Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Concrete material science: Past, present, and future innovations☆

Henri Van Damme

Massachusetts Institute of Technology, Civil & Environmental Engineering Dpt, Cambridge, MA, USA
Multiscale Materials Science for Energy and the Environment (MSE), The Joint CNRS-MIT Laboratory, Cambridge, MA, USA
ESPCI Paris, 10 rue Vauquelin, 75231 Paris cedex 05, France

ABSTRACT

Concrete is flying off, but it is simultaneously facing tremendous challenges in terms of environmental impact, financial needs, societal acceptance and image. Based on an historical approach of the science of concrete and reinforced concrete in particular, this paper calls for the exploration of radical changes in three key aspects of concrete use: reinforcement, binder content, and implementation methods. More precisely, it is suggested that, in parallel to the introduction of robotic fabrication methods, digital technologies may be key for the introduction several innovations like (i) rebar-free reinforcement using non-convex granular media; (ii) compression-optimized concrete structures, using topology optimization, architectural geometry, and 3D-printing or origami-patterned formworks; (iii) truly digital concrete through the coupling of massive data collection and deep learning.

1. Concrete: Material, system and icon

Concrete, the mix of aggregates with water and cement, is flying off. Its best commercially traced and documented component, Portland cement or its variants, has been experiencing an unprecedented development since the turn of the millennium, matched only during a few years after WW2 (Fig. 1) [1–3]. Almost twenty years after this rebound, no obvious sign of slowing down is detectable, as this paper is written. Unloved by the majority and yet ubiquitous, concrete is one of the pillars of our developed societies, on equal foot with silicon, oil and gas, each in its own field: infrastructures, high rise, and large residential buildings for concrete; information and communication technologies for silicon; and, so far, transportation for oil and gas. More concrete is produced than any other synthetic material on earth. Twice as much concrete and mortar is used in construction – roughly 35 billion tons [4] – as the total of all other industrial building materials including wood [5], steel [6,7], plastic [8] and aluminium [9]. Roads, bridges, tunnels, dams, power plants, ports, airports, dikes and seawalls, waste- and fresh water plants and networks, all these infrastructures rely on the extensive use of concrete, just like the foundations of our buildings, if not the entire buildings themselves.

There is a wide consensus that the exceptional recent growth of cement and concrete consumption on the global scale is due to a handful of actors only among the emerging countries, China in particular [1,2]. But there are also good reasons to consider that the reason for this lasting growth resides in the current converging needs in developed and developing countries. Beside a huge affordable housing challenge, the world is presently also facing a fantastic infrastructure challenge [10,11]. Infrastructure is the foundation which makes social and economic life possible. It connects people, communities, and businesses. Developed countries face the challenge of maintaining and upgrading their extensive (Box 1) but ageing transport, power, water, and telecommunication networks, whereas developing countries dedicate a large fraction of their national income to satisfy basic human development needs – access to water, sanitation, electricity, and affordable housing – and still fall short of their goal. It is estimated that between now and 2030 an investment larger than the value of today's worldwide infrastructure (over 50 trillion dollars) will be required simply to keep up with projected global GDP growth [11]. The energy transition and the ongoing climate change are probably not going to mitigate the needs. Renewable energy facilities like wind farms require a substantial amount of concrete for their implementation and the rise of the oceans level will likely trigger the construction of thousands of km of protective dams. Actually, there seems to be no other material that could replace concrete in the foreseeable future to meet our societies' legitimate needs for infrastructure, housing, shelter and protection, by the unique property of cement and water transforming a pile of aggregates into rock in a few hours at room temperature.

The social picture is less engaging. Alternatively lauded or execrated, concrete is also the most controversial among all building materials. In spite-, and perhaps because-, of its emblematic role in the development of the modern world, it is crystallizing our expectations,

☆ This paper is dedicated to the memory of Gilles Chanvillard and Ellis Gartner.

E-mail addresses: henrivd@mit.edu, henri.vandamme@espci.fr.

https://doi.org/10.1016/j.cemconres.2018.05.002
Received 22 January 2018; Received in revised form 28 April 2018; Accepted 7 May 2018
0008-8846/

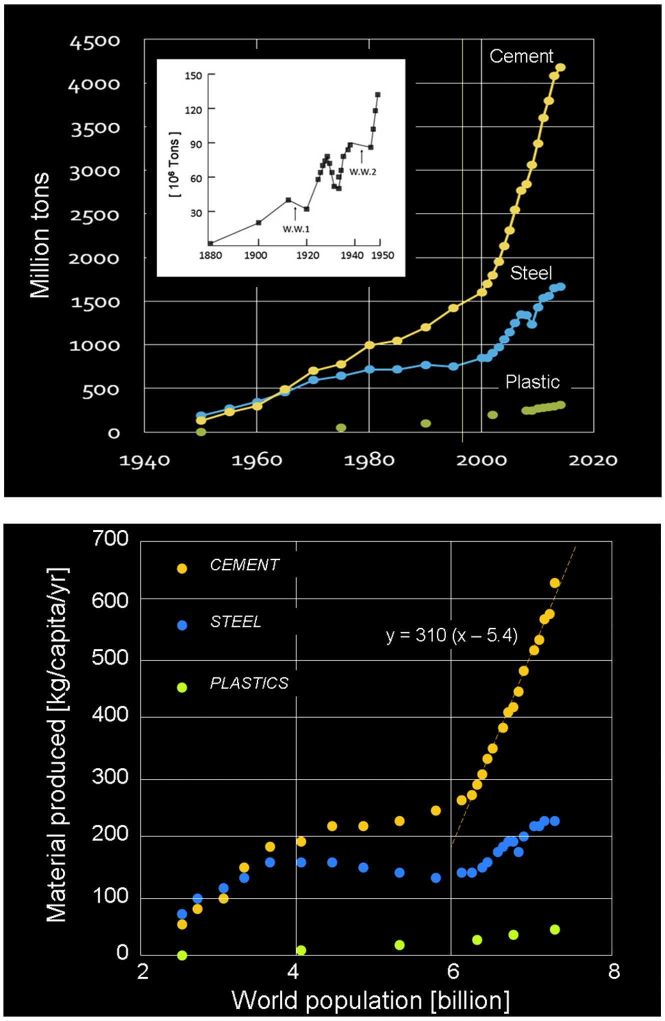

Fig. 1. Top: Comparative evolution of the post-WWII global cement, steel, and plastic productions (data from [1,2] and [6–8]). The inset shows the earlier cement production [3]. Note the strong impact of the 1929 economic crisis on cement production and the hardly noticeable effect of the 2008 crisis, faded away by the growth of emerging economies. Bottom: Same data plotted as material use per capita vs world population.
(Courtesy F.-J. Ulm).

our disappointments and sometimes our hates. Constantly oriented toward modernity and heavily loaded with moral values like honesty, simplicity, functionalism, optimism or communalism by star architects and city planners of the modern movement, concrete has been facing the violence of revolt when people came to compare the promises with the brutality of many urban renewal schemes in the late 20th century and the monotony of contemporary suburban development [20,21]. Widely perceived as dull and repetitive – "in short, a sort of frightening metonymy of the industrial age" [22] – concrete has been so far failing to meet its social promises. In our increasingly ecosensitive early 21st century, concrete is now also blamed for its contribution to carbon emissions and climate change, and to a variety of environmental problems like loss of farm land and increased vulnerability to natural hazards (floods in particular, due to increased imperviousness of soils), destruction of landscapes, loss of biodiversity, destruction of social link, loss of traditional constructive cultures, or depletion of natural resources, sand in particular [23,24]. Taken together, it is an extraordinarily severe indictment that concrete is facing. However, a bit of scrutiny is enough to realize that most of these criticisms are the objections to our dominating socio-economical model itself, concrete just happening to be a particularly ubiquitous and vivid symbol of this paradigm [25].

In a more technical perspective, concrete has also to accept its intrinsically multifaceted or even ambiguous nature. Compared with other building materials, concrete in general and reinforced concrete in particular is indeed heavily loaded with dichotomies [25]. Stretched between liquid and solid, granular and colloidal, gel and crystalline, smooth and rough, compact and porous, metal and mineral, compression and tension, brittle and ductile, material and process, material and structure, experimentation and computation, engineers and architects, technicality and art, worthless and precious, historical and unhistorical, concrete is permanently moving or transgressing the frame of taxonomy [25]. Frank Lloyd Wright went as far as to call it a "mongrel" material, being neither one thing nor another [26].

Actually, whether reinforced with rebars, tendons, fibers, or a combination of those, or even not reinforced at all, concrete is first of all a construction *system*, in which the material itself is intimately coupled to an implementation and a construction method. It was already so in the early days of the mid-nineteenth century, not much after the discovery of modern Portland cement, when the mixture of aggregates, cement and water was implemented in a barely wet state and rammed between movable form to make walls or on a falsework to make arches. Concrete became even more system-like when reinforcement was introduced. The hundreds of patents filed between ~1870 and ~1905 on the subject and the many companies to which they gave birth were all promoting concrete as a particular construction *system*, with a distinctive combination of matrix, reinforcement, structural type, and construction method, sometimes with the help of early computation methods [27–29]. The invention of prestressed concrete in 1928 [30], by removing the dichotomy between tension and compression (perfectly prestressed concrete is supposed to work exclusively in compression), was a radical change in the use of concrete. It might be considered as a step toward simplicity but, in practice, it is the opposite due to its increased computational content and the deep modification in design it led to. More recent developments like self-placing concrete (also termed self-compacting, self-consolidating, or self-leveling concrete) [31] or ultra-high-performance-concrete (UHPC) [32], follow the same trend. Both were initially intended to improve performances and to simplify the construction system (no vibration, less or no passive reinforcement), but the price to pay is a much sharper mix design and a loss of robustness. The same is true for 3D-printable concrete, which has the potential to lead to a totally new construction system. However, while the initial intend was to simplify the traditional construction process and to improve its low productivity [33], the final result is the massive introduction of digital technologies and new stringent requirements in terms of thixotropy and self-adhesion [34].

The *science* of concrete is actually a relatively recent science, contrary to that of cement. Many of the middle nineteenth century inventors were neither scientists nor engineers and several among the main innovators and company leaders of the end of the century were still self-made builders. The marriage between two materials as different as iron and mortar seemed counterintuitive and even counternature to many engineers. For some time, reinforced concrete was considered "uncomputable" [35]. In addition, two questions were shedding doubt on the durability of reinforced concrete. One was the adhesion of hardened cement to iron. Many were convinced that the iron-cement interface would fail soon or later. This led to some hard-to-implement reinforcement systems like the one patented by Paul Cottancin in 1889. Instead of heavy bars, Cottancin was using meshes made of one single iron wire with lots of convolutions supposed to compensate for the bad adhesion [35,36] (note that with the advent of robotic techniques, this may become an attractive technology, see Section 4). A patent was even filed in 1869 on the incorporation of glue in concrete in order to secure adhesion [35].

The other question that was impeding the development of concrete is the matching of the thermal expansion coefficients. Surprisingly, corrosion of the steel reinforcement was apparently not a major