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Potential applications of nanotechnology in pavement engineering

This article focuses on current and potential developments in pavement engineering where the unique properties of nanomaterials can be used to improve the built environment. The original paper on which this article is based was chosen as Best Paper (Pavements) for 2009 by the SAICE Transportation Division

INTRODUCTION

Nanotechnology is the term used to cover the design, construction and utilisation of functional structures with at least one characteristic dimension measured in nanometres. The field of nanotechnology has developed in major leaps during the past 10 years, driven mainly by factors such as dedicated initiatives in the field, improvements in the characterisation equipment and a new understanding of the chemistry and physics of matter on the nanoscale.

Recently, specific applications for nanotechnology have emerged in the engineering field. Although much is being written in this regard, a lot may be deemed speculation and it still requires a quantum leap to bridge the dimensional divide between nano- and macrostructures.

From the familiar definitions of chemistry, physics, engineering and, more specifically, pavement engineering, it is clear that the objectives of science and engineering differ in that the sciences are more concerned with the composition, structure and interrelationships of matter, while engineering is more concerned with applying these principles in support of humanity, although it depends on the principles developed in the sciences. It is important to realise that, while chemistry and physics generally focus on the smaller scales to enable a more detailed understanding of matter, engineering typically focuses on the scale where the matter works together to perform a certain function (e.g. cement particles that combine with aggregate particles to form a concrete road pavement or building). The scale dimensions thus differ – from the nanoscale understanding for the sciences to the macroscale understanding for engineering. Nanotechnology should not be implemented in the pavement engineering arena merely because it is a new technology, but to address specific challenges that cannot be readily solved using existing macroscale technologies.

In this article current needs in the pavement engineering field are summarised as a basis for discussing the research context and the potential applications and benefits of nanotechnology to pavement engineering. Two areas where nanotechnology and pavement engineering can complement each other are identified and specific examples of current and potential nanotechnology-based applications discussed. Finally, challenges in exploiting the unique properties of nanomaterials in pavement engineering are discussed. Overall, the article demonstrates that, although most of the fundamental developments in nanoscale science and technology are occurring in the fundamental physics and chemistry fields, the potential for this technology to impact on the quality of life of society at large is huge. In this summarised version, only selected highlights are discussed and the reader is referred to the full paper for a more thorough understanding of the topic (see reference details at the end of this article). All reference citations have therefore been excluded from this summarised version.

PAVEMENT ENGINEERING CONTEXT

The scale chasm between typical nanotechnology and pavement engineering can be illustrated by considering the potential application of carbon nanotubes (CNTs) as fibres in fibre-reinforced concrete. Typically, the volume of steel or polypropylene fibres

Table 1 PIARC Technical Committees for road infrastructure

Name of Technical Committee	Identified issues	Summarised strategies
Road pavements	Selecting adequate pavement types and road techniques	Develop long-life/perpetual pavements
	Maintaining pavements	Recycle materials in existing pavements
Road bridges and related structures	Increasing the durability and safety of structures	Focus on methods to postpone maintenance and prolong life
Earthworks, drainage and subgrade	Promoting optimal use of local materials	Identify methods for treating soils and application of local/in situ materials
Management of road infrastructure assets	Not applicable to this article	
Road/vehicle interaction		

used for such an application would be in the region of 2%. If it is assumed that the application rate of CNTs in the concrete will be similar to that of steel fibres, this translates to approximately 270 kg of steel fibres (for a steel-fibre-reinforced pavement of 1 km – 7,4 m wide and of 100 mm thick concrete) being replaced by 52 kg of CNTs. A typical pavement rehabilitation project (10 – 100 km in length) may require 520 – 5 200 kg of CNTs. However, the economical production of such volumes of CNTs may not currently be realistic. The dimensional jump from nanoscale to macroscale thus influences the potential usage of nanomaterials.

A clear understanding of the expectations of a novel technology is required in order to evaluate it and ensure that it can deliver optimally. Only once the needs have been defined can applications be explored. An expectation list of nanotechnology for pavement engineering is thus required. Pavement engineering projects that focus specifically on the delivery of sustainable road pavements to the travelling public are typically funded by public money, and therefore the public needs assurances that this funding is not being wasted.

Based on the proceedings of the recent International Conference on Asphalt Pavements (ICAP), PIARC (Permanent International Association of Road Congresses) meeting, Transportation Research Board (TRB) annual meeting, Conference on Asphalt Pavements in Southern Africa (CAPSA) and South African Transportation Conference (SATC), the major current needs for pavement engineering can be summarised as in Table 1.

The major current needs in pavement engineering where nanotechnology could play a role are probably the improved use of existing and available materials, and the processing of these materials to meet the specifications of perpetual pavement structures. The main criteria for a sustainable pavement are:

- Minimising the use of natural resources
- Reducing energy consumption
- Reducing greenhouse gas emissions
- Limiting pollution
- Improving health and safety, and risk prevention
- Ensuring a high level of user comfort and safety.

RESEARCH CONTEXT

The Organisation for Economic Cooperation and Development (OECD) defines four types of research:

- Basic research – theoretical work undertaken to acquire new knowledge of the underlying foundations of phenomena, without particular applications in view
- Oriented basic research – carried out with the expectation that it will produce a broad base of knowledge likely to form the basis of the solution to expected problems
- Applied research – original investigation undertaken to acquire new knowledge and directed primarily towards a specific practical aim or objective
- Experimental development – systematic work drawing on knowledge gained from research and practical experience that is directed to producing new materials, products and devices.

It is apparent that the majority of chemistry- and physics-based research is focused on the first two research types, while the focus of engineering research is on the last two. The following examples show the route that research into nanotechnology should take:

- Basic research – discovery of the buckyball and CNT
- Oriented basic research – research into the basic properties of CNTs and the potential impact on the environment
- Applied research – evaluation of the manufacturing processes and the compatibility and effects of CNTs with cement and aggregate
- Experimental development – application of CNTs as fibres in fibre-reinforced concrete and as sensors in roads.

All four types/steps are required to ensure success in this research, and none of them can be ignored in a novel field such as nanotechnology to enable applications in traditional fields such as pavement engineering. It must be ensured that the ultimate pavement does not fail prematurely through inadequate understanding and knowledge of the CNT. The problem statement for potential applications of nanotechnology in pavement engineering can therefore be summarised as follows:

- Identify current needs that cannot be addressed effectively using current technology.
- Identify potential nanotechnology solutions that may be applicable in the pavement engineering field.
- Marry the two concepts to identify nanotechnology solutions with the highest potential benefit-cost ratios and focus on specific developments in those fields.

ENGINEERING APPLICATIONS

The two areas with the highest potential benefit-cost ratio where nanotechnology can potentially support pavement engineering were identified as:

- Development of improved materials
- Characterisation of existing and novel materials

Development of improved materials

This is the area where probably the most can be achieved to enable beneficial impacts from nanotechnology in pavement engineering. Most of the wide range of materials used by pavement engineers for the construction and maintenance of road pavements are natural materials that are modified using products such as bitumen, cement and other chemical admixtures. The bulk of the material, however, remains naturally occurring aggregates and soils. There are often problems in the application of these materials for specific conditions, i.e. incompatibility between certain aggregates and binders, deterioration of the material during certain environmental conditions and deterioration with use. Current examples from the literature where nanotechnology techniques have been applied to enhance pavement engineering materials are:

Fracture behaviour

The nanolevel characteristics of fracture mechanics need to be understood to improve structural engineering on a macroscale. This includes understanding how dimensional scales interact with each other, and how crack development takes place on a nanolevel in the bituminous binder/aggregate interface and in concrete pavements.

Self-healing materials

Nanoscale effects that are already being utilised and studied include the modelling of self-healing materials (cracks that develop in the pavement layers may self-heal based on the introduction of microcapsules into the cement matrix) and the self-healing of fly ash in pavement materials (previously observed).

Concrete enhancements

Understanding of the bottom-up manufacturing process that occurs in nature is seen as potentially powerful as it provides the opportunity to possibly obtain cost-effective nanomaterials for use in concretes. CNTs are typically viewed as one of the most promising developments impacting on concrete performance, while the exploitation of the changing properties of materials at nanoscale provides novel potential applications in concrete.

Incorporation of TiO_2 into concrete to make it a material that can perform certain photocatalytic activities has been well developed and applied. Typically, the photocatalytic reaction is exploited to provide self-cleaning surfaces and also to remove NO_x, SO_x, NH_3 and CO pollution from urban areas through a chemical reaction triggered by naturally occurring ultraviolet light. International pilot projects have already proved the benefits of this development.

Carbon nanotubes

Fibre-reinforced concrete (FRC) is produced when fibres are added to a concrete mix to control plastic and drying shrinkage cracking. The fibres also lower the permeability of the FRC and produce greater impact, abrasion and shatter resistance. Vital properties required for the fibres in FRC include diameter, specific gravity, Young's modulus and tensile strength. Various researchers have investigated the option of using CNTs as fibres in FRC.

The addition of CNTs to concrete increases the hydration rates and causes strong bonds to develop between the CNT and the cement paste. Increases of up to 70% in the compressive strength of CNT-reinforced concrete, and decreases of up to 12% in the heat conductivity of the concrete have been observed.

One of the potential benefits of CNT reinforcement of concrete that was not found in the literature is the fact that CNTs will not corrode in corrosive environments as happens in steel FRC (specifically promising in marine environments).

Bituminous materials

The RILEM Technical Committee for Nanotechnology-based Bituminous Materials focuses on the identification of material characterisation and modelling issues and challenges at the nano- and microstructural level in an effort to provide bituminous materials with superior environmental and traffic loading resistance.

Examples of the potential application of nanotechnology techniques to enhance material properties that are currently under investigation are as follows:

Thin films or self-assembled monolayers (SAM)

The objective is to change the properties of the surface of the host material. Typical reasons for such a change include incompatibility between the aggregate and the binder used and the need to improve the bonds between the host and the binder. There may also be a need to prevent bonding between two materials, and in such cases changes in the surface morphology/chemistry of the two materials may be required.

The adhesion between aggregate and bitumen is receiving ongoing research attention. The potential for applying SAMs to aggregates to prevent stripping between the two materials and thereby improving the performance of the asphalt should be evaluated.

Some siliceous aggregates react with the alkali hydroxides in cement, causing expansion and cracking over a period of many years – termed the alkali-silica reaction (ASR). Precoating of these aggregates can prevent the type of reaction, rendering currently unsuitable aggregate economically suitable for concrete applications.

Nanophosphor

A major road safety need in rural Africa is the illumination of road pavements to improve visibility and road safety. The potential use of nanophosphors combined with road surfacing materials or paints for this purpose has been evaluated. Nanophosphors are nanoscale crystalline structures with a size-dependent bandgap that can be altered to change the colour of light. Current research findings have shown that nanophosphors can be added to traditional pavement materials such as concrete, bitumen and road paint to enable these materials to become luminescent after exposure to light. Research is also ongoing to further investigate issues such as the increase in luminescence duration, the types of bond that form between the nanophosphors and the substrate materials, and the upscaling of manufacturing techniques to enable practical amounts of nanophosphor to be manufactured.

Sensors

One of the well-publicised possibilities of nanomaterials is the development of sensors that act as part of the substrate that is being observed, thereby allowing very fine measurements on a small scale and obviating the need to add external sensors to a system. Whereas external sensors tend to interfere with the mechanics of the system being monitored, the incorporation of sensors as part of the matrix of the system means that the matrix may actually be able to provide feedback and problems regarding bonding between the sensors and the matrix are obviated. The application of CNTs in traffic monitoring is an example of such an application, although the analysis of the data gathered may still require further work.

Development of alternative materials

In typical asphalt pavements bitumen (a by-product from crude oil) comprises about 0,5% of the mass and between 5 and 17% of the cost of a road. However, if bitumen is not available, an alternative binder is required for the bonding of the aggregates in asphalt. Internationally, it is the opinion that reserves of crude oil are decreasing. The direct implication for pavement engineering is that the price of bitumen may increase drastically in future as availability decreases and efforts are being made to develop alternative and sustainable binders. The application of manufacturing and characterisation techniques developed in the nanotechnology field may assist in the development of new sustainable alternatives with the required properties to ensure cost-effective construction and maintenance of pavements.

Other materials

One of the changes that a material undergoes when used at the nanoscale is that the ratio of surface area to volume typically increases drastically. Clays are often encountered in pavement engineering and they pose very specific problems as their response to changes in moisture content and their platelet structure cause most of them to have low friction angles and make some of them expansive. Traditional treatments of the problem include stabilisation of the clay using materials such as lime, treatment with sulphonated petroleum products and removal of the material from the pavement structural layers. Research into the behaviour of clay minerals in the nanotechnology field is providing new insights into the fundamental properties of clays. Application of this new knowledge may lead to alternative methods for the stabilisation of the clays found in road reserves, and may thus lead to less expensive methods for using these materials in the pavement structure. Characterisation of materials using high-resolution equipment, such as scanning electron microscopy (SEM) and atomic force microscopy (AFM), has led to new insights into their submicroscopic properties, identifying potentially better methods for their treatment.

Characterisation of existing and novel materials

Developments in characterisation techniques that have occurred during the past decade in nanotechnology have opened the door to observations of pavement engineering materials on a scale not available before. This has brought about a major change in the way that materials are being observed and also in the understanding of the behaviour of these materials. Some examples are given below:

Table 2 Hierarchy of possible pavement engineering observation techniques

General wavelength bands	X-ray wavelength 10 to 10-2 nm	Visible wavelength 400 to 700 nm	Infrared wavelength 103 to 106 nm
Indication of currently used technology and resolution of features	NCI*	Satellite images mm resolution	Infrared satellite images mm resolution
		Aerial photographs/ LIDAR km resolution	Infrared airborne images km resolution
		Standard photos m resolution	NCI*
	Computerised tomography (CT) scans mm resolution	Microscope images mm resolution	
	SEM images mm resolution	NCR**	
	NCR**	AFM images nm resolution	

NCI* = No current images, used typically in pavement engineering
NCR** = Neutron capture radiography

Observation techniques

For pavement engineering these techniques range from the macroscale, where satellite images are used to observe macroscale phenomena, down to the nanoscale, where matter is studied in its smallest observable form. The hierarchy of possible observations, including the smaller scales obtained from SEM and AFM, are shown in Table 2.

Characterisation of materials – AFM

AFM has been used in characterising bituminous binders and their respective properties, correlating the surface morphology with the constituents of the bitumen. It was concluded that the AFM data can be used to improve understanding of the precipitation of the asphaltenes in the bitumen and the interaction between the aggregate surface and bitumen in asphalt.

AFM has also been used to investigate the structural morphology of crumb rubber bitumen at the interfacial regions, especially during ageing. Phase-detection AFM was used to evaluate bitumen morphology and it was found that bitumen can be classified into three groups, based on the different visible domains.

Ongoing work at the CSIR focuses on the correlation between bitumen ageing and elastic stiffness as measured using AFM. A clear difference has been observed between the surface morphology of four bituminous binder types aged at different temperatures (see Figure 1).

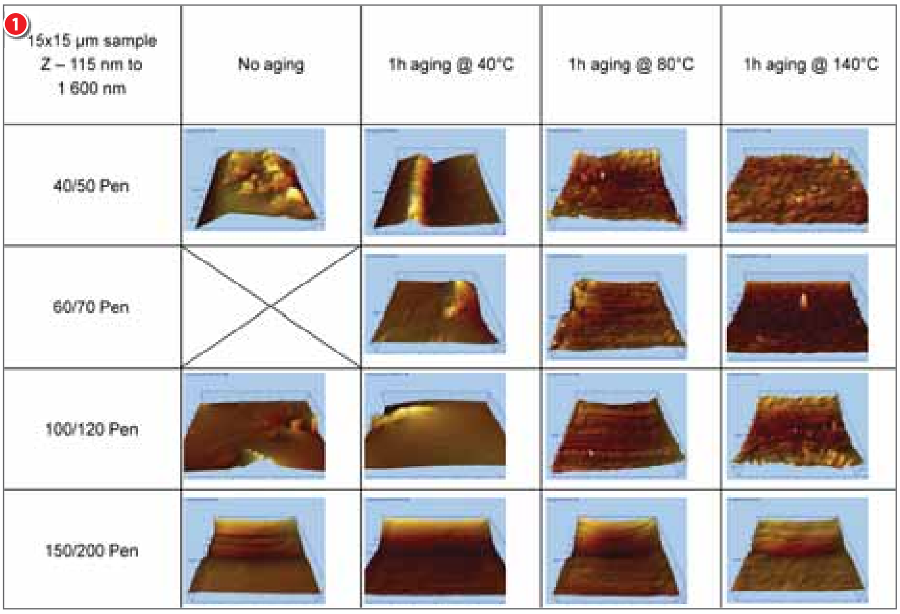
Characterisation of materials – SEM

SEM was used to evaluate the microtexture of two similar sands that behaved differently when being stabilised with various non-standard soil stabilisers. None of the typical engineering tests provided insight into the reason why the stabilisation did not work similarly for the two types of sand evaluated. SEM investigation showed that the difference lay in the fines that were not identified in the standard grading analysis of the sands, which allowed the stabilisers to bond better or worse with the sand grains.

CHALLENGES

Although there are a large number of potential ideas and applications for nanotechnology in pavement engineering, it is important to remain realistic and to identify and accept the current limitations and challenges inherent in this field. These may be summarised as follows:

1 Surface morphologies of four bituminous binders aged at three different temperatures and observed using an atomic force microscope



Costs

The costs of most nanotechnology equipment and materials are currently relatively high. This is due partly to the novelty of the technology, but also to the complexity of the equipment. However, in the case of the nanomaterials, costs have been shown to decrease over time and it is expected that, as manufacturing technologies improve, the costs of the materials will decrease. Whether such decreases will render the materials as run-of-the-mill pavement engineering materials will have to be seen. Current opinion is that in special cases the materials will enable unique solutions to complicated problems; this will make them cost-effective and will lead later to large-scale application of these specific technologies.

Environment

The effect of various nanomaterials on the natural environment is a hot topic in nanotechnology and environmental research. Some work in this regard shows that the potential effects may be minimal. As pavements are constructed in the natural environment, all materials used in the construction and maintenance of pavements need to be compatible with the natural environment and their effects on the natural environment should be minimal. Typical potential problems in this regard include the leaching of materials into ground water, the release of materials into airways through the generation of dust on unpaved roads and exposure to potentially harmful materials during construction and maintenance operations.

Scale

The unique environment of the pavement 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 (nanoscale) properties remain applicable, cost-effective and energy-efficient at these scales.

CONCLUSIONS

The main conclusions that can be drawn are:

- The application of nanotechnology developments in the field of pavement engineering can lead to advances in solving general engineering problems.
- Most of these applications first need to be scaled to the dimensional applications that are typical for the pavement engineering environment.
- The technical effectiveness and cost-effectiveness of available technologies should be evaluated as part of the evaluation of nanotechnology solutions in engineering.
- Fundamental research into the properties of engineering materials to improve understanding of their performance is an important output of nanotechnology characterisation of pavement materials.
- The development of novel materials and the improvement of existing materials in response to a scarcity of natural materials have become possible through the application of nanotechnology techniques to traditional pavement materials.

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ARTICLE REFERENCE

The original paper on which this article is based can be obtained from the

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