RESEARCH AND APPLICATION OF NANOTECHNOLOGY IN TRANSPORTATION

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ABSTRACT

Nanotechnology is the science concerned with the design, construction and utilisation of functional structures with at least one characteristic dimension measured in nanometres. Compared to typical transportation engineering structures (roads, bridges, etc), the two fields thus operate on hugely divergent dimensional scales. Traditionally, nanotechnology has been concerned with developments in the fields of microelectronics, medicine and materials sciences. However, the potential for application of many of the developments in the nanotechnology field in the area of transportation engineering is growing.

Current research in this area focus on the development of improved materials for construction of transportation facilities, characterisation of traditional materials used in transportation facilities and the application of techniques and knowledge developed in the broader transportation engineering field to understand and characterise processes in nanotechnology.

In this paper a broad overview of the potential application of various nanotechnology developments in the transportation engineering field is discussed, and the potential for further basic research that may lead to improved transportation systems is evaluated. The focus is on the potential effects that the technology may have on aspects such as safety, durability, economics and sustainability of the transportation infrastructure. The most important challenge in this endeavour is that of scaling nanotechnology to ensure that the benefits that are gained through working in the nano-sphere (research level) are also realistic in the macro-sphere (application level) dominated by transportation engineering.

1. INTRODUCTION

Nanotechnology is a field that is dominated by developments in basic physics and chemistry research, where phenomena on atomic and molecular level are used to provide materials and structures that perform tasks that are not possible using the materials in their typical macroscopic form. Transportation engineering is the field that is on a macro level concerned with the movement of people and goods over macroscale distances to ensure that the economy can function. A chasm exists between these two disciplines in terms of the operational scale (10^{-9}m to 10^{3}m). However, materials form the building blocks of any transportation infrastructure, and thus it is prudent to evaluate the potential effects of nanotechnology developments on transportation engineering.

In this paper a short introduction is provided on the background to nanotechnology and transportation engineering. Based on a definition of the broad objectives of transportation engineering, the potential areas where nanotechnology can benefit transportation

Proceedings of the 27th Southern African Transport Conference (SATC 2008) 7 - 11 July 2008
ISBN Number: 978-1-920017-34-7 Pretoria, South Africa
Produced by: Document Transformation Technologies cc Conference organised by: Conference Planners

engineering are defined and discussed. Research conducted in nanotechnology to solve challenges in the transportation engineering field is discussed, and some potential future applications for solving looming transportation engineering challenges are suggested.

2. BACKGROUND ON NANOTECHNOLOGY AND TRANSPORTATION

2.1 Nanotechnology background

Nanotechnology is the term used to cover the design, construction and utilization of functional structures with at least one characteristic dimension measured in nanometers (Kelsall et al, 2004). The field of nanotechnology has developed in major leaps during the past 10 years. These developments were mainly driven by factors such as dedicated initiatives in the field (e.g. the National Nanotechnology Initiative) (Goddard et al, 2007), improvements in characterisation equipment and a new understanding into the chemistry and physics of matter on the nanoscale. Nanoscale science can be divided into three broad areas, e.g. nanostructures, nanofabrication and nanocharacterisation with typical applications in nanoelectronics, nanomaterials, life sciences and energy (Nanopolis, 2005).

There are typically 12 types of nanostructures (Table 1), 10 types of fabrication methods and 12 types of characterisation methods that can be defined. It is important to realise that these types of structures, fabrication methods and characterisation methods are continually developing and also that these focus on the nanotechnology field directly, and that as such these structures or methods can not directly be scaled up to typical transportation engineering dimensions. Many of the properties of these materials depend on the materials being available on the nanoscale, and therefore a major part of the research into developing transportation applications is focused on the dimensional chasm that exists between the nanoscale and the macroscale worlds.

Table 1 Types of nanostructures, fabrication methods and characterisation methods (Nanopolis, 2005)

NANOSTRUCTURES	FABRICATION METHODS	CHARACTERISATION METHODS
Aerogels Carbon nanotubes Dendrimers Magnetic molecules Metallic nanoparticles Nanoclays Photonic crystals Quantum corrals Self-assembled monolayers Nanowires Semiconductor quantum dots Fluorescent semiconductor nanocrystals	Electron-beam lithography Nano-imprint lithography Chemical vapour deposition Focused ion beams Pulsed laser deposition Sputtering deposition Molecular self-assembly Hydrothermal synthesis Molecular beam epitaxy Electrospinning	Atomic Force Microscopy (AFM) Electrostatic force microscopy Magnetic force microscopy Scanning Electron Microscopy (SEM) Scanning near-field optical microscopy Scanning tunnelling microscopy Transmission electron microscopy Infrared spectroscopy Nuclear magnetic resonance Optical tweezers Mass spectrometry Ultraviolet and visible spectroscopy

2.2 Transportation background

Transportation engineering focuses on the processes required to provide, operate and manage the required infrastructure to allow vehicles (road, track and airborne) to travel. In this process there are a number of requirements that need to be met. These include the supply and maintenance of a route (road or track) and the management of the vehicles using the route. The objectives of transportation engineering can be defined in various forms, of which one way involves the definition of the four main requirements for a successful transportation system. This can be defined as the supply of a safe, durable, economical and sustainable facility for the movement of goods and people. These four functions are probably those that the general public typically require from an operational transportation facility, and most of the aspects of transportation engineering can be discussed under these headings. In the remainder of this paper the research and potential applications of nanotechnology in transportation engineering are discussed around these functions.

3. RESEARCH AND APPLICATIONS

The specific areas within transportation engineering infrastructure where the application of nanotechnology may have an influence can be defined in various ways. The potential areas of application identified by for instance Partl et al (2004) forms part of the supply of a durable transportation infrastructure facility in terms of improving the internal material properties.

3.1 Safety

The supply of a safe transportation facility is probably the overriding requirement from the general public. This aspect if mostly concerned with the properties on the surface of the facility (and therefore the materials that the facility have been constructed of), as these are the portion of the facility that interacts with the vehicles using the facility. The focus in this area is thus mainly on the improvement of the interfacial stresses and strains that occur between the vehicles and the facility. The safe usage of the facility also falls under this category, and therefore aspects such as visibility and signage are also important.

In the application of the various nanotechnology solutions to this focus area, the methods through which the surface of a material can be altered to improve the service of the material to the user are thus prime. In this regard the various types of Self-Assembled Monolayers (SAM) that can be applied to the surface of existing materials to improve aspects such as their hardness, durability, skid resistance and water resistance constitutes potential applications.

Some specific research in this area involves the incorporation of nanoscale silicon carbide into tyre manufacturing elastomers to improve the wet skid resistance and decrease the abrasion of the tyre by up to 50 per cent (Wang et al, 2002). The application of ZnO_2 to infrastructure to render the surfacing hydrophobic has been attempted in research environments. Further development may lead to hydrophobic road surfaces causing quicker run-off from the road and lessening the chances of hydroplaning (Degussa, 2008; Hou et al, 2007).

In terms of the usage of the facility, visibility is one aspect where the application of nanotechnology is already showing promise. This is through the improvement of the materials used for the application of signage to the facility, or the incorporation of the signage into the facility through the application of materials such as nanophosphors. Current work in regard (Steyn, 2008) shows promise in terms of rendering infrastructure surfaces auto-luminescent, thereby providing guidance to traffic at night.

3.2 Durability

The requirement for a durable transportation facility links to both the requirement that the facility should be able to provide service with a minimum requirement for maintenance, and the requirement that the facility should be sustainable. The sustainability aspect is covered further on in this paper. The durability requirement focuses on the potential perpetual use of the facility with the minimum requirement for disruptive maintenance and rehabilitation.

For this aspect the main benefit that nanotechnology can provide to transport engineering is in terms of the improvement of the materials. This can be provided through the improvement of existing materials or the development of novel materials. The main requirement for these developments is that the material should be able to operate under the applied regime of applied stresses and strains – both internally and externally. In terms of internal stresses and strains the material should provide the required cohesion to keep the internal structure of the material intact, and also provide the required adhesion between the particles and the binder used in the material (i.e. bitumen, cement etc). The focus is thus on those aspects of nanotechnology where the forces and bonds between particles are investigated and the long-term durability of these bonds under a range of cycle stresses and strains are improved.

In this regard current research into the improvement of flexural and shear strengths of concrete through the application of various nano-sized particles has already gone far in terms of improving the quality of the material itself. Increases of up to 50 per cent in the shear strength (Munoz et al, 2008) of concrete have been reported. Abrasion resistance for concrete pavement applications was shown to increase by between 90 per cent and 180 per cent upon addition of nano-sized SiO_2 and TiO_2 to the cement mortar (Li et al, 2006).

3.3 Economical

The client for most transportation engineering facilities is the general public, and therefore most of these projects are funded through taxpayer money (or at least facility-user money). It is thus required to ensure that the provision of transportation facilities is also done in the most economic way possible. In terms of economical facilities the focus is on the short term, long-term and life cycle cost aspects. Both initial construction and ongoing maintenance costs thus needs to be evaluated. It is also important to realise that for many transportation facilities, the facility already exists and the main potential benefit that nanotechnology may have on its life is through appropriate maintenance actions. In a country such as South Africa, a large portion of the road network is established and thus the potential solutions should focus on the methods through which the life of these facilities can be extended and enhanced, and not through a replacement of the facility. Finally, it is also important to evaluate the effect of the potential solution after the facility is discarded. This is especially important where the potential effect of the nano materials used in the application needs to be accounted for in the environment. More information is provided on this aspect in the section on challenges.

The focus in this area lies mainly in the area of aspects such as the cost of the nano-solution that is proposed (fabrication still focuses mainly on small scale quantities of nanomaterials and laboratory installations) and the long-term effect of environmental influences (i.e. solar radiation, water, traffic) that affect the effectiveness of the solution. Potential maintenance actions that can ensure minimum maintenance of transport infrastructure will have a direct influence on the life-cycle cost as well as delay costs during maintenance of the facilities. In this regard the development of automatic crack fillers and treatments for prevention against corrosion of reinforcement are potential areas of development.

The typical solutions indicated under the durability aspects in the previous section of this paper will also potentially affect the economical aspects of infrastructure provision for transportation. Benefits that can be obtained through the application of stronger materials should ultimately result in the decrease for the amount of material (i.e. thinner concrete layers for pavements) affecting the construction cost. Obviously, the life-cycle effects in terms of durability and expected maintenance requirements of the material should be included in any cost evaluation. The general service life of infrastructure can be increased through the improvement of the resistance of the infrastructure to environmental effects. In this regard the various types of nano-composite coatings that can be applied to concrete surfaces (i.e. bridge abutments and pillars) (Arafa et al, 2005; Papakonstantinou, 2005) is an example of prolonging the life of the facility. Most of these coatings differ from traditional coatings in terms of the way in which they bond to the substrate material, providing a more robust layer that binds chemically with the substrate.

The incorporation of sensing elements that can provide timeous indications of changes in the properties of infrastructure materials to ensure timeous maintenance is another area where potential developments may cause cost savings. However, most of the work in this regard (on a nanoscale) is currently performed in the areas of biological and chemical sensors, and further developments will be required to obtain realistic systems.

3.4 Sustainability

In terms of the need for sustainable pavements Maher et al (2006) defined the main criteria for a sustainable pavement as follows:

- Minimizing the use of natural resources;
- Reducing energy consumption;
- Reducing greenhouse gas emissions;
- Limiting pollution (air, water, earth, noise);
- Improving health, safety, and risk prevention, and
- Ensuring a high level of user comfort and safety.

In terms of the potential effect of nanotechnology on transport infrastructure the focus in terms of sustainability would thus again lies in the realm of modification of existing materials that may be harmful to the environment, either through their general application in the infrastructure, or through their production or extracting them from the environment in the first place. Further, the focus can be on the efficient re-use of existing materials either through reworking them and changing the structure to ensure that the properties of the materials are improved to provide a longer life. Materials can be modified to enable construction at lower energy levels (i.e. lower temperatures) to lower the energy requirements for the construction process. Prevention of health and safety effects through the modification of existing materials to enable an inert material that does not cause damage to the environment any more can be investigated (i.e. modification of asbestos to prevent the release of fibres into the airways). Limiting pollution of air and waterways through the flocculation of materials and thereafter chemically binding them to the substrate in the facility – i.e. binding particulates from vehicles through TiO_2 process with elements in concrete to lower NO_x pollution (Cassar, 2005).

4. CHALLENGES

As with most developing technologies, a major number of challenges exist during the initiation of the application of the technology into reality. It is important to be realistic and identify and plan for the limitations and challenges inherent in this process. In this section a short summary of selected challenges and limitations affecting application of nanotechnology in transportation engineering are provided. The following main challenges and limitations can be defined:

- Dimensional chasm;
- Upscaling of fabrication;
- Costs, and
- Environmental and health issues.

4.1 Dimensional chasm

The unique environment of the transportation engineer who works with large volumes of material should always be appreciated when evaluating potential applications of nanotechnology. The effects on manufacturing capacity and performance of the nanomaterials when combined with bulk aggregates and binders should be evaluated to ensure that the beneficial properties of the nanomaterials are still applicable and cost- and energy-efficient at these scales.

4.2 Upscaling of fabrication

Current efforts in the field of nanotechnology are focused on the fabrication, characterisation and use of these materials on a nanoscale (or at best on a micro scale). This leads to most of the development work focusing on very small quantities of material that is typically far removed from the type of quantities required for typical transportation infrastructure. One of the potential solutions to this is to focus on the nano materials to act as catalyser, thereby reducing the amount of nano material required substantially. Another viewpoint is that for many applications, the material does not necessarily have to be used on a nano scale to obtain a major improvement in benefits. This would be the case with reduction of the dimensions of cement, where a substantial improvement in strength can already be obtained through the large scale milling of the cement to a finer form than the traditional form. Although the cement may not be purely a nano material as yet (having at least one dimension of less than 100 nm), the benefits obtained would already be substantial (Garcia-Luna and Bernal, 2005).

4.3 Costs

The costs of most nanotechnology materials and equipment are relatively high. This is due to the novelty of the technology and the complexity of the equipment used for preparation and characterization of the materials. However, costs have been shown to decrease over time (similar to developments with most novel technologies) and the expectations are that, as manufacturing technologies improve, these costs may further decrease. Whether the expected decreases will render the materials as run-of-the-mill transportation engineering materials will have to be seen, and depends largely on the benefits rendered through the application of these materials. Current opinion is that in special cases, the materials will enable unique solutions to complicated problems that cause them to be cost effective, which will lead to large-scale application of these specific technologies. In other cases the traditional methods for treating the problem may still remain the most cost effective. It is the challenge to the transportation engineer to solve real-world transportation infrastructure problems and provide a facility to the general public at a reasonable cost.

4.3 Environmental and health issues

The effect of various nanomaterials on the natural environment is hotly debated in nanotechnology and environmental research. Various ongoing investigations focus on the uncertainty regarding the potential effects of materials that exist on the nanoscale with properties that are different than when using the material on a micro or macro scale (NNI, 2003). Some work in this regard shows that the potential effects may be minimal (Tong et al, 2007). As transport infrastructure are provided in the natural environment, all materials used in the construction and maintenance of these facilities need to be compatible to the natural environment and their effects on the natural environment should not be negative. Typical potential problems in this regard include leaching of materials into groundwater, release of materials into airways through the generation of dust and exposure to potentially harmful materials during construction and maintenance operations.

One of the main reasons for using nanomaterials often specifically include the different performance of the material on the nanoscale, and also the different effect that it has on the environment when used on the nanoscale. In cases such as improved methods for purification of water, the different effect on potentially deadly microbes in the water is specifically the reason why the nanomaterials are being used (Hassan, 2005; Savage and Diallo, 2005). A clear distinction is thus required between controlled and sought-after effects on the environment and uncontrolled and unexpected effects on the environment.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the information discussed in this paper, the following conclusions are drawn:

- Nanotechnology is a rapidly expanding area of research where novel properties of materials manufactured on the nanoscale can be utilised for the benefit of transportation infrastructure, and
- A number of promising developments exist that can potentially change the service life and life-cycle cost of transport infrastructure.

Based on the information discussed in this paper, the following recommendations are made:

- Focused research into the timeous and directed research into nanotechnology for transport infrastructure should be pursued to ensure that the potential benefits of this technology can be obtained to provide longer life and more economical transport infrastructure.

6. ACKNOWLEDGEMENTS

The acting Director for CSIR Built Environment is thanked for the permission to publish this paper.

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