Produce and use with care

Every step in the life cycle of a material leaves a footprint on our planet. From the extraction or harvesting of raw materials to their conversion into familiar products, and then from the daily use of such products to their disposal, each phase has to be managed responsibly to avoid the risks related to the depletion of resources, increase in CO_2 emissions and waste accumulation. Due to their large worldwide consumption, the environmental impact of some materials is particularly critical. For instance, concrete is one of the most important construction materials used in houses and infrastructure, where it is usually combined with metal alloys for structural reinforcement and decorative purposes. Metals are also used in a wide range of applications, from kitchen tools to vehicles and rocket engines. We asked experts in concrete research and metallurgy their opinions of the critical aspects related to the sustainable production, use and disposal of these materials, and their views on the strategies that are being adopted and may be further explored to decrease the environmental burden of these commodities. In the case of concrete, partial or complete replacement of one of its components, Portland cement, is essential to cut the CO_2 emissions and energy consumption caused by its production. Defect engineering of metal alloys may be a viable approach to tune the mechanical response of structural materials without increasing the number of elements included in their composition.

Towards sustainable concrete

Paulo J. M. Monteiro, **Sabbie A. Miller** and **Arpad Horvath** provide an overview of the challenges and accomplishments in reducing the environmental burden of concrete production.

Except for water, concrete is the most consumed material in the world by mass. With an estimated yearly consumption approaching 30 billion tonnes, concrete outpaces the per capita production of any other material (Fig. 1), and the demand worldwide is ever-growing. In fact, developing countries are investing massively in new infrastructures, and developed countries are facing the challenge of upgrading or replacing their ageing infrastructure. For instance, in 2017 the American Society for Civil Engineers assigned an overall grade of D+ to the United States' infrastructure and reported that there are 188 million daily trips across structurally deficient bridges in the US (http://www.infrastructurereportcard.org). With such an extensive consumption, it is clear that research efforts to increase the sustainability of concrete are important to control the environmental burden of this commodity.

An essential component of concrete is cement, a powder that when in contact with water creates hydration products that 'glue' rock fragments (aggregates) into concrete. The production of traditional cement, called Portland cement, requires heating the basic raw materials — limestone and clay — to 1,450 °C. Due to the calcination of the limestone and fuel combustion, the manufacture of 1 tonne of cement releases approximately 1 tonne CO_2. Its manufacturing is currently responsible for 8–9% of the global anthropogenic CO_2 and 2–3% of energy use, and projections suggest that a 50% increase in annual production of cement should be expected by 2050. With current emission factors and energy consumption, this would lead to an additional 85–105 Gt of CO_2eq emissions over the next 33 years and 420–505 TJ of energy demand (equivalent to the world's greenhouse gas emissions from 2009 and 2010 combined, and the world's primary energy supply in 2005)[1].

Improving the sustainability of cement production by reducing the amount of CO_2 generated and energy used is an important and enduring challenge. One strategy being used is the development of modified Portland cements[2] with the goal of reducing the calcining temperature and hence the energy use. Reduction of CO_2 emissions by adopting 'carbon capture and storage' or 'carbon capture and reuse' technologies in cement production is becoming an attractive and active research area, but still remains uneconomical. Alternative approaches focus on replacing Portland cement in the concrete composition, particularly using cements based on alkali-activated binders often called inorganic polymers or geopolymers. However, these new non-Portland cements lack building codes and data on their long-term durability, and thus urge the development of realistic accelerated tests (experimentally validated durability modelling) and careful analysis of field performance (such as those being conducted for heavy-duty pavements, foundations and precast panels made with alkali-activated binders[3]). Due to long lead times required for the completion of such tests, Portland cement will likely continue to be the primary cement for several decades.

Partial replacement of Portland cement can be achieved by incorporating industrial by-products, such as coal fly ash and iron blast-furnace slag, which can also improve many properties of concrete. There is great interest in developing new sources of such supplementary cementitious materials that can be scaled up worldwide — comprehensive research has shown that calcined clays[4], for instance, are excellent sources. The use of these alternative materials, combined with the optimization of calcium silicate hydrate — the principal binding phase of the concrete matrix — is a promising path for achieving enhanced performance and more durable concrete. Several advanced techniques, including high-resolution synchrotron X-ray spectromicroscopy, high-pressure X-ray diffraction and total scattering methods are being employed to study calcium silicate hydrate. Coupled with advanced atomistic modelling[5], the results are providing the blueprint of how to optimize concrete from the ground up. Interestingly, these characterization tools are also being successfully used to unlock the secrets of the durable and resilient ancient Roman concrete[6].

Improved sustainability can also be achieved by making the life cycle of concrete structures more resilient through improved material performance, integrated structural design with risk-based durability modelling, and optimized construction methods. Recent improvement in material performance includes the use of multiscale fibre reinforcement, steel with improved corrosion resistance, advanced chemical admixtures to improve the rheology of fresh concrete, creation of self-healing concrete — that is, concrete containing limestone-producing bacteria or polymer microcapsules capable of healing microcracks — and development of ultra-lightweight cement composites with low thermal conductivity for energy-efficient buildings[7]. There is also intense research in using recycled aggregates, thus reducing waste and depletion of natural resources. Through concurrent assessment of material properties and environmental impacts associated with the production and use of concrete, mixtures and specialized concretes can be better engineered to both meet performance requirements and improve the sustainability of construction applications. This has also required the development of new metrics for comparison of concrete mixtures, case-based analyses, and formation of new frameworks for assessment[8]. The use of material data repositories and big data analysis will expedite innovation in 'smart' concrete.

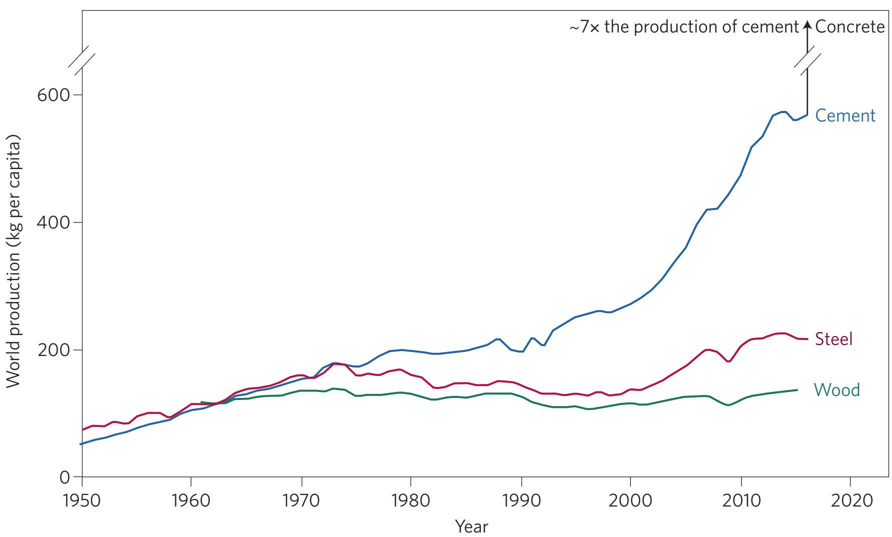

Figure 1 | Historical growth in infrastructure material demand as exemplified through per capita cement, steel and wood production. Note the over ten-fold growth in cement production over the past 65 years relative to the approximately three-fold increase in steel production and nearly stagnant production of wood per capita. Of additional significance, the production of cement correlates approximately to a mass of concrete that is seven-fold larger than that of cement alone. Data taken from refs 11 (steel and cement) and 12 (wood).

Looking ahead, improved policy measures are necessary to fulfil local demands for infrastructure, while meeting global needs to reduce emissions and resource exploitation. Regulatory approaches including improved performance standards, mandatory technologies, economic instruments — such as taxing and subsidies — and voluntary actions will facilitate improved sustainability of cement-based materials, their application and their use[9]. Re-engineering cement and cement-based materials is critical to meeting global emissions goals[10]. Researchers are now well-equipped to tackle the challenge of creating the new generation of concrete, which will require: the development of models, tools and methods to design and construct resilient concrete structures routinely with a lifespan of up to 200 years; the creation of smart self-healing concrete with long-lasting embedded sensors; the use of computer-aided molecular design to manufacture tailor-made chemical admixtures to control the rheology and hardening of concrete containing alternative binders; and the development of disruptive construction methods, including 3D printing. With improvements in production and performance, even if the use of concrete increases, its contribution to global anthropogenic CO_2 emissions could be kept in check. ❐

Paulo J. M. Monteiro and Arpad Horvath are in the Department of Civil and Environmental Engineering of the University of California, Berkeley, California 94720, USA. Sabbie A. Miller is at the Department of Civil and Environmental Engineering of the University of California, Davis, California 95616, USA. P.J.M.M. is also in the Materials Sciences Division at Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA.
e-mail: monteiro@ce.berkeley.edu; sabmil@ucdavis.edu; horvath@ce.berkeley.edu

References

1. Miller, S. A., Horvath, A. & Monteiro, P. J. M. *Environ. Res. Lett.* **11,** 074029 (2016).
2. Juenger, M. C. G., Winnefeld, F., Provis, J. L. & Ideker, J. H. *Cement Concrete Res.* **41,** 1232–1243 (2011).
3. Provis, J. L. *Cement Concrete Res.* http://dx.doi.org/10.1016/j.cemconres.2017.02.009 (2017).
4. Antoni, M., Rossen, J., Martirena, K. & Scrivener, K. *Cement Concrete Res.* **42,** 1579–1589 (2012).
5. Shahsavari, R., Buehler, M. J., Pellenq, R. J.-M. & Ulm, F.-J. *J. Am. Ceram. Soc.* **92,** 2323–2330 (2009).
6. Jackson, M. D. *et al. Proc. Natl Acad. Sci. USA* **111,** 18484–18489 (2014).
7. Kurtis, K. E. *MRS Bull.* **40,** 1102–1108 (2015).
8. Gursel, A. P., Masanet, E., Horvath, A. & Stadel, A. *Cement Concrete Comp.* **51,** 38–48 (2014).
9. Scrivener, K. L., John, V. M. & Gartner, E. M. *Eco-Efficient Cements* (UNEP, 2016).
10. Biernacki, J. J. *et al. J. Am. Ceram. Soc.* http://dx.doi.org/10.1111/jace.14948 (2017).
11. Kelly, T. D. & Matos, G. R. Historical statistics for mineral and material commodities in the United States. *US Geological Survey* http://minerals.usgs.gov/minerals/pubs/historical-statistics/ (2014).
12. Forestry production and trade. *FAO* http://www.fao.org/faostat/en/#data/FO (2017).

Acknowledgements

S. Kevan, K.E. Kurtis, C. Johnson, M.C.G. Juenger, J. Moehle, R. Myers, and R. Shahsavari are thanked for their help.