materiales de Construcción*, *64*(315), 022.

Pan, R. K., Petersen, A. M., Pammolli, F., & Fortunato, S. (2018). The memory of science: Inflation, myopia, and the knowledge network. *Journal of Informetrics*, *12*(3), 656−678.

Provis, J. L. (2014). Geopolymers and other alkali activated materials: Why, how, and what? *Materials and Structures*, *47*, 11−25.

Provis, J. L., & Van Deventer, J. S. (Eds.), (2013). *Alkali activated materials: State-of-the-art report, RILEM TC 224-AAM* (Vol. 13). Springer Science & Business Media.

Provis, J. L., & Van Deventer, J. S. J. (Eds.), (2009). *Geopolymers: Structure, processing, properties and industrial applications*. Cambridge, UK: Woodhead Publishing.

Ripple, W. J., Wolf, C., & Newsome, T. M. (2019). World Scientists' Warning of a Climate Emergency. *BioScience*. Available from https://doi.org/10.1093/biosci/biz088.

Screen, J. A., & Deser, C. (2019). Pacific Ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean. *Geophysical Research Letters*, *2019*.

Service, R. (2020). Red mud is piling up. Can scientists figure out what to do with it? https://www.sciencemag.org/news/2020/08/red-mud-piling-can-scientists-figure-out-what-do-it.

Tabone, I., Robinson, A., Alvarez-Solas, J., & Montoya, M. (2019). Submarine melt as a potential trigger of the North East Greenland Ice Stream margin retreat during Marine Isotope Stage 3. *The Cryosphere*, *13*(7), 1911−1923.

Tanski, George, Wagner, Dirk, Fritz, Michael, Sachs, Torsten, & Lantuit, Hugues. (2018). Impetuous CO_2 release from eroding permafrost coasts.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A., . . . Hugelius, G. (2019). Permafrost collapse is accelerating carbon release.

Turner, L., & Collins, F. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*, *43*, 125−130.

UN (2019). How certain are the United Nations global population projections? https://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2019-6.pdf.

van Deventer, J. S. J., Provis, J. L., Duxson, P., et al. (2010). Chemical research and climate change as drivers in the commercial adoption of alkali activated materials. *Waste Biomass Valor*, *1*, 145−155.

Vence, X., & López Pérez, S. D. J. (2021). Taxation for a circular economy: New instruments, reforms, and architectural changes in the fiscal system. *Sustainability*, *13*(8), 4581.

Wan, Q., Rao, F., Song, S., Morales-Estrella, R., Xie, X., & Tong, X. (2018). Chemical forms of lead immobilization in alkali-activated binders based on mine tailings. *Cement and concrete composites*, *92*, 198−204.

Wallace-Wells, D. (2017), The Uninhabitable Earth: Famine, economic collapse, a sun that cooks us: What climate change could wreak — sooner than you think, New York Magazine.

Xiao, H., Zhang, F., Miao, L., San Liang, X., Wu, K., & Liu, R. (2020). Long-term trends in Arctic surface temperature and potential causality over the last 100 years. *Climate Dynamics*, *55*(5), 1443−1456.

Zhang, J., Shi, C., Zhang, Z., & Ou, Z. (2017). Durability of alkali-activated materials in aggressive environments: A review on recent studies. *Construction and Building Materials*, *152*, 598−613.

Zhang, P., Wang, K., Li, Q., Wang, J., & Ling, Y. (2020). Fabrication and engineering properties of concretes based on geopolymers/alkali-activated binders-a review. *Journal of Cleaner Production*, 120896.

Further reading

Obenaus-Emler, R., Falah, M., & Illikainen, M. (2020). Assessment of mine tailings as precursors for alkali-activated materials for on-site applications. *Construction and Building Materials*, *246*, 118470.