Nanotechnology in Construction: A Roadmap for Development

by P.J.M. Bartos

Synopsis: Compared with other major industrial sectors, the construction industry has lagged behind in awareness of the potential for exploitation of nanotechnology. Both the awareness and actual exploitation in construction are now increasing; however, progress is uneven, especially in the current early stages of its practical exploitation. A roadmap then becomes a useful tool, a template, for predictions of trends and developments connecting nanotechnology and construction. The Roadmap for Nanotechnology in Construction (RoNaC) outlined in this paper is aimed at facilitating identifications of desirable aims/destinations for construction research and technical development (RTD) over a short-to-medium timescale (up to 25 years). The RoNaC was developed as an aid for forecasting research and investment directions. It provides guidance to construction industry, investors, and national/international bodies supporting research and development about the diverse pathways toward current nanotechnology-linked expectations, aims, and targets in this very large and economically significant domain. The complexity of the construction domain is such that a single overall chart would be far too general in a scale so large that it would become incomprehensible. Sectorial or "topical" charts have been developed instead of a single "map", and three examples of such charts have been worked out to illustrate this approach. Requirements for adequate research infrastructures, effects of appropriate drivers, and diverse vehicles for RTD are considered together with an assessment of the "environment" conducive to progress along the pathways and directions indicated in the charts.

Keywords: construction; forecasting; guidance; nanotechnology; research and development; roadmap; trends and aims

Peter J.M. Bartos *is past President of the UK Concrete Society, an Emeritus Professor of Civil Engineering, former Director of the Advanced Concrete and Masonry Centre and the Scottish Centre for Nanotechnology in Construction Materials at the University of Paisley, Scotland. He holds Honorary Professorship in Civil Engineering at the Queen's University of Belfast. He is a Fellow of RILEM, where he has chaired technical committees including TC197-NCM on Nanotechnology in Construction Materials from 2002 to 2007.*

1. INTRODUCTION

Nanotechnology is a recently developed, major enabling tool, already well established in several sectors of science, which is expanding rapidly into applied sciences, technology and engineering. Nanotechnology enhances our understanding of "origins" of key properties of everyday materials and structures; of manufacturing processes and interactions between materials, structures, external elements and internal components. It leads to development of advanced characterisation and eventual prediction and control of properties of materials at a sub-micron level. Its potential for development is such that it is often considered as the industrial revolution of the 21st century. Applications of Nanotechnology are expected to lead to better, cleaner, cheaper, faster and smarter products. In addition, much more effective use of basic resources and development of environmentally sustainable production processes is predicted.

The purpose of a Roadmap is to chart of trends and developments, which, in this case, link nanotechnology and construction and provide a useful tool, a template, for their predictions. The Roadmap for Nanotechnology in Construction (RoNaC) has been aimed at facilitating identifications of desirable aims/destinations for construction RTD over a short-medium timescale (up to 25 years). The RoNaC was developed as an aid in forecasting RTD directions and helping to inform and guide construction industry, investors and national/international bodies supporting research and development about the diverse pathways towards current nanotechnology linked expectations, aims and targets in this very large and economically very significant domain.

The Roadmap for Nanotechnology in Construction was initially developed at the Scottish Centre for Nanotechnology in Construction Materials, attached to the Advanced Concrete and Masonry Centre of the University of Paisley. It had been a deliverable of the 5th FP project "NANOCONEX" (2002-2003) [1], which was subsequently presented to and consulted with membership of RILEM International Technical Committee TC 197-NCM on Nanotechnology in Construction Materials (2002-2007). Its earliest version was introduced as part of the E-CORE & ECCREDI conference on "Building for a European Future – Strategies & Alliances for Construction Innovation", held in Maastricht, the Netherlands, in October 2004 and presented at the 2nd International Symposium on Nanotechnology in Construction (NICOM2) in Bilbao, Spain, in November 2005.

The RoNaC is also based on a State of the Art report [2] which was prepared by the Scottish Centre for Nanotechnology in Construction Materials (Dr. W. Zhu, Prof. P.J.M. Bartos) as part of the European 5th FP project "NANOCONEX" (2002-2003) and later adopted by the RILEM TC197-NCM on Nanotechnology in Construction Materials [3]. The State-of-the-Art report [2, 3] examined and evaluated current development and applications, awareness and perceptions, and future potential of nanotechnology in the construction industry by surveying construction professionals and leading researchers and by studying publications and reports in relevant fields.

Information and data from the State-of-the-Art report [2] helped to establish the benchmarks for the development of the RoNaC. With the 5th FP European project NANOCONEX running and a proposed 6th FP Network of Excellence on Nanotechnology in Construction (project EXINAC) being considered, the original survey gave priority to Europe. However this was later complemented by a study of a global range of sources on existing knowledge, proposed and current R&D activities in nanotechnology that are potentially applicable to any part of the construction sector. Contributions presented at the 1st International Symposium on Nanotechnology in Construction, Paisley, UK, June 2003 [4], active links with the TC-197 NCM on Nanotechnology in Construction Materials, established under the auspices of RILEM in 2002, and events organised and documents produced by the UK Institute of Nanotechnology [5] and other organisations were reviewed and their conclusions considered. The 2nd International Symposium on Nanotechnology in Construction (NICON2) in Bilbao, Spain in November 2005 confirmed the emerging trends and indicated several new projects exploiting nanotechnology [6]. The 3rd Symposium (NICOM3), to be held in Prague in spring of 2009, will provide new information and a forum for discussion and updating of the RoNaC [7].

Construction industry differs from many other sectors of industry in that it is not connected directly to research and development of the new nano-scale tools, which was stimulated by nano-science, usually in the more fundamental scientific domain. Construction has only recently started to appreciate the potential impact of Nanotechnology on a significant scale. Compared to many other industrial sectors, relatively few instances have been reported where Nanotechnology has been already successfully exploited and a major product has already reached open markets. Awareness of the potential for exploitation of Nanotechnology in construction has improved over the last few years, but much more remains to be done. Nano-related RTD in construction has been recently established in a few sectors; however, it can be still described as "emerging". Advances are very non-uniform, leading to a particularly pronounced fragmentation and often to a distinct isolation of current centres of nano-related construction research and development. These are very important, construction-industry specific circumstances, accounted for in the RoNaC.

Detailed analysis of the fragmented nature of nano-related RTD in construction is provided in the NANOCONEX/RILEM TC197-NCM State-of-the-Art report [2, 3].

Four underlying reasons for this situation are identified, relating to:

- ***Inherently different nature of the construction industry.*** This leads to many inventions being adapted from other industries or from related sciences, rather than invented within the construction industry itself. Construction tends to be much more an exploiter of ideas and inventions than their creator. This partly due to specific characteristics of its final products, which tend to be very complex, non-mass produced and requiring a relatively long service life. Such characteristics differ greatly from those of products from microelectronics, IT or even automotive industries.

- ***Very low historic level of investment into construction RTD.*** This represents a major hindrance in exploitation of nanotechnology. In many countries the level of investment in construction research has been distinctly the lowest across the whole of the manufacturing industry. Margins of profitability within construction and in related industries have been always very small. Such a situation slows down progress and hinders particularly advance along the development paths/routes exploiting nanotechnology, which already exist and in a creation of new ones.
- ***Very high initial capital investment invariably required in nano-related RTD.*** This is a major obstacle, applicable to all industrial sectors. The rate of obsolescence of nano-instrumentation is equally very high. Any substantial commercial returns are not being available earlier than within a mid- to long-term time-scale.

2. ROUTES AND PATHWAYS

The RoNaC charts are plotted against a timescale, which provides a measure of how distant the required or desirable research/development destinations are from a situation in 2004, which is considered as the starting point at the baseline. The timescale extends to 25+ years ahead. However, the greater is the extension of the time interval into the future, the greater are the potential errors and the lesser is the reliability of forecasts in this rapidly and very unevenly developing field.

It has been found entirely impracticable to produce one all-encompassing single map for all of the construction in which all the routes and /pathways of progress would be shown. The reason for this was the existence of a multitude of "pathways", criss-crossing each other. Many are seen today as relatively "thin", faint and indistinct ones, which is how they are seen today, but which, in future, they may (or may not!) become well-established, densely "trafficked" wide principal routes/highways of progress and development. An early attempt to show them all in one chart/roadmap, with all the numerous possible intersections, interactions and feedbacks, produced a tangled mass of connections resulting in and an illegible and incomprehensible document.
Solution of this problem of presentation appears to have been found in the creation of a number of simpler charts in which the nano-related construction research pathways and/or routes, heading towards a common specific "destination", have been clustered. An example is the Chart 2: "Buildings of Future", where the destination has been defined in a number of highly desirable goals and outcomes summarised and presented in the chart. Some of the pathways shown appear in another chart(s). This is to be expected, as Nanotechnology is fundamentally an "enabling technology", where one advance, especially when it is a major advance, is very likely to underpin progress towards

desirable goals in more sectors than in its original one. It would be also possible to indicate the current status of the pathways as is common for traditional roadmaps (e.g. note which roads were existing, under construction or just planned), but this was felt to be the next stage in the RoNaC development. The activities shown in the specimen charts have colour coding to indicate existing pathways (red).

3. TIMESCALE

The RoNaC charts were plotted against a timescale, which provides a measure of how distant the required or desirable research and development destinations were from a "benchmark" situation in 2004, which was considered as the starting point at the baseline. The timescale extends to 25+ years ahead. However, the greater is the extension of the time interval into the future, the greater are the potential errors and the lesser is the reliability of forecasts in this rapidly and very unevenly developing field.

There are three specific Charts shown in this document. However, these should be also considered as examples of how to construct a RoNaC chart. It is possible to re-define the goals/aims, introduce new, additional goals/aims over the time-scale, re-trace the pathways and re-assess the information available, leading to new lists of activities, pathways and known (or expected) connections to selected "common" goals. There is sufficient information already available in the State-of-the-Art reports [2, 3] the proceedings of the 1st and 2nd International Symposia on Nanotechnology in Construction [4, 6], from the soon to be published final documentation from the RILEM TC 197 NCM and other more specific papers and sources, to provide data for production of new charts in a similar format.

It is important to appreciate that the "routes/pathways" shown in the charts are in many instances only now being formed or traced. Additional ones may develop in due course, and may not even exist as yet. It would be possible to indicate their current status as is common for traditional roadmaps (roads existing, under construction or just planned), but this was felt to be the next stage in the RoNaC development.

4. RESEARCH INFRASTRUCTURES

The very existence, or the construction, of roads and pathways critically relies on the availability of relevant supporting infrastructure, which itself has to be upgraded and developed with passage of time, to maintain it in an active, effective shape, fulfilling their role in supporting research, development and practical exploitation of nanotechnology. Progress towards highly desirable but inevitably only medium-long term goals will slow down very much, perhaps even stop entirely, if the necessary infrastructures were not maintained and periodically upgraded, mainly because of inadequate funding provisions.

The research infrastructures, which "pave the way" include:

- Instrumentation and methodologies for nano-scale investigations, e.g. for characterisation of properties at nano-scale, nano-assembly and fabrication, analytical techniques and imaging at molecular/atomic scale.
- Descriptive and eventually predictive numerical models, which include a linkage across the whole scale, from nano-to-macro size.
- Standardisation of basic nano-scale metrology equipment and provision of means for an assessment of their performance. Development of new, more effective tools for a meaningful nano-scale characterisation of materials.

Instrumentation and metrology at nano-scale are developing at a very fast pace, which inevitably brings with it a rapid rate of obsolescence. The rate of obsolescence is comparable to that seen in the IT sector; however "hardware" costs of nano-scale instrumentation and costs of its maintenance/calibration/upgrading, even on only a moderate scale, are much higher than in the IT sector.

5. VEHICLES, DRIVERS, KNOWLEDGE AND BUSINESS ENVIRONMENT

Not all of the pathways/routes, including their intersections, shown on the attached Charts, may be immediately very clear and recognisable to potential developers and exploiters. The choice and understanding of the research "vehicles" needed to pursue specific goals and the capability of their "drivers" to steer them along correct routes to desired outcomes and destinations, require adequate prior ***knowledge*** of both Nanotechnology and the relevant sector(s) of construction industry in all instances.

The greatest impact on the construction industry and the economy within the timescale of the Roadmap is likely to come from an enhancement in performance of materials arising from an improved understanding and control of their structure on micro-to-nano-scale and from an improvement of their production processes. The eventual total impact will be almost always very substantial, due not necessarily to radical technological leaps forward but mainly to massive quantities in which basic ("bulk") construction materials are used. Most of the advances along the specific research routes and pathways of RTD are predicted to be incremental, leading to a relatively steady progress related to existing, namely the "bulk" materials and technologies. Such a relatively steady progress will be strongly influenced by developments in the research "infrastructure", such as in equipment. It may be that some of the expected improvements will not take place and there will be a waiting period with only a small or even zero advances, until a breakthrough occurs and the capability of the equipment (infrastructure) is instantly and significantly upgraded.

An improved understanding of structure-properties relationships and an ability to control the structure of many materials on the nano-scale will provide opportunities for major advances in materials science. Such breakthroughs will enable the "materials by design" approach to replace the traditional "trial and error" one, enabling properties of a material to be tailored for a specific requirement. It will also lead to development of new approaches to extend the life of existing structures and to prevent/arrest deterioration in the new build.

Many of the basic and most significant drivers such as market pull, venture capital involvement, competitiveness and prospects of higher financial returns will be either weak or not established if an environment conducive to acquisition of adequate and relevant knowledge is not present. All the drivers of progress in this area rely critically on knowledge and information.

Construction industry is a very substantial domain, in Europe alone its turnover is estimated at about 1000 billion Euros [8]. However, it is also estimated that 97% of employees working within it are employed by enterprises with less than 10 staff. In such circumstances, acquiring the required minimum of knowledge, which is at present inadequate if not entirely largely absent, will be unacceptably slow without it being facilitated by a targeted national or supra-national support.

The way ahead - an exploitation of the directions such as those shown in the specimen RoNaC charts will be not be easy and straightforward as the knowledge required at different levels of construction-related staff tends to lag behind the advance of nanotechnology.

There is strong evidence that in the absence of an environment conducive to acquisition of adequate knowledge through education and training, many of the basic and most significant drivers such as market pull, venture capital involvement, competitiveness and prospects of higher financial returns will be either weak or not established. Numbers of skilled research related personnel at both the scientific/supervisory level and at the supporting staff/technician level, who possess the required combination of knowledge related to construction and nanotechnology, appear to be still too low to provide the manpower required to steer and move efficiently forward the “vehicles” for expansion of nano-related RTD in construction.
Indications are that countries leading the development and exploitation of Nanotechnology, such as the USA and European Union (in both overall and national programmes [8, 9], have realised the necessity of providing a major financial support from state/government sources. The US government set up the National Nanotechnology Initiative in the year 2000, which has committed an initial funding over one billion US dollars of public funds to facilitate the additional commitment of private venture capital for specific developments through its different agencies [8]. Unfortunately, all but a very small fraction of the public funding for nano-related RTD appears to have been channelled either into non-construction industries or into development of the nano-scale research infrastructure used primarily to support non-construction research.

Investment into research infrastructure can be of benefit for construction and it can “smooth/pave” some of the development paths shown in the Charts. However, in practice, such facilities tend to be under non-construction related management and many of the already established access routes are already crowded by nano-science related research “vehicles” with very little or no construction linkage. Benefit to construction from such nanotechnology related investments is therefore likely to be disproportionately low compared with the economic significance of construction, which, in EU contributes approximately 10% of GDP. Other significant drivers are emerging, which gain significance in terms of construction and nanotechnology. These include climate change and the associated issues on a global scale and urban redevelopment and in some countries.

6. ROADMAP AND CHARTS

A roadmap for the whole of construction, including all the existing and proposed pathways for development would be illegible. The "scale" would have to be adjusted, but then the roadmap would become too coarse to make it comprehensive and legible. As a result, such a complex overall chart would not reveal adequately details necessary for an appreciation and understanding of the links, relationships and dependencies of varied significance between the pathways shown.

The RoNaC should therefore comprise a collection of "sectorial" charts such as the examples attached, each focused on a coherent cluster of aims and destinations. Aims and destinations, which are expected to be of significance for construction in the medium-long term 3 include:

- Understanding basic phenomena (interactions, processes) at nanoscale: e.g. cement hydration and formation of nanostructures, origins of adhesion and bond, pore structure and interfaces in concrete, mechanisms of degradation, relevant modelling/simulation based design tools, etc.
- Bulk "traditional" construction materials with a modified nano-structure: e.g. concrete, bitumen, plastics modified with nanoparticulate additives, special admixtures and new processing techniques modifying internal nanostructures etc.
- New high performance structural materials: e.g. carbon nanotubes, new fibre reinforcements, nanocomposites, advanced steels and concrete/cement composites, biomimetic materials, etc. Materials with extended durability in extreme service conditions.
- High performance new coatings, paints and thin films: e.g. wear-resistant coating, durable paints, self-cleaning/anti-bacteria and anti-graffiti coatings, smart thin films, etc.
- New multi-functional materials and components: e.g. aerogel based insulating materials, efficient filters/membranes and catalysts, self-sensing/healing materials, etc.
- New production techniques, tools and controls: e.g. more energy efficient and environmental friendly production of materials and structures, novel processes with more intelligent and integrated control systems, etc.
- Intelligent structures and use of micro/nano sensors: e.g. nano-electromechanical systems, biomimetic sensors, paint-on sensors, and self-activating structures/components, etc.

- Integrated monitoring and diagnostic systems: e.g. for monitoring structure defects and reinforcement corrosion, environmental changes/conditions, and detecting security risks, etc.
- Energy saving lighting, fuel cells and communication devices: e.g. efficient and cheap fuel cells and photovoltaics, LED based lighting, etc.

Three Charts are shown as examples of the “clustering” of aims/destinations. The paths emerge from a baseline to the left of the Chart. If appropriate, the baseline can be split into separate “blocks”, indicating that it comprises distinctly different sub-areas of research. Each sub-area may consist of several recognised and related research streams/directions.

Progress forecast along each of the identified nano-related RTD activity paths is shown against a linear timescale from 0 to 25+ years. Activities, which are shown to begin within the interval of 0-32 years, are already being pursued or about to commence. Aims/destinations, common to each of the charts, are shown on the right hand side and basic characteristics/parameters of the aims are also listed there.

Each research activity is represented by a simple elongated rectangular box, which may suggest a very precise and sudden start and finish, and a uniform intensity of the activity throughout its expected duration. However, this is a simplification, which has been adopted for the sake of clarity, and because it is impossible to predict the inevitable variations in the intensity/magnitude of research during each of the activities. There may be ups and downs, and even breaks/discontinuities, when funding may drop below the level required to sustain advance. Unexpected and at that time perhaps temporarily insuperable technological problem, may be encountered on the path followed, or even an unexpected dead end may be encountered, for example by discovery of a hitherto unknown ecological or health & safety threat or danger. It is also realistic to expect that each of the activities will gradually develop in its intensity and volume. Some of the activities showing early starts are already being pursued.

Each “activity box” is therefore presented in a simplified linear and parallel direction, with only major interactions indicated as “diagonal” connecting lines. As has been mentioned before, some of the activities will be using common paths/routes and share the infrastructure. There are therefore many overall “integrating” features because of the commonality of some of the nano-scale approaches, a feature likely to be well appreciated, representing the inherent multi-disciplinarity of RTD exploiting advances in nanotechnology.

A general activity, which is beginning to be much more appreciated, and which will become soon an integral part of any of the specific (“boxed”) activities shown is an **evaluation of health and safety**, both during the process of research and development and regarding practical products/applications. There are concerns especially about the capability of nanoparticles to pass through natural bio-boundaries in living organisms and safety precautions must be maintained even though evidence on adverse effects on health is still limited. It is now therefore very urgent to provide an adequate national and international legislative cover for nanotechnology and avoid potential health and safety problems which would undermine confidence in nanotechnology in general and dramatically slow progress.

7. SPECIMEN CHARTS

Chart 1: Traditional Bulk Construction Materials
This chart (Fig. 1) covers basic existing construction materials. Here, even incremental improvements achieved by the exploitation of nanotechnology will lead to big commercial and environmental/societal gains because of the extremely high "multiplying factors" attached to such materials. Activities shown follow generally the "top-down" approach, in which an existing material is improved through knowledge and modifications carried out down at the micro-nano level.

Chart 2: Buildings of Future
This chart (Fig. 2) shows activities leading to a much higher standard and much more environmentally acceptable, and eventually fully sustainable, building construction. Achievements reached by routes shown in Charts 1 and 3 will be associated with activities shown in this Chart.

Chart 3: Novel Construction Materials
This chart (Fig. 3) follows primarily the "bottom-up" development direction, where materials of substantially altered properties and much high performance are "built" or "assembled" from the basic nano-scale constituents (molecular - atomic level). Related activities are shown in same colour coding.
It is important in all cases to note the "unforeseen developments", a box that covers developments not even thought of at present.

8. CONCLUSIONS

Nanotechnology in construction remains in an "emerging, early development" state. Its uneven progress, prevailing fragmentation and the specific nature of the construction industry limit the accuracy of the forecasts shown in the RoNaC.

The RoNaC presented includes three specimen charts covering the most common "clusters" of construction research activities, where nano-based research and development activities are already carried out and several routes/pathways are already established. Additional charts can be developed for specific activities or aims/destinations.

Reliability of predictions regarding commencement, duration and end of activity decreases rapidly as the commencement time becomes more distant from present (time zero).