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Review

The future of construction materials research and the seventh UN Millennium Development Goal: A few insights

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HIGHLIGHTS

▶ Research on construction materials still seems unable to recognize the importance of the 7th MDG.
▶ Nanotech research on infrastructure materials can help to fulfil the 7th MDG.
▶ Biotechnology can allow for the development of exceptional and fully biodegradable materials.
▶ Standardization can help to overcome the gap between materials research and market use.
▶ Interdisciplinary research is needed to avoid misguided research lines without a clear and useful social goal.

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ABSTRACT

Although the unsustainability of the human civilization has been recognized long ago, little has ever been done to change it. During the last century, materials use increased 8-fold and as a result Humanity currently uses almost 60 billion tons (Gt) of materials per year. The construction industry alone consumes more raw materials than any other economic activity. However, research on construction materials still is excessively focused on their mechanical properties with minor concerns regarding environmental considerations. In September of 2000 189 UN member states signed the Millennium Development Goals (MDGs), in which the seventh goal is related to environmental sustainability. This is a cornerstone event of paramount significance. However, research in the field of the built environment especially on the field of construction materials still seems unable to recognize its importance. This paper provides some insights on future construction materials research priorities in the context of the seventh MDG. It reviews publication patterns on the field of construction materials highlighting investigations gaps and misdirected research lines. It addresses the importance of nano and biotech hot areas and briefly analyzes the gap between research and market use.

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1. Introduction

One of the oddest features of the humankind is the fact that it uses a huge amount of resources, including non-renewable ones, leaving traces of pollution in the consumption process. To make matters worse, only a few countries consume the majority of the resources. This means that this process will tend to get worse when the majority of the humankind is able to afford the same consumption patterns. Meadows et al. [1] used a computer model based on the fixed-stock paradigm to study the interactions between population, food production, industrial production, pollution and the consumption of non-renewable resources. As a result, they predicted that during the 21st century the Earth́s capacity would be exhausted resulting in the collapse of human civilization as we know it. An update of this study was published in 1992 [2] showing that some limits had already been crossed. During the last century, materials use increased 8-fold and, as a result, Humanity currently uses almost 60 billion tons (Gt) of materials per year [3]. The most important environmental threat associated to its production is not so much the depletion of non-renewable raw materials [4], but instead, the environmental impacts caused by its extraction, namely extensive deforestation and top-soil loss. In 2000, the mining activity worldwide generated 6000 Mt of mine wastes to produce just 900 Mt of raw materials [5]. This means an average use of only 0.15%, resulting in vast quantities of waste, whose disposal represents an environmental risk in terms of biodiversity conservation, air pollution and pollution of water reserves. As a result, since the 1970s there were 30 serious environmental accidents in mines, 5 of which occurred in Europe [6] like for instance the 2010 Kolontar environmental disaster (Fig. 1). This is rather disturbing because Europe has high environmental standards which mean that countries in which such high standards do not exist environmental disasters could happen much more frequently. Since materials demand will double in the next 40 years, the environmental impacts will therefore increase in a drastic manner [4]. The global construction industry consumes more raw materials (about 3000 Mt/year, almost 50% by weight) than any other economic activity, which shows a clearly unsustainable industry. Also, in the next years the construction industry will keep on growing at a fast pace. For instance, between 2012 and 2017, India will invest 1 trillion dollars in infrastructures [7]. In the USA, the needs for infrastructure rehabilitation alone are estimated to be of over 1.6 trillion dollars in the next 5 years, where about 27% of all highway bridges are in need of repair or replacement [8]. China will need 40 billion square meters of combined residential and commercial floor space over the next 20 years – equivalent to adding one New York City every 2 years [6]. In September of 2000, 189 countries signed the Millennium Development Goals (MDGs) [9,10]. The Declaration embodies "*a comprehensive approach and a coordinated strategy, tackling many problems simultaneously across a broad front*". The 7th MDG intends to ensure environmental sustainability because as it reads "*Prudence must be shown in the management of all living species and natural resources, in accordance with the precepts of sustainable development*". The 7th MDG goal includes the following actions:

- To make every effort to ensure the entry into force of the Kyoto Protocol, preferably by the tenth anniversary of the United Nations Conference on Environment and Development in 2002, and to embark on the required reduction in emissions of greenhouse gases.
- To intensify our collective efforts for the management, conservation and sustainable development of all types of forests.
- To press for the full implementation of the Convention on Biological Diversity and the Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa.
- To stop the unsustainable exploitation of water resources by developing water management strategies at the regional, national and local levels, which promote both equitable access and adequate supplies.
- To intensify cooperation to reduce the number and effects of natural and manmade disasters.

However, in all the tens of thousands of Scopus referenced journal papers related to the construction sector published since the year 2000, only five had direct references to the MDGs. Alwood et al. [4] also recognize that researchers have paid too little

Fig. 1. One million cubic meters toxic red mud spilled into Kolontar village (Hungary) after aluminium mine tailing collapse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

attention to the crucial issue of materials efficiency. A possible explanation for that gap relates to the fact that the University curricula (especially in the case of practitioners that act on the construction sector) havent yet been adapted in order to incorporate sustainable development principles [11]. As Zielinski [12] puts it "*the traditional narrow technical formation produces graduates that are, using the German language expression "fachidiot"...we must reform university curricula to provide the integration of technical science, economics and humanistic knowledge about man*". Since "*engineering is not more important than ethics...and science is not more important than policy and law*" [13] a new kind of engineering education is therefore needed to address sustainable development principles. Another, more realistic explanation relies on the fact that although some researchers are well aware of sustainable development constraints they are much more concerned in pursuing "Wall Street-payoff" research lines.

2. Publication patterns on the field of construction materials

In the last 5 years almost 2500 papers were published on Elsevier-Construction and Building Materials. The term "sustainable" appears in 241 papers, "sustainability" in 64 and "eco-efficient or eco-efficiency" were mentioned only in 6 papers. It is then possible to say that only approximately 10% of the published papers were, in some degree, related to environmental concerns. That is the same percentage found for the ASCE-Journal of Materials in Civil Engineering. These figures also show that the eco-efficiency concept, which is more accurate than the general term "sustainable", has not yet successfully entered this field. The concept of eco-efficiency was first introduced in 1991 by the World Business Council for Sustainable Development (WBCSD) and includes "*the development of products and services at competitive prices that meet the needs of humankind with quality of life, while progressively reducing their environmental impact and consumption of raw materials throughout their life cycle, to a level compatible with the capacity of the planet*" [6]. Compressive strength is the most used keyword in 548 papers while the keyword "recycling" appears only in 125 papers (5%), which shows that the classical mechanical properties approach is still on the lead in the 21th century. A 7% figure was found for publications on the same period on the ASCE-Journal of Materials in Civil Engineering. These percentages are rather odd if we consider, for instance, the fact that according to the Revised Waste framework Directive No. 2008/98/EC, the minimum recycling percentage for construction and demolition wastes-C&DW by the year 2020 should be of at least 70% by weight. Currently, the average recycling rate for EU-27 is just 47%. The Communication "A resource efficient Europe" [14] also shows the determination of the EU in emphasizing the importance of recycling. The benefits of a proper C&DW management are not solely environmental. As the recent report Strategic Analysis of the European Recycled Materials and Chemicals Market in Construction Industry [15] states that the market for recycled construction materials generated revenues of €744.1 million in 2010, and is estimated to reach €1.3 billion by 2016. One positive aspect must, however, be highlighted: regarding the 241 papers mentioned above they have increased in a steady manner from the 18 published in 2008 to the 88 published in 2012. However, an accurate lineal projection of this evolution ($r^2 = 0.97$) shows that in the year 2017, the number of "sustainable" related papers in Elsevier-Construction and Building Materials will be only of around 180 a year. Environmentally speaking, this is clearly insufficient. On the other hand, while some publications concern the rehabilitation of infra-structures (which is in itself an eco-efficient construction activity) they used, however materials which are clearly unsustainable. Lets take the case of fibre reinforced polymer (FRP), for instance. This material is considered a hot structural material and was mentioned in 244 publications. Unfortunately, chlorine is one of the primary resources of FRP. Chlorine is associated to the production of dioxins and furans that are extremely toxic and bio-cumulative. As such those can be considered misdirected research lines. Additionally, several scientist groups already suggested that chlorine industrial based products should be prohibited. This means that a relevant part of the publications in the field of construction and building materials wouldnt merit this expression (in terms of research efforts) if toxicity aspects werent a field outside the boundaries of the construction industry practitioners. Since 1930, more than 100,000 new chemical compounds have been developed and insufficient information exists concerning the health assessments of 95 percent of the chemicals (of which a relevant part is used in construction products). Only on March 9th did the European Union approve the Regulation (EU) 305/2011 related to the Construction Products Regulation (CPR) that will replace the current Directive 89/106/CEE, known as the Construction Products Directive (CPD). A crucial aspect of the new regulation relates to the information regarding hazardous substances. While the CPD only considered a very limited range of dangerous substances (e.g. formaldehyde and pentachlorophenol), the CPR links this subject to the Regulation (EC) No 1907/2006 (Registration, Evaluation, Authorization and Restriction of Chemicals – REACH Regulation) [16]. Nowadays there is still an excessive focus on the mechanical properties of construction materials without a shred of concern regarding environmental considerations. A clear focus on eco-efficiency is needed. Multidisciplinary approach is also needed to avoid misdirected investigations

3. Nanotechnology for eco-efficient construction materials: A high payoff area

Nano-technology is a hot investigation area which according to the definition presented by Drexler relates to the production with dimensions and precision between 0, 1 and 100 nm ($1\ nm = 1 \times 10^{-9}\ m$). However, it is important to remember that two decades before Drexler definition, the physicist Richard Feynman made a speech entitled "*There's plenty of room at the bottom*". This speech that took place in a Meeting of the American Physical Society in 1959 at CalTech and is considered to mark the beginning of the nanotechnology era [17]. In 1981, an expert group appointed by the European Commission was not able to agree on a definitive delineation of nano-technology, but instead, came up with the working definition for nano-science and nano-tecnology (NST) as "the manipulation, precision placement, measurement, modeling or manufacture of sub-100 nm scale matter" [18]. The very fast evolution of the research in this area can be assessed by the fact that the growth rate of "nano-title-papers" in the 1992–2001 10 year period, which followed an exponential law with a doubling time of 2 years [18]. Even more astonishing are the economic estimates which have predicted that products and services related to nanotechnology could reach several hundred billion Euros in the present decade [19]. So far, dozens of countries are already proceeding national strategies on this field as well as executing national nanotechnology plans [20,21]. Countries are trying to achieve an advantageous position "*so that when nanotech applications begin to have a significant impact in the world economy, countries are able to exploit these new opportunities to the full*" [22]. Europe has assigned 4.865 billion euros for "Nanosciences, Nanotechnologies, Materials and new Production Technologies" in 7th Framework Programme for the 2007–2013 period. The United States, with an act dedicated to Nanotechnology, established a 3.679 billion dollars funding for the 2005–2008 period [23]. As for China, this country has identified nanotechnology as one of the priority mission areas in its national agenda of science and technology development and investment in its R&D is escalating. As a result, this country has emerged as one of the key global players in this field, producing the second largest number of nanotechnology papers behind the United States [24,25]. Arnall and Parr [22] quote Mihail Roco, the senior advisor for nanotechnology to the NSF who stated that "*early payoffs will come in electronics and IT, and medicine and health*". Malanowski and Zweck [26] also mention that, although by the year 2015 it is expected that almost all fields of industry will be affected by nanotechnology, the most influence will be "*chemistry, life sciences and electronics*". It is then no surprise to find out that very few nanotech applications are already in use by the construction sector. It seems that this sector has somehow been neglected by the nanotech research efforts. In fact, when searching for the terms "nanotechnology" and "eco-efficient construction" in all fields of papers published in Scopus referenced journals, only five appear and all of them related to cement and concrete. Of course much more nanotech papers have been published in the field of cement and concrete. However, there are very few when compared with other hot (payoffs) fields. It is somehow comprehensible that, in economic driven societies nanotech research has so far been focused mainly in high profit areas like the aforementioned ones. However, it is rather strange that the same societies so easily forget the value of services provided free of charge by Nature that reach almost 33 billion (10^{12}) dollars/year [27]. As a comparison, the global GDP in the same period was of 18 billion (10^{12}) dollars per year, roughly half the value of the services and products provided by Nature. Not to mention the economics of environment problems like, for instance, the probable meltdown of the world economy associated with global warming. If we act now, the cost of all the services and products to combat climate change will be 1% of the GDP, otherwise, an economic depression of about 20% GDP may take place [28]. It would be advisable or even just common sense that "higher" goals should drive nanotechnology priorities. The seventh UN Millennium Goal related to environmental sustainability is one that in the author's opinion should merit a special attention. That is why the eco-efficiency of the construction industry should also be at the core of the nanotechnology attention [29]. Just because it is one of the largest and most active sectors in the world and because in the next decades it will keep on growing at a very fast pace. This sector has a very high environmental impact. It is responsible for carbon dioxide gas emissions and for the depletion of large amounts of non-renewable resources whose extraction can result in environmental disasters like the one that in 2010 took place in the Hungarian village of Kolontar village.

3.1. Infra-structure materials: A neglected area

Concrete is by definition a perfect example of an infra-structure material. It is by far the most used material on Earth, reaching presently about 10 km^3/year [30]. For comparison, the amount of fired clay, timber, and steel used in construction represent, respectively about 2, 1.3 km^3 and 0.1 km^3 [31]. The main binder of concrete, Portland cement, represents almost 80% of the total CO_2 emissions of concrete, which in turn, are about 6–7% of the planet's total CO_2 emissions. This is particularly serious in the current context of climate change and gets even worse considering Portland cement demand is expected to increase almost 200% by 2050 from 2010 levels thus reaching 6000 million tons/year [32]. These astonishing figures shows the importance of concrete in the materials efficiency context. Also, as Professor Claes-Goran Granqvist of Uppsala University put it, when he wrote to the first author of this paper earlier this year *"Indeed it is strange that concrete, for example, is so seldom regarded as a nanomaterial"*. It is strange, in the context of the Earth́s capacity exhaustion and it is not strange, in a "Wall Street-payoff" driven research. The use of nanotech research efforts to assist in the "greening" process of concrete includes the use of nanoparticles (Fig. 2) to enhance the mechanical properties of concrete and also its durability [33]. It also includes calcium leaching control. This degradation process consists in the progressive dissolution of the cement paste by the migration of calcium atoms to the aggressive solution. The different cement paste phases have different degradation rates. While Portlandite dissolves completely in the aggressive solution, the CSH gel solely undergoes a slight porosity increase [34–36]. Calcium leaching is responsible for an increase in concrete porosity and, consequently, increased permeability; this allows water and other aggressive elements to enter concrete, leading to carbonation and corrosion problems. Also, increasing concrete durability from 50 to 500 years would mean a reduction of its environmental impact by a factor of 10 [37]. It is also worth noticing that, according to Hegger et al. [38], the increase in the compressive strength in concrete would mean a reduction in reinforced steel amount by as much as 50%. So far

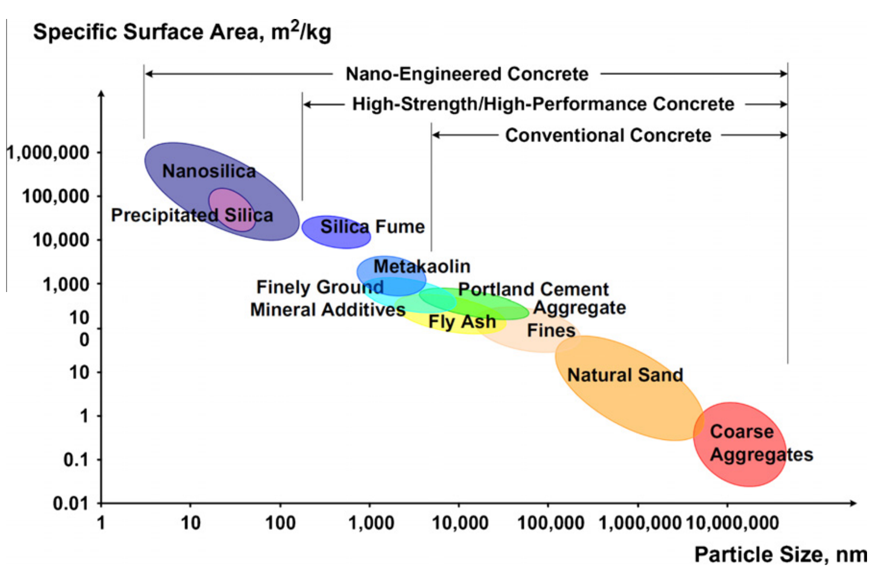

Fig. 2. Particle size and specific surface area related to concrete materials [33] (from the article of Sanchez and Sobolev. Constr Build Mat 24, 2060–2071).

concrete structures assessment required the use of several devices that are attached to or embedded in the concrete elements. This procedure is expensive and in the case of embedded devices may be responsible for property loss and may induce concrete degradation. Self-sensing concrete provides an alternative way of monitoring concrete reinforced structures with a much lesser cost and with less environmental impacts [39]. Previous investigations [40] reported an increase by 40 times in the electric conductivity of cement pastes with nanoparticles, which means a high sensing ability potential. Recent investigations [41] confirm the ability of nanoparticles for the development of self-sensing concrete composites. Nanotechnology also has a huge impact in the eco-efficiency of pavement materials [42]. "*In the US alone over 550 million tons of hot-mix asphalt is produced annually for construction projects. Increasing traffic loads and traffic volume, combined with the rising cost of asphalt, have led to an urgent need to improve the durability, safety and efficiency of asphalt pavements through asphalt modification*"[43]. The use of nanoparticles can also be used to enhance the service life of asphalt binder pavements [44]. The use of nanoclay modifications helps to increase the stiffness and ageing resistances. Nanoclay also decreases the moisture damage potential of asphalt mixtures [45]. Other authors reported an increase in the rutting resistance when carbon nanoparticles are used [46,47]. Nanotech research on infrastructure materials can help in the development of more eco-efficient ones thus helping to fulfil the 7th MDG.

3.2. Materials for energy efficiency: Pursuing the buck

Another relevant aspect of the high environmental impact of the construction industry relates to the high energy consumption in buildings (aprox. one-third of the worlds energy) which accounts for a relevant part of the world greenhouse gas emissions. In Europe buildings are responsible for more than 40% of the energy consumption and greenhouse gas emissions [48].

The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) [49] has been recast in the form of the 2010/31/EU [50] of the European Parliament. One of the new aspects of the 2010/31/EU is the introduction of the concept of the nearly zero-energy building. The article 9 of the European Directive establishes that, by the 31st of December of 2020, all new constructions have to be nearly zero-energy buildings. However, new buildings have limited impacts on overall energy reduction as they represent just a tiny fraction of the existent building stock. These buildings constitute, therefore, the greatest opportunity for energy efficiency improvements [51]. High performance thermal insulator materials are consequently deemed necessary towards eco-efficient construction. These include nanoporous thermal insulators and partial vacuum thermal insulators (Fig. 3) [52]. Also, since the majority of energy losses in a building occur through windows, the utilization of silica nanogel to construct highly energy-efficient windows constitutes a very important nanotech feature [53]. The extraordinary nanotech findings in the field of thermal insulator materials are positive but have not been driven by environmental concerns but instead by the high profit return of the energy efficiency market. A recent report shows that the global market for energy efficient building will go from 68 billion dollars in 2011 surpassing 100 billion dollars by 2017 [54].

3.3. Photocatalytic applications: Low attention on a critical issue

The most known application of nanomaterials in the construction industry relates to the photocatalityc capacity of semiconductor materials. TiO_2 is the most used of all because of its low toxicity and stability [55]. When TiO_2 is submitted to UV rays (320–400 nm), in the presence of water molecules, it leads to the formation of hydroxyl radicals (OH) and superoxide ions (O2−). Those highly oxidative compounds react with dirt and inorganic substances promoting their disintegration. Photocatalys of TiO_2 is also responsible for an increase of the contact angle between water droplets and a given surface, leading to super-hydrofobic or super-hydrophilic surfaces as it increases their self-cleansing capacity. The first application of self-cleaning concrete took place in the church "Dives in Misericordia" in Rome. This building is composed by 346 prestressed concrete blocks made with white cement and TiO_2 [56]. Visual observations carried out 6 years after construction revealed only slight differences between the white colour of the outside concrete surfaces and the inside blocks [57]. Diamanti et al. [58] studied mortars containing TiO_2 having noticing reductions in the contact angle between water and solid surface of almost 80%. In the last years, the use of nanotechnology enabled the development of several construction materials (concrete, mortars, plasters, paints, tiles and glasses) with self-cleaning, air depollution, antibacterial and properties [59–62]. Another photocatalysis research line concerns the water purification [63–65]. Around 1.2 billion people live in areas of physical scarcity and 500 million people are approaching this situation (Fig. 4). However, and in spite of being an important priority of the 7th MDG, this research line didn't receive the same research efforts as other photocatalysis related areas. Since the year 2000 around 16.000 papers

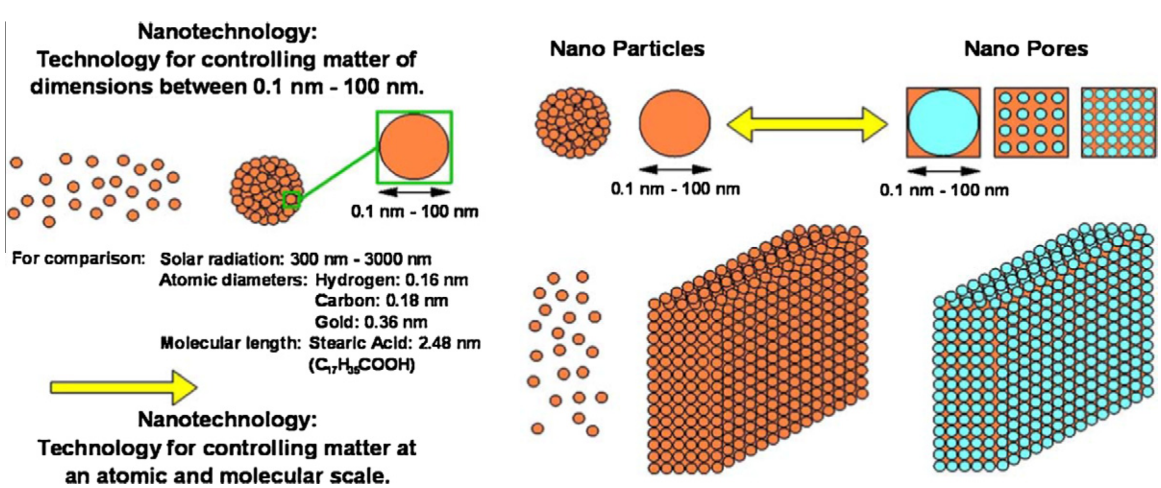

Fig. 3. Nanotechnology and its application on high performance thermal insulation materials [52].

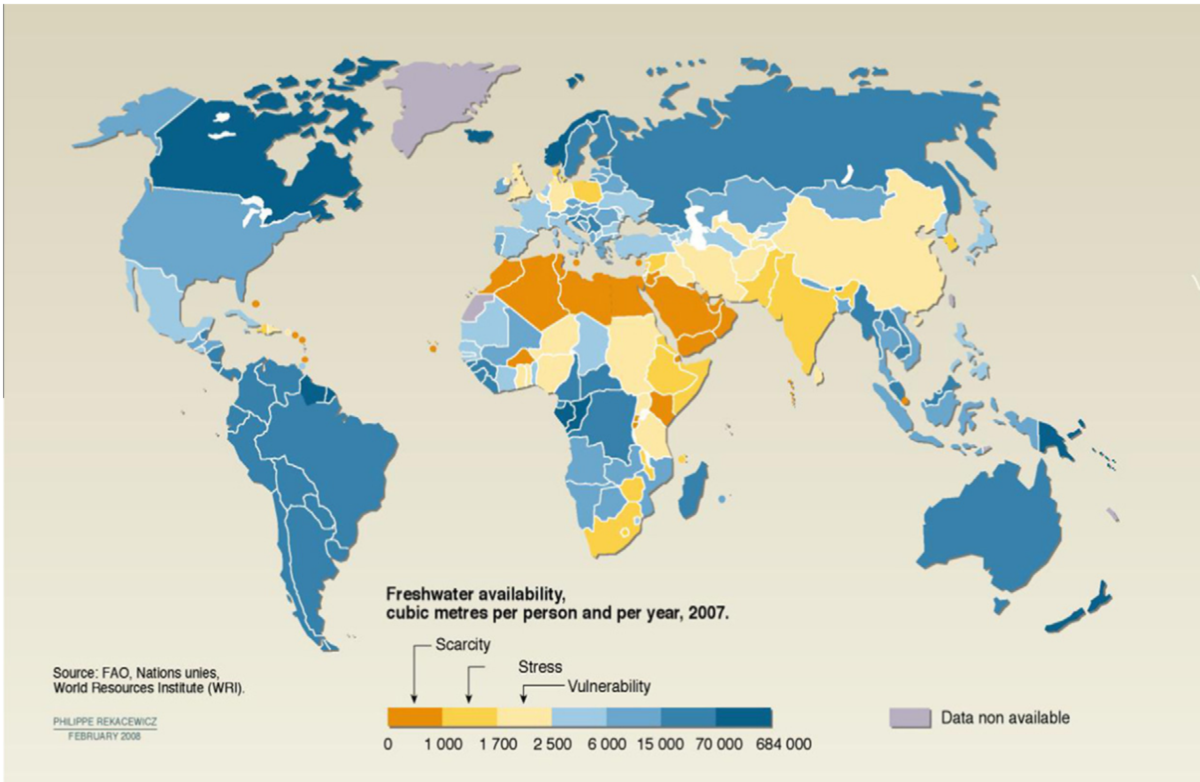

Fig. 4. Water scarcity-vital water graphics. UNEP.

concerning photocatalysis have been published in Scopus referenced journals, however, only 2.5% were related to water purification. Probably because water scarcity is not a priority problem for rich countries that finance the majority of nanotech research efforts. At least not with the same magnitude as it happens for less developed countries.

3.4. Biotech based materials: The real green solution

As a result of the recent ‘‘sustainable’’ approach on construction materials made by the European Construction Products Regulation (CPR) – 305/2011 this will make that the future choice of construction products will be based on their environmental impact assessed by its life cycle analysis (LCA). Unfortunately, since almost all construction products are not environmentally friendly, this is the same as choosing between the less of two evils. Another drawback of LCA is the fact that it does not take into account the possible future environmental disasters associated with the extraction of raw materials. This means that, for instance, the LCA of the aluminium produced by the Magyar Aluminium factory, the one responsible for the toxic red mud flood in the town of Kolontar (Hungary), should account for this environmental disaster. Only then construction products will be associated with their true environmental impact. Since that it is almost impossible to put in practice this means that new and truly environmentally friendly construction materials are needed. An innovative approach to solve this and other current technological problems faced by the human society encompasses an holistic way of perceiving the potential of natural systems [66]. Recent nanotechnology achievements regarding the replication of natural systems may provide a solution to solve the aforementioned problems. The continuous improvement of these systems carried out over millions of years, has been leading to materials and ‘‘technologies’’ with exceptional performance and that are fully biodegradable. For instance the abalone shells are made with 0.2 mm thickness layers, and each is made by a ‘‘mortar’’ of 0.5 μm thickness of calcium carbonate crystals bind altogether with a protein. The final result is a composite material with a toughness 3000 times greater than the toughness of the calcium carbonate crystals [67]. Another example comes from the spider silk (Fig. 5) which possess a strength/mass ratio that exceeds the steel ratio and toughness higher than Kevlar® fibres [68–71]. Another biomimicry related finding very useful for the construction sector relates to the natural glue produced by mussels and barnacles. Being as good as synthetic adhesives, it that allows them to maintain a high adhesion to submerged rocks [72–74]. The great advantage relates to the fact that synthetic adhesives are based on epoxy, melamine-urea–formaldehyde, phenol or organic solvents. These compounds are toxic and responsible for eczema and dermatitis,

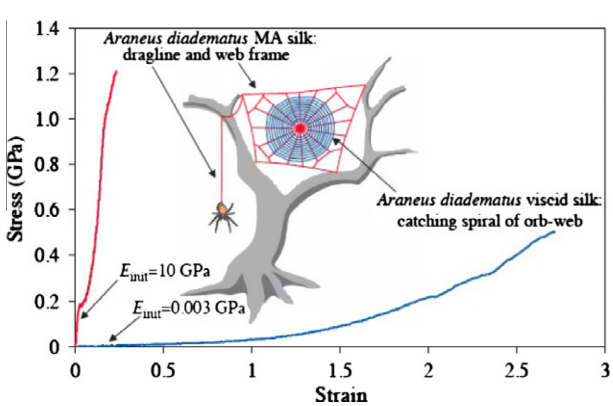

Fig. 5. Stress–strain curves for major ampullate (MA) gland (red) and viscid silk (blue) from the spider *Araneus diadematus*. Einit = initial stiffness [70]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and even cancer [16]. Analysis of bioinspired materials requires knowledge of both biological and engineering principles thus constituting a new research area that can be termed as biotechnology. Although this area has rapidly emerged at the forefront of materials research, the fact is that the study of biological systems as structures dates back to the early parts of the twentieth century with the work of D'Arcy W. Thompson, first published in 1917 [75]. Recent findings show that this area seems to be able to provide a solution to concrete durability enhancement by means of biomineralization, a phenomenon by which organisms form minerals and which was first used for crack repair [76]. Biotechnology could constitute, in the future, a hot area allowing for radical changes in the eco-efficiency of construction materials.

4. The gap between materials research and market use

Recently, The White House released a white paper describing the initiative *Materials Genome Initiative for Global Competitiveness* [77] produced by the National Science and Technology Council. It states that "*the time it takes to move a newly discovered advanced material from the laboratory to the commercial market place remains far too long...the time frame for incorporating new classes of materials into applications is remarkably long, typically about 10 to 20 years from initial research to first use*". Although the authors of this paper agree on the fact that materials research take too long to get to the market they are not sure that the solution for this problem relies just on the replacement of trial and error experimentation by "*virtually experimentation with powerful and accurate computational tools*". At least for construction materials it is too optimistic to believe in that. On one hand, the use of such complex computation tools would increase their price therefore lowering its economic competitiveness. And as Jennings and Bullard [78] state it "*it is utterly unfeasible to expect the construction industry to adopt multiscale modeling tools that require years of training and considerable computational expense to operate*". On the other hand some construction materials are very difficult to study at a nanoscale level. For instance, the challenges of concrete, the most used material by the construction industry, include: "*(1) great difficulty in characterizing the nanostructure due to its delicate and nearly amorphous structure, (2) heterogeneity across six orders of magnitude in length scale, and (3) its sensitivity to both the chemistry of the reactive components of the starting cement and the environmental conditions, particularly temperature and humidity, during curing and service*" [78]. The authors believe that the real problem concerning construction materials research is not so much the time between discovery and market use but instead the huge amount of materials research knowledge already generated that is not used by the construction industry. Part of problem relates to the conservative nature of the construction industry that in general chooses low cost solutions. An excellent proof of that comes from the fact that 31 years after Professor Roger Lacroix coined the expression "high performance concrete-HPC", still only 11% of the concrete ready-mixed production corresponds to the HPC strength class target [79]. This percentage remained unchanged for the past decade. A second part of the problem relates to the need of new and updated standards. For instance the existent standards on the use of recycled aggregates on high strength concrete limit its content to no more than 30% in volume, although investigations results on this field already allow for much higher replacing rates [80]. Another example on the lack of updated standards concerns geopolymers. Van Deventer et al. [81] show how the development of new standards that address the specifics of geopolymers is pivotal to their commercialization. Standardization is therefore crucial step to translate construction materials research efforts into practical applications for the construction industry [82]. To find out how construction materials research lines can fit green specifications [83] is also of special interest to the construction industry. A third part of the problem relates to the fact that most investigations have no practical use at all. They are just narrow minded investigations justified by scientific curiosity. The first part of the aforementioned problem can be tackle by the scientific community turning the benefits of the investigations more visible to the construction industry. Showing that some low cost solutions can be less cost-efficient on the long term is an interesting and practical approach on this problem. This would require the collaboration between construction materials investigators and specialists on the economic field. The second part is of more difficult solution since the scientific community is not responsible for the standardization process. The third part of the problem requires multidisciplinary approach to avoid misdirected investigations. The purpose and specially the benefits of construction materials research must be made clear prior to the investigations. A focus on the research lines directly related to the 7th MDG should in future deserve a special attention.

5. Conclusions

Earths capacity is on the verge of exhaustion which could result in the collapse of human civilization as we know it. Still very little has been done to cope with that problem. For instance although materials use increased 8-fold and Humanity currently uses almost 60 billion tons (Gt) of materials per year, research on construction materials still has an excessive focus on their mechanical properties with minor concerns regarding environmental considerations. In September of 2000, 189 UN member states signed the Millennium Development Goals (MDGs), the seventh goal being related to environmental sustainability. The Declaration embodies "*a comprehensive approach and a coordinated strategy, tackling many problems simultaneously across a broad front*". However, research in the field of built environment special on construction materials still seems unable to recognize its importance. Part of the problem is due to the fact that the University curricula havent yet been adapted to incorporate sustainable development principles. Another to the fact that although some researchers are well aware of sustainable development constraints they are much more concern in pursuing "Wall Street-payoff" research lines. Publication patterns on the field of construction materials show that only 10% of the published papers were in some degree related with environmental concerns. It also shows that relevant materials research efforts were wasted on materials with a toxic profile which is a clear sign of narrow investigations. Nano-technology is a hot investigation area where countries are investing billions of euros, however, most research efforts are put in areas like electronics, medicine and health that will generate a high profit return. A strange option in face of the probable meltdown of the world economy associated with global warming. And a suicidal one in an exhausted Planet. Since concrete is by far the most used construction material on Earth, being associated with 6–7% of the planet's total CO_2 emission it would merit more nanotech research efforts thus helping to fulfil the 7th MDG. Nanotechnology has given a huge input in the development of high energy efficient construction materials like vacuum thermal insulators and silica nanogel based windows but the only reason was less the greenhouse gas emissions savings but instead the fact that the global market for energy efficient building will go from 68 billion dollars in 2011 surpassing 100 billion dollars by 2017. In the last years the use of nanotechnology enable the development of several construction materials (concrete, mortars, plasters, paints, tiles and glasses) with self-cleaning, air depollution, antibacterial and properties due to the use of nanomaterials with photocatalityc capacity. Another photocatalysis research line concerns the water purification, however, and in spite of being an important priority of the 7th MDG, this research line received very little research efforts. Recent nanotechnology achievements regarding the replication of natural systems may provide a solution to a lot of the technological problems face by Humanity. The continuous improvement of these systems carried out over millions of years, has been leading to materials and "technologies" with exceptional performance and that are fully biodegradable. Analysis of bioinspired materials requires knowledge of both biological and engineering principles thus constituting a new research area that can be termed as biotechnology. Another important problem concerning construction materials research is the fact that a huge amount of materials research knowledge is not used by the construction industry. This gap can be overcome by standardization in order to translate research efforts into practical applications for the construction industry. Interdisciplinary research is also as important to avoid misguided research efforts. Interdisciplinary research is also as important to avoid misguided research efforts like the FRP case mentioned in Section 2. Interdisciplinary research will also reduce materials research efforts that are focused only on materials science aspects towards short term practical applications driven by clear social goals like for instance the 7th MDG.

References

[1] Meadows DL, Meadows DH, Behrene JRW. The limits to growth. MIT Press; 1972.
[2] Meadows DL, Meadows DH, Randers J. Beyond the limits: global collapse or a sustainable future. Earthscan; 1992.
[3] Krausmann F, Gingrich S, Eisenmenger N, Erb K-H, Haberl H, Fischer-Kowalski M. Growth in global materials use, GDP and population during the 20th century. Ecol Econ 2009;68:2696–705.
[4] Allwood J, Ashby M, Gutowski T, Worrell E. Material efficiency: a white paper. Resour Conserv Recy 2011;55:362–81.
[5] Whitmore A. The emperor's new clothes: sustainable mining. J Cleaner Prod 2006;14:309–14.
[6] Pacheco-Torgal F, Jalali S. Eco-efficient construction and building materials. London, UK: Springer Verlag; 2011.
[7] Chakraborty S, Iyer N, Krishna P, Thakkar S. Assessment of civil engineering inputs for infrastructure development. New Delhi: Indian National Academy of Engineering; 2011.
[8] Davalos JF. Advanced materials for civil infrastructure rehabilitation and protection. New York: Seminar at The Citty College of New York; 2012.
[9] Annan K. We the peoples: the role of the United Nations in the 21st century: freedom from want. United Nations; 2000. <http://unpan1.un.org/intradoc/groups/public/documents/un/unpan000923.pdf>.
[10] UN. United Nations millenium declaration; 2000. <http://www.un.org/millennium/declaration/ares552e.pdf>.
[11] Pacheco-Torgal F, Jalali S. Does engineering students need sustainable development courses? In: ICEE 2007 International conference on engineering education –the moving frontiers of engineering, Coimbra; 2007.
[12] Zielinski Wojciech. Vision of an engineer in the 21st century. In: 9th International conference on engineering education, S.Juan; 2003.
[13] Dator J. Universities without quality and quality whithout universities. On the Horizon, vol. 13 no. 4. Q Emerald Group Publishing Limited; 2005, p. 199–215. ISSN: 1074-8121.
[14] COM. 21: A resource-efficient Europe – flagship initiative under the Europe 2020 strategy, Brussels; 2011.
[15] Strategic analysis of the European recycled materials and chemicals market. Frost & Sullivan. <http://www.frost.com/prod/servlet/report-toc.pag?repid=M579-01-00-00-00>.
[16] Pacheco-Torgal F, Jalali S, Fucic A. Toxicity of building materials. Cambridge: Woodhead Publishing Limited: 2012.
[17] Pacheco-Torgal F, Jalali S. Nanotechnology: advantages and drawbacks in the field of building materials. Constr Build Mater 2011;25:582–90.
[18] Glanzel W et al. Nanotechnology. Analysis of an emerging domain of scientific and technological endeavour. Steunpunt O&O Statistieken, Leuven; 2003.
[19] Compañó R, Hullmann A. Forecasting the development of nanotechnology with the help of science and technology indicators. Nanotechnology 2002;13:243–7.
[20] Rieke V, Bachmann G. German innovation initiative for nanotechnology. J Nanopart Res 2004;6:435–46.
[21] Soltani A, Tabatabaeian S, Hanafizadeh P, Soofi J. An evaluation scheme for nanotechnology policies. J Nanopart Res 2011;13:7303–12.
[22] Arnall A, Parr D. Moving the nanoscience and technology (NST) debate forwards: short-term impacts, long-term uncertainty and the social constitution. Technol Soc 2005;27:23–38.
[23] Salerno M, Landoni P, Verganti R. Designing foresight studies for nanoscience and nanotechnology (NST) future developments. Technol Forecast Soc Change 2008;75:1202–23.
[24] Wang G, Guan J. The role of patenting activity for scientific research: a study of academic inventors from China's nanotechnology. J Inform 2010;4:338–50.
[25] Wang G, Guan J. Modeling the dynamic relation between science and technology in nanotechnology. Scientometrics 2012;90:561–79.
[26] Malanowski N, Zweck A. Bridging the gap between foresight and market research: integrating methods to assess the economic potential of nanotechnology. Technol Forecast Soc Change 2007;74:1805–22.
[27] Costanza R, D'arge R, De Groot R, Farber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capital. Nature 1998;387:253–60.
[28] Stern N. Stern review on economics of climate change. Cambridge University Press; 2006.
[29] Pacheco-Torgal F, Diamanti M, Nazari A, Granqvist C. Nanotechnology for eco-efficient construction: materials, processes and applications. Cambridge, UK: Woodhead Publishing Limited Abington Hall, in press.
[30] Gartner E, Macphee D. A physico-chemical basis for novel cementitious binders. Cement Concrete Res 2011;41:736–49.
[31] Flatt R, Roussel R, Cheeseman CR. Concrete: an eco-material that needs to be improved. J Eur Ceram Soc 2012;32:2787–98.
[32] Pacheco-Torgal F, Labrincha JA, Jalali S, John VM. Eco-efficient concrete. Cambridge, UK: Woodhead Publishing Limited Abington Hall, in press.
[33] Pacheco-Torgal F, Miraldo S, Ding Y, Labrincha J. Targeting HPC with the help of nanoparticles. An overview. Constr Build Mater 2013;38:356–70.
[34] Carde C, Franqois R, Torrenti J. Leaching of both calcium hydroxide and C–S–H from cement paste: modeling the mechanical behaviour. Cement Concrete Res 1996;26:1257–68.
[35] Kamali S, Gerard B, Moranville M. Modeling the leaching kinetics of cement based materials—influence of materials and environment. Cement Concrete Compos 2003;25:451–8.
[36] Haga K, Sutou S, Hironaga M, Tanaka S, Nagasaki S. Effects of porosity on leaching of Ca from hardened ordinary Portland cement paste. Cement Concrete Res 2005;35:1764–75.
[37] Mora E. Life cycle, sustainability and the transcendent quality of building materials. Build Environ 2007;42:1329–34.
[38] Hegger J, Nitsch A, Burkhardt J. Hchleistungbeton im fertigteilbau. Betonwerk Fertigteil – Technik 1997;2:81–90.
[39] Pacheco-Torgal F, Gonzalez J, Jalali S. Sustainable monitoring of concrete structures. Strength and durability performance of polymer-modified self-sensing concrete. Int J Sust Eng 2012;5:170–4.
[40] Nasibulin A, Shandakov S, Nasibulina L, Cwirzen A, Mudimela P, Habermehl-Cwirzen K, et al. A novel cement-based hybrid material. New J Phys 2009;11:023013. doi: 10.1088/1367-2630/11/2/023013.
[41] Ding Y, Chen Z, Tian H, Pacheco-Torgal F, Zhang Y. Diphasic conductive concrete with nano materials and carbon fiber for self-sensing of strain. In: 15th European conference on composite materials-ECCM15, Venice, Italy; 2012.
[42] Steyn W. Potential applications of nanotechnology in pavement engineering. J Transport Eng 2009;135(10):764–72.
[43] You Z, Mills-Beale J, Foley JM, Roy S, Odegard GM, Dai Q, et al. Nanoclay-modified asphalt materials: preparation and characterization. Constr Build Mater 2011;25(2):1072–8.
[44] Jahromi SG, Khodaii A. Effects of nanoclay on rheological properties of bitumen binder. Constr Build Mater 2009;23(8):2894–904.
[45] Goh SW, Akin M, You Z, Shi X. Effect of deicing solutions on the tensile strength of micro- or nano-modified asphalt mixture. Constr Build Mater 2011;25(1):195–200.
[46] Xiao F, Amirkhanian AN, Amirkhanian SN. Influence of carbon nanoparticles on the rheological characteristics of short-term aged asphalt binders. J Mater Civil Eng 2011;23(4):423–31.
[47] Xiao F, Amirkhanian AN, Amirkhanian SN. Long-term ageing influence on rheological characteristics of asphalt binders containing carbon nanoparticles. Int J Pavement Eng 2011;12(6):533–41.
[48] Lechtenbohmer S, Schuring A. The potential for large-scale savings from insulating residential buildings in the EU. Energy Efficiency 2011;4:257–70.
[49] European Union. Directive 2002/91/EC of the European parliament and of the council of December 16th, 2002 on the energy performance of buildings. Official Journal of the European, Communities; January 4th 2003.
[50] European Union. Directive 2010/31/EU of the European parliament and of the council of May 19th, 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 18 June, 2010.
[51] Xing Y, Hewitt N, Griffiths P. Zero carbon buildings refurbishment––a hierarchical pathway. Renew Sust Energy Rev 2011;15:3229–36.
[52] Jelle B. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. Energy Build 2011;43:2549–63.
[53] Jelle BP, Hynd A, Gustavsen A, Arasteh D, Goudey H, Hart R. Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Solar Energy Mater Solar Cell 2012;96:1–28.
[54] Pike research. Energy efficient buildings: Global outlook; 2011.
[55] Djebbar K, Sehili T. Kinetics of heterogeneous photocatalyticdecomposition of 2,4-dichlorophenoxyacetic acid over TiO_2 and ZnO in aqueoussolution. Pestic Sci 1998;54:269–76.

[56] Cassar L, Pepe C, Tognon G, Guerrini G, Amadelli R. White cement for architectural concrete, possessing photocatalytic properties. In: 11th International congress on the chemestry of cement, Durban; 2003.
[57] Chen J, Poon C. Photocatalytic construction and building materials: from fundamentals to applications. Build Environ 2009;44:1899–906.
[58] Diamanti M, Ormellese M, Pedeferri M. Characterization of photocatalytic and superhydrophilic properties of mortars containing titanium dioxide. Cement Concrete Res 2008;38:1343–53.
[59] Mellott NP, Durucan C, Pantano CG, Guglielmi M. Commercial and laboratory prepared titanium dioxide thin films for self-cleaning glasses: photocatalytic performance and chemical durability. Thin Solid Films 2006;502:112–20.
[60] Hüsken G, Hunger M, Brouwers H. Experimental study of photocatalytic concrete products for air purification. Build Environ 2009;44:2463–74.
[61] Ballari MM, Hunger M, Hüsken G, Brouwers H. NO_x photocatalytic degradation employing concrete pavement containing titanium dioxide. Appl Catal B 2010;95:245–54.
[62] Kolarik J, Toftum J. The impact of a photocatalytic paint on indoor air pollutants: sensory assessments. Build Environ 2012;57:396–402.
[63] Theron J, Walker JA, Cloete TE. Nanotechnology and water treatment: applications and emerging opportunities. Crit Rev Microbiol 2008;34:43–69.
[64] Cloete TE, Cloete TE, de Kwaadsteniet M, Botes M. Nanotechnology in water treatment applications. UK: Ciaster Academic Press; 2010.
[65] Brame J, Li Q, Alvarez PJ. Nanotechnology enabled watertreatment and reuse: emerging opportunities and challenges for developing countries. Trends Food Sci Technol 2011;22:618–24.
[66] Martin J, Roy E, Stewart A, Fergunson B. Traditional ecological knowledge (TEK): ideas, inspiration, and designs for ecological engineering. Ecol Eng 2010;36:839–49.
[67] Meyers M, Lim C, Nizam B, Tan E, Seki Y, McKittrick J. The role of organic intertile layer in abalone nacre. Mater Sci Eng 2009;C29:2398–410.
[68] Porter D, Vollrath F. Nanoscale toughness of spider silk. Nanotoday 2007;2:3.
[69] Lee S, Pippel E, Gosele U, Dresbach C, Qin Y, Chandran C, et al. Greatly increased toughness of infiltrated spider silk. Science 2009;324:488–92.
[70] Gosline JM, Guerette PA, Ortlepp CS, Savage KN. The mechanical design of spider silks. J Exp Biol 1999;202:3295–303.
[71] Harrington M, Masic A, Holten-Andersen N. Iron-clad fibers: a metal-based biological strategy for hard flexible coatings. Science 2010:216–20.
[72] Hedlund J, Berglin M, Sellborn A, Andersson M, Delage L, Elwing H. Marine adhesives as candidates for new biomaterial. In: Transactions – 7th world biomaterials congress; 2004.
[73] Khandeparker L, Chandrashekhar A. Underwater adhesion: the barnacle way. Int J Adhes Adhes 2007;27:165–72.
[74] Kamino K. Molecular design of barnacle cement in comparison with those of mussel and tubeworm. J Adhes 2010;86:96–110.
[75] Chen P-Y, McKittrick J, Meyers M. Biological materials: functional adaptations and bioinspired designs. Prog Mater Sci 2012;57:1492–704.
[76] Pacheco Torgal F, Labrincha J. Biotechconcrete: an innovative approach for concrete with enhanced durability. Constr Build Mater, in press.
[77] Materials genome initiative for global competitiveness; 2011. <http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf>.
[78] Jennings H, Bullard J. From electrons to infrastructure: engineering concrete from the bottom up. Cement Concrete Res 2011;41:727–35.
[79] ERMCO. Statistics of the year 2010. Boulevard du Souverain 68, B-1170 Brussels, Belgium; 2011.
[80] Pacheco-Torgal F, Ding Y, Miraldo S, Abdollahnejad Z, Labrincha J. Are geopolymers more suitable than Portland cement to produce high volume recycled aggregates HPC? Constr Build Mater 2012;32:1048–52.
[81] Van Deventer JSJ, Provis J, Duxson P. Technical and commercial progress in the adoption of geopolymer cement. Miner Eng 2012;29:89–104.
[82] Sanjuan M, Zaragoza A, Agui J. Standardization for an innovative world. Cement Concrete Res 2011;41:767–74.
[83] Lam P, Chan E, Chau C, Poon C, Chun K. Environmental management system vs green specifications: how do they complement each other in the construction industry? J Environ Manage 2011;92:788–95.