The Transformation of Construction by Concrete

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In this paper I argue that concrete has played a critical role in the complete transformation of construction from a local demand-led craft to a global supply-led industry, a transformation not just of technique, but of labour processes and organisation. I do not aim to deepen existing studies of concrete in terms of materials science, structural or architectural significance. Instead, I am trying to pinpoint the place of concrete in the modern world, identifying and explaining the specific effects it has on that world. This is very much a story of the 20th century, the 100 years it took concrete to change the world. Looking beyond the historiography of architecture and engineering, I concentrate on the production history of a material that ranks alongside steel, coal and oil in significance. In 2009, about 3.5 tons of concrete were produced for each person on the planet, and world production of cement will reach 3.5 gigatons in 2012, more than half of it from China.[1] World cement production is now half as much as hard coal; it is double that of crude steel and demand for it continues to grow ahead of GDP growth rates in most economies.[2]

Modern concrete is produced through investment in capital-intensive processes and equipment. Cement production, the winning of sand and aggregate and the batching, mixing and distribution of concrete have transformed the entire commercial and organizational basis of construction worldwide.[3] Concrete represents a shift in knowledge capital from the demand side of construction to the supply side bringing with it structural change in the labour process – more knowledge in management, less in manual work. Concrete has fostered the rise of the structural engineer at the expense of the architect and the domination of engineering knowledge through the intellectual property held by the cement producers.

The emergence of concrete as a constructional material between 1890 and 1910 is the most astonishing development in the whole history of building technology. It is a scientific material invented in the laboratory that now touches the life of all people on the planet in many different ways. But it is a dull material, neither precious nor distinctive, and it has not been attractive to historians of technology.[4] It is often thought too humdrum to be of possible significance; "Le béton? Mais c'est de la boue!" scoffed French academician Georges Gromort, when asked about concrete's expressive possibilities (Simonnet 2005, 189). Concrete is indeed banal and ubiquitous, but by its sheer volume it is certainly a significant technology. Cyrille Simonnet (2005) goes so far as to suggest that in France about 80% of the *weight* of all types of annual construction now consists of concrete, whether or not reinforced. The history of its production reveals ways in which concrete has quietly redrawn the commercial landscape of construction during the twentieth century.

The production of cement, evolution of a global industry

Two essential developments launched the extraordinarily rapid spread of concrete construction around the world, the availability by 1900 of cement in quantities and of a quality to match demand, and techniques for using that cement in new forms of construction that could be commercialised. From the second half of the 19th century patented artificial hydraulic cements, sold in sacks or barrels, found an immediate and insatiable market from massive urbanization in developed countries then up to the First World War in industrial expansion, manufacturing and infrastructure. High sales volumes from early applications allowed the industry to mature rapidly and prices to reduce, thus making cement attractive for use in buildings, despite early resistance from architects and engineers. Success also inspired massive speculation in cement making as a capitalist undertaking, particularly in America where labour costs were high and fuel costs low. Efficient large-scale cement production relied absolutely on the capital-intensive mechanization of all its aspects. By 1900 estimated world production had reached more than 9,000,000 metric tons.[5]

Western Europe and America were the two main arenas of cement production, each accounting for about half of world production.[6] Cement factories had become established in Europe from the 1850s and during the latter part of the century Germany contributed most to the development of the material.[7] Progress was rapid; by 1885 German cements were three times as strong as the English cements of 1860. The emphasis was on quality control of ingredients, on product chemistry and on test procedures. By 1887 German production had reached one million tons.

The decisive revolution in production, though, was not German. It came in kiln design and it came from America. The calcination of stone in traditional kilns, a development of lime-burning technique but using higher temperatures, was a labour-intensive batch process that produced unevenly burned clinker. Large tubular kilns rotated mechanically, and with forced fuel supply to burn their contents more evenly, greatly improved product quality and output while dramatically reducing labour costs. Several patents to this effect were granted in England, notably to Frederick Ransome in 1885, but all the experimental kilns built were commercial failures.[8] The rotary kiln introduced technical problems, such as how to cool the continuous stream of hot clinker emerging from the kiln at around 1300^0C. These problems were solved through American, not English, patents in 1895-1896 (Davis 1924, 166). It was an important moment in American cement history. The superior strength of artificial Portland cement caused demand to rise despite its high price relative to abundant native natural cement. Entrepreneurs saw that if the price of Portland could be brought down to $1.50 a barrel from double that in 1880, then natural cement would be driven out of the market (Lesley 1924, 260).

The key figure in the advance of cement production technology was Thomas Edison. This episode in his eventful career, a development that had monumental consequences for all of construction in the 20th century, goes virtually unmentioned in the history of technology.[9] There's plenty about Edison's relatively unsuccessful attempts to cast entire concrete houses in a single mould, an ambition that figures in the historiography of industrialized building because it associates a great inventor with an ambition of modernism. But there is little about how he successfully invented the modern integrated cement-making plant.

Backed by a million dollars of venture capital from Philadelphia investors, Edison planned kilns 150 ft in length mixing air with the powdered coal to raise temperatures, aiming to halve fuel consumption per barrel of cement while producing 1,000 barrels in 24 hours.[10] To improve cement quality he furthered the German insistence on precise quantities, pioneering meticulous electrically controlled batching, weighing and mixing machines. The Edison Portland Cement Company was established in 1899 and, by 1907, despite developmental difficulties, Edison's long kilns achieved his original goal of 1,000 barrels a day to became established as an industry standard. Fierce price competition between cement producers ensured their rapid adoption both in the US and in Europe.

The growth in scale of production that Edison saw as necessary to achieve significant competitive economy applied to more than just kilns. The winning and transportation of cement's raw materials had to be scaled up by the use of ever-larger steam shovels [Edison's ore plant at Ogden boasted the largest in the world for a time]. The crushing of the cement clinker and its reduction in ball and tube mills to a fine consistent powder, the packing of the cement into barrels and bags, its distribution to local and distant markets, and its on-site batching, mixing and placing as concrete, all led to new machinery and techniques, at which America excelled. By 1900 American machinery began to supplant European machines even in Europe, where Edison's long kilns quickly became established, generating ever more royalties (Cody 2003, 32). Thomas Smith of Milwaukee, for example, produced highly successful Tilting Concrete Mixers, as well as crushers and mills, initially made in the US and shipped to distributors around the world. Telsmith equipment was used in great quantity on the Panama Canal from 1904. By 1906, the United States could claim to rank first among Portland cement producing countries in terms of both quantity and quality, and the domestic product now sold for less than a dollar per barrel.

Output continued to increase at a remarkable rate and was slowed only by the World Wars and by the depression years of 1930-1933. By the year 2000, world cement production had reached an astonishing 1,660,000,000 metric tons, but even this rate of growth has been eclipsed by recent Asian development that pushed 2006 world production to 2,550,000,000 metric tons, half produced in China (United States Geological Survey [USGS], 2006).

Statistics for worldwide cement production are few, but the most systematic are those of the US Geological Survey who have measured world output since 1926 [62,400,000 metric tons]. Global cement demand is expected to reach 3,500,000,000 metric tons in 2012. A USGS graph of world production 1930-2000 clearly shows the dramatic effect of recent Asian development (Fig. 1). Worldwide requirements for sand

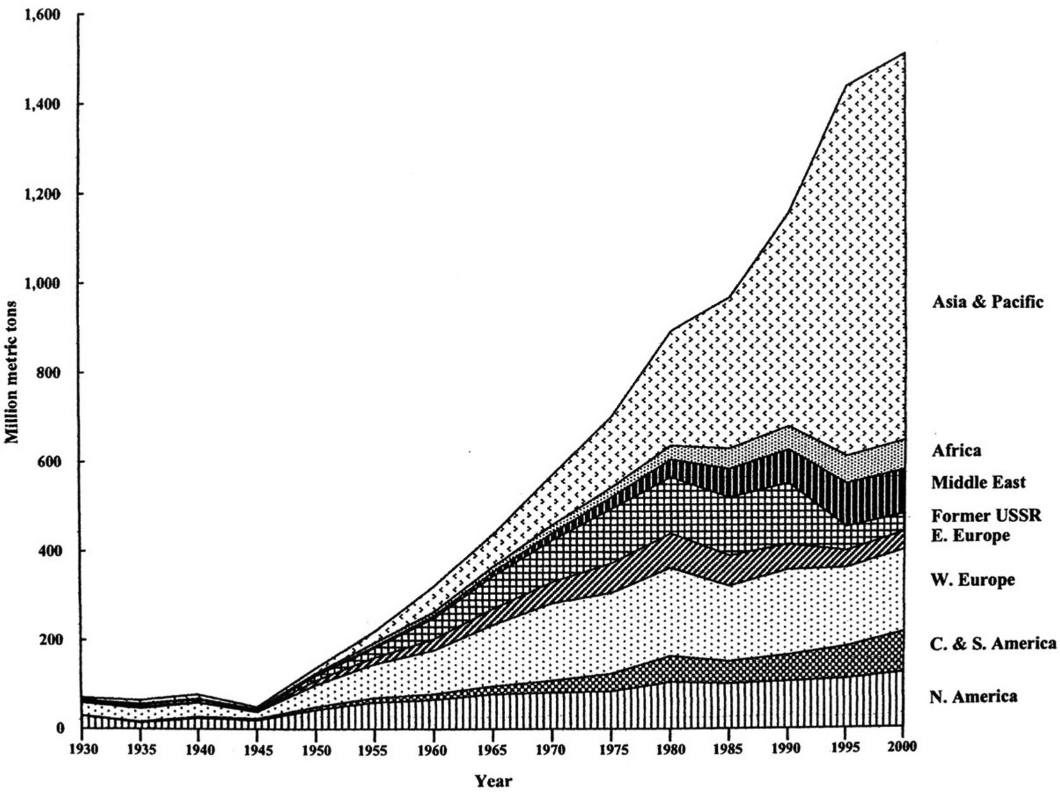

Fig. 1: *World cement production 1930-2000* (van Oss and Padovani 2002).

and aggregate, although not collected systematically, can be extrapolated quite accurately from global cement production; 35 gigatons of aggregates were needed in 2010.

Notwithstanding important improvements in product chemistry and the diversification of basic artificial cement into a family of specialist products with particular properties [quick-setting, high-strength, chemical resistant, etc.], and despite refinements in production technology, most cement produced around the world in 2000 was basically similar to that of 1900. Product uniformity and stability are key factors in cement's success.

If cement is the "magic powder," what is concrete?

Cement is a "magic powder" in the sense that it makes valuable concrete from worthless stone (Hadley 1945). The salient characteristics of mass concrete are its ability to set under water, its density, about 2.5 tonnes per cubic m.[3], its great strength in compression and its relative weakness in tension. It is this last property that led to the introduction of metal reinforcement in concrete when used in buildings for floors, beams and columns where tensile [bending] stresses are experienced (Newby 2001; Sutherland 2001). By 1900 concrete was being used extensively in foundations and increasingly for structural floors and frames in buildings, a development spurred by a more general search for fireproof construction, as a result of increasing urban density. In contrast to traditional materials concrete is made with a low cost industrial product, cement, and much larger volumes of easily obtainable sand and aggregate. Cement is thus an amplifier and transformer of low grade natural materials in terms of value – ferroconcrete is not "extracted from nature as a compact material, but created via the laboratory that intelligently exploits the properties of these almost worthless materials and through their combination increases their separate capacities many times over" (Giedion 1928, 150).

Just as the cement of 1900 strongly resembles the concrete of 2000, so too does the concrete. What had evolved over the century, however, was the range of uses to which concrete was put, uses able to absorb the ever-growing capacity of cement producers. From early in the century concrete had dominated civil engineering work such as poured pavements and roadways, dams, bridges and viaducts, building on early success in foundation works and harbours where its hydraulic property gave it exclusive value. Cement output was further absorbed by a new manufacturing industry evolved for secondary products such as pipes and culverts, kerbstones, roof tiles, railroad sleepers, building blocks, fencing systems, pre-stressed planks and beams, creating markets for a vast range of commodity building products, appropriating much that had previously belonged to the artisan world of building. But it was not until the early 1920s that reinforced concrete became established as a conventional building material to challenging the dominance of steel.

Concrete and cement imposed new disciplines not only on the immediate processes of design and construction, but on the extraction and distribution of raw materials. Insatiable demand for concrete has led to a persistent culture of mechanisation and production engineering in order to gain economies of scale and price advantage, both in cement making and the quarrying of aggregates.

The beginning of the 20th century marked a decisive encounter between the speculative and capital-intensive heavy industries of quarrying and cement production, and artisanal building, a local and highly contingent production sector that used traditional and mostly natural materials, in which labour had remained stubbornly more significant than capital, except in heavy civil engineering. In no other aspect of construction was this new use of capital so closely tied to the end product of building: construction absorbed less than 20% of steel production, but it used 100% of cement output. Yet there was no obvious defined way in which concrete might make its mark on building, despite its widespread adoption in civil engineering works. After 1885 the crucial mechanism for the diffusion of reinforced concrete became a series of patent systems manipulated by resourceful engineer-contractors, leaving architects at a disadvantage from which it took them a generation to recover (Saint 2008, 207). The patents in these systems mostly described ways of reinforcing concrete, first with iron then steel rods, so that beams and columns, floor slabs and walls could be made that would overcome the weakness of concrete in tension. For the promoters of systems, it was important to control the entire process of design and construction because it stood so far beyond conventional construction practice that it could not be entrusted to general contractors. The design of reinforced concrete depended on emerging methods in statics for analysing indeterminate structures, but there was still a significant component of empirical testing that needed to be controlled; second, the quality control of cement used and the processes of mixing and sample testing were fundamental to commercial success, so laboratory processes and site procedures became integral aspects of the system-builder's practice.

The most entrepreneurial of the concrete system promoters, Coignet and Hennebique in France, Wayss and Freytag [Monier patent holders] in Germany and Ernest Ransome in America, each developed complete concrete constructional systems including structural frames, piling and foundations, floors and walls, roof structure and façades. They paid great attention to design detail, material quality and construction process including testing, in a scientific way, but allied to commercial acumen. And their building systems were typically developed without architects (Addis 2007, 421). These systems were intended to build industrial and commercial buildings – sheds, mills and factory buildings. In France and Belgium, Hennebique concentrated at first on the industrial towns of the northeast;[11] in England, his licensee L.G. Mouchel built postal buildings for the Office of Works and a variety of utilitarian buildings for the Great Western Railway. In America, Ernest Ransome developed a simplified version of Hennebique's reinforcement, precast beams and improvements in concrete handling equipment and, by 1903, had built the United Shoe Machinery Corporation factory, the largest concrete building to date, three storeys high with vast glazed façades. By 1909, Hennebique operated 63 licensee offices around the world linked by up to the minute reports and pictures in the house journal *Le Béton Armé* (Delhumeau 1999).

These construction systems, conceived to build cost-effective anonymous factories and warehouses remain largely ignored in the architectural literature, despite clear evidence that they influenced architectural discourse in fundamental ways. Such buildings were the product of new labour relations and technical developments after 1900, and were commonplace and highly uniform across America (Slaton 2001). The system builders had effectively commoditized the actual process of construction. They had industrialized building through their insistence on uniformity of materials and processes within Taylorized disciplines.[12] Furthermore, their quest for a marketable architectural expression for their simple repetitive designs and austere regular framing, happened just when progressive architects and critics were becoming ready to accept the frank expression of commercial values in utilitarian structures.

The story of concrete during the 20th century: Concrete commodities

Reinforced concrete drove new processes of system building, but most building is not systematized. Buildings are made up of parts that must be made or bought and then incorporated into construction. And concrete was suited to the fabrication of a very wide range of products, or parts of buildings, either as an *ersatz* replacement for natural materials or as the basis of new products not previously made.

Manufactured products could absorb cement production capacity, offset market fluctuations, and take advantage of shortages and price spikes in traditional materials. Most precast concrete products required only limited capital equipment and little fuel cost. With relatively low entry cost, many different types of company entered the market, often as an expansion of other activities. By 1950 concrete roof tiles had overtaken sales of clay and slate in Britain, but were just part of a great diversity of concrete products including floor and roof slabs, piles, wall blocks, fencing posts, sills and lintels, paving and kerbs, pipes and products for use in agriculture that had been gradually gaining ground since the 1920s (Bowley 1966, 89). Demand for these precast products grew with their availability through merchants, even when they offered little or no price advantage. Some products, like lightweight concrete blocks, earned positions as *ersatz* innovations in periods of acute scarcity of bricks and bricklayers, becoming conventional, and eventually entering the texts and teachings of construction. They were actively developed in Europe, the UK and the USA. But although they were transforming the practice of building, they remained largely unremarked by historians of architecture and construction (Bowley 1960, 233).

Other commoditized uses of concrete included road paving and ready-mixed concrete sales. America led the world in both these developments from 1914 onwards. Roosevelt's New Deal agencies of the mid-1930s built 255,000 miles of roads, after which cement concrete had reached near parity with asphalt concrete. Concrete was the material of choice for Germany's autobahn program from 1931 onwards, and it was the material of choice during Britain's inter-war speculative housing boom of endless ribbon development, a success that survived into peacetime thanks to asphalt shortages; the first motorways were also largely made of cement concrete.

Ready-mixed concrete delivery was invented in Baltimore as early as 1913 and by 1916, Stephen Stepanian of Columbus, Ohio, had developed a self-discharging motorized transit mixer that was the predecessor of the modern ready-mixed concrete truck. Ready-mixed concrete is an invention that escapes mention in general construction histories, and yet now consumes over 66% of total world cement output [75% of output in the US]. It represents a massive organizational shift in materials handling, and consequently in the organization of virtually all building work (Cassell 1986).

The concrete products and processes described here have not arisen in response to demand from the owners of buildings or from architects and engineers. They are purely entrepreneurial, and they have created, or become, part of very large-scale markets, closely tied to the fortunes of the cement makers, merchants and builders. They definitely represent a form of industrialization, as fruits of capital and mechanization. They stand outside the narratives of architecture and engineering, and yet they have affected those worlds in profound ways.

How has the use of concrete transformed construction?

The story of concrete is also a story of how science came into construction. The characteristics of concrete – a synthetic chemical product combined in a wet mix of precise proportions with natural materials – forced scientific thinking onto the commercial context of building; not just into the cement-maker's R&D laboratory, but in the routine application of scientific and technological knowledge in everyday building. Each step of concrete making demands regularity and uniformity, science-based quality control, replacing the tacit knowledge of the artisan builder.

By 1900 there were technical standards and specifications for concrete in all developed economies, together with codes of practice for testing and inspection that stressed correct method and procedure more than mere results. It was a triumph for materials scientists, helping to build up the testing and teaching of concrete within academic engineering departments, forging instruments of scientific and social authority for their proliferating graduates, many of whom went to work directly for contractors [supply side] rather than to the more traditional consulting engineers [demand side]. Concrete engineers spearheaded a social transformation of site work through the demanding rituals of preparing for and placing concrete. Protocols for technical work in the form of specifications started to be embodied in contracts and estimates, carrying scientific knowledge into the realms of liability and reputation.

Around 1900 the disciplines of concrete begin to impinge on conventional channels of control between building owners who pay for projects and contractors who provide the materials and services. While the owner's consultant architects and engineers continued to specify buildings in terms of design, they now needed to have full regard to model specifications for cement and concrete most of which originated with the manufacturers of those building materials, albeit promoted through trade and professional associations such as the American Concrete Institute or the British Cement Association. This represented a crucial shift, the management of commercial relations through science-based technical criteria controlled by the producers. These criteria became embedded in standards, in structural design methods, in codes of practice and in general professional behaviour, fuelled by the technical "advice" services of the cement producers, the system builders and the pre-cast product industry.

The transformations outlined above have had pervasive and subtle effects on the practices of architecture and engineering. The direction of influence is from industry to art, and industry controls the relationship. These transformations have crystallized throughout the 20th century as the direct results of the industrialization of cement and concrete production. The intellectual capital of construction today lies clearly within a supply side dominated by giant global businesses.

Cement and concrete today

High transportation costs for a low-margin product like cement and for its raw materials, plus refinement of cement-making plant, have led to wide global distribution of productive capacity, and today there are some 1,500 integrated cement production plants around the world, a quarter of which are controlled by just four companies.[13] Consolidation of the cement industry into international giants over the last 25 years, greatly helped by increased mobility of capital, is similar to that in other extractive and commodity product markets. Controlling new markets is an essential path to growth for products that are highly normalized and that are sold at low price. Companies must capture market share where per capita consumption of cement is increasing, as in Asia. Operating globally, the market leaders aim for economies of scale, but they must also avoid market price fluctuations. Demand management and currency hedging are achieved through global trading, fundamental to the modern cement market. Cement manufacturers must also ensure that the markets they serve are able to absorb their output, and this they do by strong participation in local markets for extracting stone, gravel and sand aggregates as well as operating thousands of ready-mix plants. To facilitate trading the big four are active with fleets of ships. Heidelberg Cement Trading, for instance, employs more than 800 ships calling at around 130 ports in 80 countries; while, in 2005, Cemex traded 17,000,000 tons of cement between 97 countries (Laserre and Picoto 2007).

In the context of globalisation it is significant that Chinese cement, accounting for half of all global production is about 85% produced in Vertical Shaft Kilns [VSK], brick-built like traditional lime-burning kilns, a technology from the early 19th century. The continuing use of VSK, labour intensive, fuel inefficient and highly polluting, is a legacy of 1960s policies to localise industry in China; little capital is required and local labour and materials are used. Only very recently, with China's still growing demand for cement and capital availability, have the global big four started to forge joint ventures to build modern integrated cement plants in China.

In the first half of the 20th century, concrete chemistry, production technology and structural applications were standardised and codified. What has continued to change and develop is knowledge of the physics and chemistry of concrete, its behaviour over time or under special conditions, and new uses found for it through engineering and architecture. The cement industry needs to gain competitive advantage through material refinements of cement and novel mix designs for concrete. Manufacturers tailor concrete for specific applications, for example the use of very high strength concrete as the preferred structural material for the tallest buildings, displacing steel as the primary structural material. Certainly the consolidation of the cement industry into global quasi-monopolies favours far-reaching concrete research. And yet, as Antoine Picon puts it: "Today more than ever, concrete appears as a socially constructed material, the characteristics of which are as much the result of complex economic and social strategies as the outcome of pure research" (Cohen and Moeller 2006, 8). Concrete has been talked up or put down in the service of an astonishing array of such social constructs, representing "change or stubborn stasis, historical continuity or brave innovation, sophisticated scientifically grounded production or coarse handiwork" (Cohen and Moeller 2006, 32). I suggest that historians of construction, in contemplating the place of concrete, should pay more attention to its actual production and its impact on construction and perhaps less to the moments of excitement it has caused architects or engineers.

Acknowledgements

I am grateful to Professor David Edgerton at Imperial College, for leading me to conceptualize the industrialization of construction in terms of production history. In particular his 2006 book has been inspiring (Edgerton 2006).

Notes

1. A key source for my research has been the publications of the U.S. Geological Survey which not only track global production of minerals and mineral products such as cement, but also address salient issues in mineral technology. Particularly valuable have been: Matos and Wagner 2003; van Oss 2005; USGS *Minerals Year Books and Summaries 1900-2006*.

2. World Coal Institute, 2008. *Coal and Steel Facts*, accessed at: www.worldcoal.org/resources/coal-statistics/

3. For Karl-Eugen Kurrer, a historian of structural theories, "the history of the modern building industry begins with the establishment of reinforced concrete construction in the first decade of the twentieth century, which also gave rise to the first modern codes of practice" (Kurrer 2008, 496).

4. Exceptions include Amy Slaton's (2001) analysis of the role of concrete production processes in the transformation of American construction in the 20th century; also Simonnet (2005) examining the evolution of formal expression in concrete and its effects on architecture. An important earlier analysis of the historical significance of concrete is provided by Collins (1959) in which the life of the French architect/builder Auguste Perret is a vehicle to explain the growing hegemony of concrete in 20th century construction.

5. Estimates of world cement production in 1900 vary between 9,000,000 tonnes in Lesley (1924, 264), a combination of US and European outputs, and ~15,000,000 tonnes, from a graph in Idorn (1997, 40). The United States Geological Survey, which is the most consistent statistical source, does not give world production figures before 1926, when the figure had reached 62,400,000 tonnes.

6. Less than five percent was made in Asia, Africa and Australia using colonial legacy technology from the second half of the 19th century.

7. Alec W. Skempton (1962) usefully periodized the development of cement into "English" (1843-1875), "German" (1875-1905) and "International" (1905-1950), in Newby (2001, 117-151).

8. Frederick Ransome's patent of 1885 is generally acknowledged as the moment of invention, but his own experimental kiln was a failure (Davis 1924, ch. 7).

9. An exception can be made for Frank Lewis Dyer (1910, ch. 20). Dyer, Edison's attorney and business partner, is frequently criticized for hagiography, yet he is one of the very few to describe Edison's work with cement.

10. An account of investment in The Edison Portland Cement Company is given in Israel (1998). Lesley reports in 1924 that Edison was Chairman of the board and that the New Jersey plant used ten 150-ft long coal fired kilns to produce 7,500 barrels [1,280 tonnes] of cement a day, double the average plant, making it a major producer on the Eastern seaboard.

11. Hennebique reported 126 projects in 1895, but it's hard to discern the scope of each project, many are for floors or structural frames only. But by 1912, there were 4,000 projects (Simonnet 2005, 74).

12. It is perhaps unsurprising that in 1905 management scientist Frederick Taylor jointly wrote/edited with prominent structural engineer Sanford E Thompson a 700-page technical "treatise on concrete plain and reinforced." It clearly echoes Taylor's interest in the potential to manage and manipulate the formless new material. The book includes detailed prescriptions for time-and-motion controlled processes of mixing and placing concrete, and it deals with the mechanisation of processes.

13. Lafarge of France, Holcim of Switzerland, Cemex of Mexico, Heidelberg of Germany, operating 424 cement plants between them (2005).

Reference list

Addis, W., 2007. *Building: 3000 years of design engineering and construction*. London: Phaidon.

Bowley, M., 1966. *The British Building Industry: four studies in response and resistance to change.* Cambridge: University Press.

Cassells, M., 1986. *The Readymixers: the story of how ready mixed concrete changed the building industry.* London: Pencorp.

Cody, J.W., 2003. *Exporting American Architecture 1870-2000*. London: Routledge.

Cohen, J.-L. and M. Moeller (eds.), 2006. *Liquid Stone: A New Architecture in Concrete*. Basel: Birkhauser.

Collins, P., 1959. *Concrete: the Vision of a New Architecture*. London: Faber.

Davis, A.C., 1924. *A hundred years of Portland cement, 1824-1924*. London: Concrete Publications Ltd.

Delhumeau, Gwenaël, 1999. *L'invention du Béton Armé: Hennebique 1890-1914*.Paris: Éditions Norma.

Dyer, F.L., 1910. *Edison: his Life and Inventions*. New York: Harper and Brothers.

Edgerton, D., 2006. *The Shock of the Old: Technology in Global History since 1900*. London: Profile Books.

Giedion, S., 1928. *Bauen in Frankreich, Bauen in Eisen, Bauen in Eisenbeton*. Translated and republished in English in 1995 as: *Building in France, Building in Iron, Building in Ferroconcrete*. Santa Monica: Getty.

Hadley, E.J., 1945. *The Magic Powder: History of the Universal Atlas Cement Company and the Cement Industry.* New York: Putnam.

Idorn, G.M., 1997. *Concrete Progress from Antiquity to the Third Millenium*. London: Thomas Telford.

Israel, P., 1998. *Edison: A Life of Invention*. New York: Wiley.

Kurrer, K.E., 2008. *The history of the theory of structures: from arch analysis to computational mechanics*, Berlin: Ernst and Sohn.

Laserre, P. and J. Picoto, 2007. *Cemex: Cementing a Global Strategy*. Paris: INSEAD Global Strategic Management Mini Case Study Series.

Lesley, R.W., 1924 *History of the Portland cement industry in the United States: with appendices covering progress of the industry by years and an outline of the organization and activities of the Portland Cement Association*. Chicago/New York: International Trade Press.

Matos, G. and L. Wagner, 2003. *Consumption of Materials in the United States 1900-1995*. Washington: U.S. Department of the Interior, U.S. Geological Survey Open-File Report 00-313.

Newby, F. (ed.), 2001. *Early Reinforced Concrete: Studies in the history of Civil Engineering, vol. 11*. Aldershot: Ashgate.

van Oss, G. Hendrik and A. Padovani, 2002. Cement manufacture and the Environment; Part 1: Chemistry and Technology. *Journal of Industrial Technology* 6 (1).

van Oss and G. Hendrik, 2005. *Background Facts and Issues Concerning Cement and Cement Data*. Open-File Report 2005-1152. Washington: U.S. Department of the Interior, U.S. Geological Survey Open-File Report 2005-1152.

Saint, A., 2007. *Architect and Engineer: A Study in Sibling Rivalry*. London: Yale University Press.

Simonnet, C., 2005. *Le Béton: histoire d'un matériau*. Paris: Editions Parenthèses.

Skempton, A.W., 1962. [Reprinted in Newby 2001).] Portland cements 1843-1887. *Transactions of the Newcomen Society* 35, 117-151.

Slaton, A.E., 2001. *Reinforced concrete and the modernization of American building, 1900-1930*. Baltimore: Johns Hopkins University Press.

Sutherland, J., D. Humm and M. Chrimes (eds.), 2001. *Historic Concrete: Background to Appraisal*. London: Thomas Telford.

United States Geological Survey. *Minerals Year Books and Summaries 1900-2006*. Includes annual summary of *Minerals in the World Economy.* http://minerals.er.usgs.gov.