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Managing the unknown: addressing the potential health risks of nanomaterials in the built environment

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MANAGING THE UNKNOWN – ADDRESSING THE POTENTIAL HEALTH RISKS OF NANOMATERIALS IN THE BUILT ENVIRONMENT

Keywords: Nanotechnology, nanomaterials, materials, innovation, health, unknowns

Nanomaterials offer significant potential for high performing new products in the built environment and elsewhere. However, there are uncertainties regarding their potential adverse health effects and the extent to which they are currently used. A desk study and interviews with those working across the construction, demolition and product manufacture sectors (n=59) identified the current state of knowledge regarding nanomaterial use within the built environment. Some nanomaterials are potentially toxic, particularly those based on fibres; others are much less problematic but the evidence base is incomplete. Very little is known regarding the potential for exposure for those working with nano-enabled construction materials. Identifying which construction products contain nanomaterials, and which nanomaterials these might be, is very difficult due to inadequate labelling by product manufacturers. Consequently, those working with nano-enabled products typically have very limited knowledge or awareness of this. Further research is required regarding the toxicology of nanomaterials and the potential for exposure during construction and demolition. Better sharing of the information which is already available is also required through the construction, demolition and manufacture / supply chains. This is likely to be important for other innovative products and processes in construction, not just those which use nanomaterials.

Introduction

Nanomaterials are those with one or more dimensions between 1 and 100 nm, and offer properties which can be very different from those of materials in their more usual 'bulk' form. For example, gold at the nanoscale can take on a range of colours (Johnston and Lucas, 2011); whilst titanium dioxide, traditionally used for its whiteness, appears transparent at the nanoscale (Schilling et al., 2010). Nanomaterials have been identified by the European Union as a Key Enabling Technology (European Commission, 2015), important for future employment, financial growth and technical innovation. There are prospects of flexible phone screens, more efficient solar panels, and advances in lithium ion battery design. In medicine, there is potential for drugs to target tumours directly without damaging surrounding tissue (Madani et al., 2011), to fight multiple sclerosis and maybe even to repair damaged spinal cords (Roman et al., 2011).

Nano-enabled concretes, coatings and window glass are being used in the construction of the built environment and this is expected to increase: it has been suggested that 50% of building products will be nano-enabled by the year 2025 (AECOM, 2014). However, it is

difficult to verify this figure – there appears to be little information available to confirm which specific products contain nanomaterials and how widely they are used. Both academic sources (e.g. Hanus and Harris, 2013) and international bodies such as the European Commission (2012) have identified that much is published about the possibilities for nanomaterials, but considerably less regarding the current uses. Even the definition of nanomaterials is disputed, with a review by David et al. (2013) highlighting the lack of consensus on how to define the key terms. For example, some discussions (including the current EU definition) focus only on materials which contain nanoparticles. Alternate definitions, such as that used by the International Organization for Standardization (BSI, 2011) encompass materials which have internal dimensions (spaces or pores) at the nanoscale even though they do not contain nano ‘particles’ as such; or those which are constructed using ‘nanotechnology’ (such as equipment which can operate at the nanoscale) even though the material itself is not nanoscale.

The lack of clear information in this area is problematic given that some nanomaterials are associated with potential health risks, and that exposure to nanomaterials may occur for those working with nano-enabled products when either constructing or demolishing buildings. Questionnaire surveys in the literature suggest that those who may be working with such products have very little awareness. For example, a survey reported in 2009 found that only 25% of respondents (from various EU countries, and working in a range of roles) knew whether or not they were working with nanomaterials (van Broekhuizen and Van Broekhuizen, 2009). A more recent study, targeting 79 experienced trainers in the construction industry in the US, found that less than half were aware that nano-enabled construction products were available, and only 13% knew of such products actually being used (West et al., 2016).

It appears, then, that the lack of knowledge regarding the use of nanomaterials in the built environment is twofold. There are deficiencies in what is publicly known, i.e. the state of knowledge as reported in the academic and manufacturers’ literature; and very little of what is known is available to those employed in the industry, who might be working with these materials and need to make appropriate decisions to manage any health risks. The research described in this paper, therefore, has been designed to address both these areas, using literature review to address the first issue and qualitative interviews to address the second. The findings are then considered using a model of ‘known knowns and unknown unknowns’. This enables exploration of possible steps to address the incomplete knowledge held in relation to nanomaterials. However, the model could also be used more generally to address the potential risks arising from new practices and processes in the built environment.

Research questions

In this paper we explore the uncertainties regarding the use of nanomaterials in the built environment. The research questions addressed are as follows:

1. What is known about nanomaterial use in construction products?
2. What is known about the toxicity of nanomaterials, particularly those used in construction products?
3. What is known about the potential for exposure to nanomaterials in construction and demolition activities?

4. What steps are required to address incomplete knowledge in this area and/or to adapt to the uncertainties

Two methods of data collection were employed. First, a desk top study evaluated academic literature, manufacturers' product data, and relevant websites to identify the scope of construction products which contain nanomaterials; and exactly which nanomaterials are contained. The aim of this was to gain an understanding of the current situation with regard to nanomaterials in construction, rather than to conduct a systematic review. The starting point was a number of key papers which have summarised or reviewed nanotechnology in the construction industry in recent years. These papers (Mann, 2006; Keleş, 2009; Teizer et al., 2009; van Broekhuizen and Van Broekhuizen, 2009; Lee et al., 2010; Greßler and Gázsó, 2012; Hanus and Harris, 2013; Singh, 2014) provided an initial overview of the field, and individual references were followed up to expand upon these findings. These papers also gave insight into some of the products available and the manufacturers working in the field.

Subsequent searches were conducted in specific areas of interest such as the health effects of nanomaterials and the assessment of nanomaterial exposure. The literature presented here is condensed from a more detailed report produced for the Institution of Occupational Safety and Health (IOSH), the funders of this research (Gibb et al., forthcoming). Three databases of nano-enabled products were examined to explore the scope of nanomaterial use in construction products. Two of these are targeted at consumers - the nano product inventory run by the Project on Emerging Nanotechnologies in the United States¹, and the Nanodatabase in Denmark². The third database was eLCOSH Nano, a specific inventory of nano-enabled construction products hosted by the Center for Construction Research and Training (CPWR) in the United States³.

Manufacturers' product sites were also studied: relevant sites were identified from the academic and web based literature above, and from marketing of products which were identified as 'nano' or as having novel properties which might indicate nano-enablement.

Secondly, semi-structured interviews were conducted (n= 59) with representatives from the construction and demolition industries in the UK, and the materials supply chain. Details of interviewees are shown in Tables 1 and 2. The exact topics discussed varied depending upon the interviewee. For those working in the manufacture or sale of nanomaterials, the discussion focussed on the nanomaterials involved, how these were used, the resulting properties and the sectors in which the products were marketed and sold. For those working in construction or demolition, the focus was on what they knew about nanomaterials, and on the likelihood of them working with products which had been identified through the desk top study as being nano-enabled.

Interviews were conducted face to face or by telephone. Handwritten notes were taken which were written up shortly afterwards. These notes were then imported into NVivo and coded. The codes used were a combination of themes which were identified in advance such as those relating to toxicity and specific nano-enabled products; and others which

¹ <http://www.nanotechproject.org/cpi/>

² <http://nanodb.dk/>

³ <http://nano.elcosh.org/>

arose from the data such as factors relating to the choice of building products and how decisions were made regarding health and safety management of new products.

Table 1 Industry sectors represented by interviewees

Industry sector	Number of interviewees (n=59)
Coatings	8
Concrete	5
Construction	9
Demolition	10
Glass	8
Architecture and design	6
Research	3
Recycling	4
Other	6

Table 2 Job roles of interviewees

Job role	Number of interviewees (n=59)
Project or site manager	20
Research or development	10
Product sales	15
Other professional (e.g. architect, designer, engineer)	11
Other	3

Findings from the desk top study and the interviews have been combined in this paper to address the first three research questions mentioned earlier. The fourth research question, concerning steps required to address incomplete knowledge and adapt to uncertainties regarding nanomaterial risk in the built environment, is considered in the discussion section of this paper.

Findings

What is known about nanomaterial use in construction products?

Review of available nano-enabled construction products showed that the most numerous were concrete, window glass, coatings and insulation materials; this is addressed in more detail in Jones et al. (2016). Examples of commonly used nanomaterials include titanium dioxide in 'self-cleaning' windows; silica fume (nanoscale amorphous silica) in self-compacting concrete; and water resistant coatings, based largely on silicon dioxide. Other applications such as road and pavement surfaces which reduce airborne pollution have

also been developed (Shen et al., 2012), although they are not yet in widespread use (Allen et al., 2008; Bartos, 2014).

Incomplete labelling of construction products made it difficult to identify with certainty the exact nanomaterial contained in most cases. For example, from 59 surface coating products identified:

- only 1 product provided detailed information about the structure and particle size of the product (this is the level of information need for accurate assessment of risk)
- 27 provided basic information about the nanomaterials involved such as 'an acrylate base with nanosilver', or 'ultra-thin SiO₂-based nano-coatings'
- 25 were identified as being 'nano' somewhere in their marketing literature or other information, but gave no further detail e.g. 'nanocomposite with low thermal conductivity', 'core nano-sized particles', or 'formulated with advanced nanotechnology'
- 6 were considered likely to be nano-enabled, due to the novel and unique material properties claimed (such as superhydrophobia or photocatalysis), but were not labelled as such.

Other products appeared to use the term 'nano' as a marketing device, including it in the product name without any obvious properties to suggest nano-enablement. More detailed information about products was difficult to obtain despite in depth investigation. In several cases a direct request to a manufacturer for further details on product ingredients was declined on the grounds that the information requested was 'commercially sensitive.'

This lack of published detail has been confirmed by others researching in this area. For example, the eLCOSH nano website of construction products in the United States lists 458 products. Of these, the nanomaterial contained is specified in less than half, and the specifics of nanomaterial content are 'rarely reported' (West et al., 2016).

Interviews with those working in the construction industry found knowledge of nanomaterials to be low, perhaps unsurprisingly given the inadequate nature of labelling. Those who had heard of nanotechnology knew very little, if anything, about it (including some who were involved in the sale of nano-enabled products); some reported knowing nothing beyond an expectation that nanotechnology was about '*Star Trek and little bugs*'.

Although most interviewees knew little about nanomaterials, they knew more about specific nano-enabled products. For example, many were using, or at least knew of others who were using, silica fume concrete, aerogel insulation or nano-coated windows. However, they were not aware that these were based on nanomaterials. Whether or not a material was enabled by nanotechnology was not a driver either for, or against, its use, even though particular properties provided by a nanomaterial might be of interest, such as self-cleaning or thermal insulating characteristics.

For example, some interviewees involved in building design mentioned that aerogel insulation materials might occasionally be used in a refurbishment because they offered high insulation properties in a limited space. Discussions with glass suppliers identified that a decision regarding whether or not to use nano-enabled glass was about a balance between the high fragility of nano coatings during window production compared and the improved thermal and visual properties of the nanomaterials compared to more traditional coatings.

In conclusion, the information which exists regarding the use of nanomaterials in construction is incomplete and difficult to find, nano-enabled products are generally poorly labelled. Those who might work with such products have low awareness regarding the nanocontent of products.

What is known about the toxicity of nanomaterials, particularly those used in construction products?

Talking about the health risk of 'nanomaterials' as a single subject is not particularly helpful, perhaps no more meaningful than to refer in generic terms to the health risk of 'chemicals' or 'gases'. There are, however, some general principles. The first is that if there are particular risks associated with the bulk (non-nano) form of a material (such as it being carcinogenic, mutagenic, genotoxic, or sensitising), these are likely to still be present in the nanoform. The second is that, in principle, smaller particles are more toxic than larger ones of the same chemical composition. The earliest research in this field was published around 25 years ago; a key finding was that particle surface area is an important predictor of toxicity (Oberdörster et al., 1990; Oberdörster et al., 1992). The implication of this can be highlighted by considering titanium dioxide - depending on the particle size and structure, nanotitanium dioxide might have a surface area of 175m²/g compared to the non-nano form with a surface area around 2m²/g (Xiong et al., 2013). The surface areas of more specialised materials are potentially even higher: Bussy et al (2012) suggest figures up to 1000 m²/g for CNTs and over 2500 m²/g for graphene.

Surface area, however, is only one part of the equation, as there are substantial differences between nanomaterials in their toxicity. Other factors also influence toxicity – a review paper by Boverhof and David (2010) identifies that these include structure, size, shape, solubility, aggregation state (whether and how the particles clump together) and surface charge. Much of the research which assesses the health effects of nanomaterials fails to adequately describe the substances tested in sufficient detail, making it difficult to compare studies and contributing to uncertainty about the toxicity of particular materials (Krug, 2014).

Other limitations in the research have also been described. For example, Oberdörster (2010) observes that much of the published research on nanotoxicity uses excessive doses, far larger than would ever occur in real scenarios. Other concerns relate to the difficulties of drawing conclusions about human health based on testing with rats and mice (Valberg et al., 2006; Kosk-Bienko, 2009). The limitations in the existing research have provoked a concern from one key figure in the field that 'raising fears based on a perceived risk that originates from dubious data is not helpful' (Oberdörster, 2010). Others have suggested that nanotoxicity should not be considered as a separate field, as the specific differences between bulk and nanomaterials are overstated and that usual toxicological principles will apply in most cases (Donaldson and Poland, 2013).

Despite the variability and contradictions in the published literature, some overall conclusions can be drawn in relation to the nanomaterials which are most likely to be used in construction products, although these are all equivocal. For example,

- Fibre-based nanomaterials are considered to be particularly problematic. This might include fibre based titanium, or silver wires, but carbon nanotubes (CNTs) are the material most commonly discussed in this context. CNTs are

fundamentally a sheet of carbon, one atom thick, rolled into a tube, and can be included in construction coatings or in concrete, although the extent of their use currently is extremely limited (Jones et al., 2016). In a paper considering the similarities between asbestos and CNTs, Donaldson et al (2013) note that any bio-persistent fibres longer than 5 µm in length and narrower than 1 µm in diameter are problematic because they can penetrate deep into the lung but are difficult for the body to break down by its usual protection mechanisms. However, there are variations in toxicity, so that fibres which are short or tangled are much less likely to be problematic and the presence of defects or additional elements might either increase or decrease toxicity (Lanone et al., 2013). One CNT variant has been identified as carcinogenic by the World Health Organisation (WHO), the carcinogenicity of the rest is 'not classifiable' (Straif et al., 2014).

- Of less concern is nanosilica, one of the most commonly identified nanomaterials in construction, being found in silica fume concrete and in many surface coatings (Jones et al., 2016). Nanosilica is typically amorphous; amorphous silica is less toxic than crystalline (quartz) silica, which is likely to be familiar to those in the industry as a major cause of ill-health. Specific studies have found, evidence of inflammatory or cytotoxic effects (McCarthy et al., 2012; Peters et al., 2004) but only at relatively high exposures to nanosilica, unlikely to occur in practice. A detailed review by Napierska et al (2010) identifies that any effects on the lungs appear to be reversible (i.e. temporary). Nevertheless, the same authors also conclude that there is insufficient evidence to declare nanosilica to be 'safe'. A review by the European Chemicals Agency (ECHA) (ECHA, 2015) has reached a similar conclusion, due to the variation between different forms of the material, and the lack of robust data.
- Nanotitanium dioxide is used to produce self-cleaning window glass and can be incorporated into coatings and concretes to reduce pollution, although it is less commonly used in this context (Jones et al., 2016). Long term toxicity studies suggest that inhalation of high doses can cause moderate inflammation of the lungs. Overall, the data are conflicting, but more studies suggest harm than do not (including those which are based on realistic doses) (Shi et al., 2013). The toxicity of nanotitanium is higher for some forms of TiO₂ than others; it generally increases as particle size falls (Stone et al., 2009) and may be higher for particles in the size range 10 – 40 nm (Chang et al., 2013).
- Nanosilver can be added to paints, coatings and other products to provide anti-microbial properties (such properties also occur with non-nano forms). Detailed reviews of the literature by Stone et al (2009) and Wijnhoven et al (2009) have both found insufficient evidence on which to judge the toxicity of nanosilver, particularly as there are few in vivo studies. A review on behalf of the European Commission (EC) (SCENIHR, 2014) reached a similar conclusion but also observed that *'Silver and nanosilver are clearly shown to have toxic potential although toxicity in general in humans seems to be low.'*

Although this information on nanotoxicity exists in the academic literature it is either not widely available to or not accessed by those making decisions about nanomaterial use. This is perhaps inevitable given that most users do not recognise the products as being nano-enabled. In this research, those specifying products did so based on the properties of the products or based on guidance from their subcontractor. Where new or unfamiliar

materials were being used, the focus of risk assessment as described by interviewees involved at the design and planning stage was largely on buildability, longevity and fitness for purpose. This involved discussions with manufacturers and suppliers, and larger organisations might commission testing if necessary to ensure that a material was fit for purpose, particularly if it was novel or being used outside its original scope. The health and safety characteristics of a material, however, were not reported as a key driver for most interviewees involved in building design, although they recognised their responsibilities to plan for workers and building user safety in other ways, for example in relation to the risk of falls from height.

Risk assessment at the construction site (for example under COSHH) was seen as the responsibility of the user's employer, and this would invariably be based on information provided by the material supplier, such as safety data sheets. However, one interviewee who specialised in risk assessment for the construction industry suggested that these were often inadequate or incomplete, and also identified that nano-enabled materials were highly likely to slip 'under the radar' as they would not be recognised during the risk assessment process. This was confirmed by the review of manufacturers' literature. None of the products identified provided any nano-specific information in the safety data sheet. This included, for example, a product which declared in its marketing literature that it was based on CNTs; but this was not mentioned in the safety data sheet and there was no information available on their size, shape or quantity.

In conclusion, the toxicity of nanomaterials is influenced by many factors. Determining the potential impact of this in the construction industry is particularly difficult given the variation between different materials; the failure of much toxicity research to specify the relevant details; and the lack of information available for construction products regarding which types of nanomaterials might be used. Those undertaking risk assessments are doing so based on incomplete information in safety data sheets. This could become increasingly problematic – for example, if and when products which contain CNTs become more widely available. The toxicity of these products cannot be properly understood without knowing the size and shape of the particles, but this information is not currently available to product users.

What is known about the potential for exposure to nanomaterials in construction and demolition activities?

To understand the risks which might arise from the use of nanotechnology, we need a good understanding not just of how hazardous or toxic particular materials are, but also what the potential is for exposure in construction activities. Factors to consider include the frequency and quantities of materials being used and the likelihood of particle release at various stages of a building's or structure's life – construction, refurbishment, demolition, and recycling.

Quantifying the extent to which nano-enabled products are being used is currently very difficult, with much contradictory information being presented. For example a 1% penetration of the coatings market is used as a basis for calculations in one study (Hincapié et al, 2015) although it is not entirely clear how this figure is calculated. Another study, which assesses nanomaterial production for the purposes of calculating likely environmental exposures, estimates that up to 3000 tonnes per year of nanotitanium

might be added to paints in Europe, and rather smaller quantities of other materials. However, the quantities of each nanomaterial used in construction products is reportedly small compared to usage in other markets, such as cosmetics and sunscreens which use around 70-80% of nanotitanium and zinc produced and textiles which use around half the nanosilver (Piccinno et al., 2012).

Future use of nano-enabled construction products is even more difficult to forecast. There is some evidence that uptake is slow and likely to continue so, reflecting inherent conservatism in the industry. From the interviews, it was identified that the key drivers when choosing materials in construction are cost, product familiarity and particular project needs. One project manager commented that, regardless of all the novel materials available, 'they just want us to put bricks on top of bricks'. Using things which were familiar and known was identified as important to ensure buildability and to help keep things 'simple'. Products needed to be 'fit for purpose, good value and risk free', and new products were less likely to offer this if they had not been in use long enough to be properly tested and proven. New products came with cost implications, not just because of the unknowns in using them but also because supply could be less reliable, which could delay a project. An interviewee working in product development and marketing acknowledged this saying, "even if we were giving it away free, they would say 'that won't work'".

However, use may increase rapidly, particularly if driven by external factors. Designers identified that client interest in sustainability was a factor in adopting new products, as were legislation and cost effectiveness. For example, it was identified by some that the widespread use of soft-coated window panes (which are nano-enabled) was a result of the recent revision to the UK's Building Regulations, which require a high degree of thermal efficiency in new buildings. In addition, the costs of these materials had fallen, making them more acceptable. Other products however, such as aerogel insulation materials, remain expensive and were considered unlikely to be used more widely unless there were particular demands or tax incentives to make their application more cost effective.

There are many activities in construction which increase the risk of exposure to nanomaterials if they are present. These include spray painting with aerosol formation, as well as cutting, sanding, drilling and machining which all create inhalation risks (Baron, 2015; Vaquero et al., 2015). However, if workers do not know they are working with nano-enabled products, they cannot factor this into their risk management processes. Those interviewed were well informed on the risks of dust exposure and inhalation generally, and many gave examples of the control measures used including water suppression, dust extraction at source and the use of appropriate PPE. However, there was also recognition that if unknown nanomaterials were present, workers would not be able to take any additional precautions required. This was particularly the case in demolition, where it can be difficult to get detailed information on the materials used in a building's construction. Some interviewees felt that the availability and quality of such information had improved in recent years. However, for other projects there would be inadequate background information: one interviewee commented that enquiries regarding the history of a building would sometimes meet the response of, 'ask Fred, he has worked here for 37 years', as there would be no records available from the original construction or subsequent modifications. This creates the potential of unmanaged nanoexposure in future years, if the uptake of such products increases.

The limited measurements reported so far in the literature suggest that most worker exposures are likely to be relatively low in practice. For example, Larrazza et al (2015) conducted research as part of the European Scaffold project. In real life scenarios, they assessed particle release from a number of construction processes (including application of nanotitanium coating and machining of nanosilica concrete) and found that workers were not overexposed to nanoparticles in any of the scenarios tested. Other studies have shown that when nano-enabled construction products are exposed to weathering and machining most of the particles released are attached to pieces of the matrix in which they are embedded, reducing their toxicity. Review of this literature by Froggett et al (2014) reported that less than one third of studies undertaken found particles which were dissociated from the matrix. In a more recent study (West et al., 2016), a machining task on a nanotitanium coated roof tile released debris that was mostly either attached to the matrix or consisted of dissociated particles which were larger than nanoscale. Only four individual free particles smaller than 200 nm were identified. The total worker exposure was below the exposure limit for nanotitanium set in the US by the National Institute for Occupational Safety and Health (NIOSH), a level which is eight times smaller than the NIOSH OEL for ordinary titanium. However, the number of studies in this field is relatively small and inconclusive; some studies do suggest that free particles might be released through a combination of weathering and machining (Busquets-Fité et al., 2013; Hirth et al., 2013). In addition, most tests have been laboratory based and used bespoke mixtures of nanomaterials rather than commercially available products in real workplaces, and therefore may not accurately predict true worker exposures.

Real time monitoring of exposure to nanomaterials is required to fully understand the risk, but is difficult, even if known nano-enabled products can be identified for testing. First, there are challenges regarding the actual measurement of nanoparticle release, particularly differentiating between released particles and background levels. Van Broekhuizen et al (2011) measured particle release from a task involving the drilling of nano-enabled concrete but found that cigarette smoking in the vicinity had a far higher impact on nanoparticle counts; the use of machinery and equipment such as forklift trucks and gas burners can also lead to peaks in nanoparticle numbers which are not directly related to the process being assessed (Kuhlbusch et al., 2004). Also, nanoparticle release from products can occur even though they were not intentionally added during manufacture. For example, it has been reported that the demolition of ordinary (non-nano) concrete results in the release of particles of all sizes, including a high number of nano sized ones (Kumar and Morawska, 2014; Azarmi et al., 2015) (although these contribute little to the overall mass of dust released). Finally, there is no real agreement on the best metrics to use when trying to predict health effects (for example particle mass, particle size, particle number, particle surface area), and many traditional occupational hygiene methods are inadequate. Individual worker exposure can be difficult to measure because of the high complexity and limited portability of some equipment (Methner et al., 2009) and the wide variation in methodologies used makes comparison of results difficult (Kuhlbusch et al., 2011).

It was noted in 2010 that, the evidence regarding potential exposure to nanomaterials was even less substantial and conclusive than that relating to their hazard profile (Savolainen et al., 2010). Unfortunately this continues to be the case. Understanding of exposure risk is impossible without improved knowledge of where nanomaterials are used and to what

extent. There are additional challenges with the measurement of exposures, and the published literature in this field is small.

Discussion

The findings presented above illustrate that there are many unknowns with regard to nanomaterials in construction products. Those working with these materials have access to very limited data, as manufacturers provide incomplete or even incorrect labelling in many cases, and safety data sheets rarely include details on nano-content.

Nevertheless, these products are being used, not particularly because they are nano-enabled, but because they provide functionality which is useful to contractors and their clients. Generally, the fact that products are nano-enabled is not known by those working with them or designing them into projects, and does not influence material choice or risk assessment processes.

Iavicoli et al (2009) suggest that the unknowns relating to nanotechnology can be considered using the model of known knowns and unknown unknowns – often attributed to the U.S. Secretary of Defense Donald Rumsfeld,⁴ but actually a term which has been used in complex industries for many years (Loch, 2008). Figure 1 summarises the knowns and unknowns relating to nanotechnology, based on literature and on the findings of this study. These reflect the overall state of knowledge, but also the challenges of knowledge not being shared across different sectors and different disciplines.

- a) The 'known knowns' are relatively straightforward. There is a wide published literature which addresses the basic principles of nanotoxicity and which has identified key risk factors such as shape, and other influencers such as particle size, agglomeration and the presence of additional materials.
- b) The 'unknown knowns' reflect that there is relevant information and knowledge that is neither recognised nor used – such as suggestions that our existing knowledge of toxicity from other fields could be put to better use in understanding nanotoxicology (Donaldson and Poland, 2013). More frustrating is the knowledge held by manufacturers which they do not share regarding the materials used in their products. As a consequence of this, designers, contractors and researchers are often working without access to relevant information. This may be of little importance if the nanomaterials being used are those with relatively low risk (such as amorphous silica), but will become more problematic if, or when, materials such as CNTs are adopted more widely. Users need to know what they are working with so that they can ask the right questions and make adequate risk assessments.
- c) The 'known unknowns' are those areas where individuals, sectors, and companies recognise the limits of their knowledge. Many of those working in construction are used to managing this, so that where new materials are being used with incomplete evidence on reliability or longevity, practitioners will either gather data to provide reassurance; or may decide not to proceed with a particular process or material because the uncertainties are too great. Those working in demolition have fewer choices and will simply have to take greater precautions (mostly based on PPE) if they have insufficient information to accurately assess risk.

⁴ <http://news.bbc.co.uk/1/hi/magazine/7121136.stm>

- d) The 'unknown unknowns' are obviously difficult to quantify. They illustrate the importance of assessing health and safety risk from innovative materials and processes early to ensure that any risks are properly understood before they are introduced on a widespread basis. History contains numerous instances of hazardous materials being identified only in retrospect, when those working with certain substances developed particular diseases. Examples in construction include Chromium VI, lead paints and of course asbestos; examples in wider society include tobacco, 'trans fats' in foods, and environmental pollutants such as chlorofluorocarbons (CFCs).

Figure 1 The knowns and unknowns of nanotechnology in construction materials

What steps are required to address areas where knowledge is incomplete in this area and/or to adapt to the uncertainties?

Action is needed to address the areas where current knowledge is inadequate, to help move nanotechnology to a position where enough is known to make good decisions. This is illustrated by the three arrows in Figure 1, and the labels alongside. The measures needed to ensure safe practice in the meantime are shown by the bar labelled 'living with uncertainty'. Similar principles are likely to apply in others areas of innovative technology in construction.

Better utilisation of knowledge

The principle here is that we could make better use of the information we have or share it more widely). Much is known from particle toxicology and nanotoxicology regarding the characteristics of materials which make them more hazardous. This information can be used to facilitate risk assessment, where more detailed information is lacking. So called 'read across' methods are being developed for nanotechnology (Bergamaschi et al., 2015). Using information which is known (for example data from asbestos, showing the toxicity of fibres with a high aspect ratio; or evidence regarding the adverse impacts of insoluble ultrafine particles from pollution) can be used to predict the toxicity of other fibres or materials. This approach is a key tenet of current research, including Nanosolutions⁵, a major project funded under the EU 7th Framework programme.

An understanding of the overall factors which influence toxicity underpins qualitative risk assessment methods such as Stoffenmanager (Van Duuren-Stuurman et al., 2012) and NanoCat (Hansen et al., 2014) designed to be used by those with limited expertise or where quantified hazard or exposure information is not available. However, such risk assessment methods rely on the user knowing that they are working with nanomaterials: yet our interviews revealed very limited awareness of nanomaterials amongst those either working in construction and demolition or those selling building products.

This lack of awareness is largely a consequence of poor labelling of nano-enabled products. A key contributor to this is the absence of specific legal requirements in this respect. There are, of course, requirements for manufacturers to gather information on the health and safety risks of their products. Under REACH (Registration, Evaluation, Authorisation & Restriction of Chemicals, 2007) in Europe, for example, manufacturers are required to assess and manage the risk from the materials that they sell and to provide appropriate information for their users through safety data sheets. Similar provisions apply in other countries such as the United States. There are no specific nano-related provisions at a European level (other than those relating to food stuffs and cosmetics) apart from the inclusion of a voluntary 'nano content' tick box on REACH applications. The EU is currently consulting on possible changes to REACH legislation to improve the availability of information to those who use nano-enabled products. This is a long term project – REACH entered into law in 2007, but has a deadline of 2018 for full implementation, and any possible changes relating to nanomaterials are unlikely to occur for several

⁵ <http://nanosolutionsfp7.com/>

years. In addition, current indicators are that the most likely outcome of the consultations will be a voluntary observatory rather than a compulsory register⁶. The lack of progress with regard to European registration and characterisation of nanomaterials has prompted France, Belgium and Denmark to introduce their own (widely varying) regulations (Bochon, 2015).

It could be argued that there is limited benefit in designers, managers and workers in construction knowing simply whether or not particular products are nano-enabled, given the lack of clarity over what this really means in health terms. However, it does at least provide them with a trigger to seek additional information from suppliers, which may encourage suppliers in turn to find out more from manufacturers, and result in improved quality of information being provided in safety data sheets. The findings of the current study in this regard are echoed by the literature. Van Broekhuizen and van Broekhuizen (2009) conducted a review of the scientific literature and web-based information in addition to almost 100 interviews and found no safety data sheets which reported the details of nanomaterials used in construction products, although information (with varying amounts of detail) was occasionally given in technical data sheets. Similar concerns have been raised more recently as part of the Scaffold project, a multisite EU funded project looking at strategies to manage nanomaterial risk in the construction industry (López de Ipiña et al., 2015). There is also evidence that some safety datasheets are not just incomplete but incorrect. Lee et al (2012) report examples of safety data sheets for nanomaterials which give exposure limits relating instead to the bulk materials – failing to distinguish for example, between graphite (which has a Working Exposure Level of up to 10mg/m³ in the UK) and CNTs (no specified limits in the UK; but in the US, the recommended limit is 1 µg /m³) (NIOSH, 2013).

Once nanomaterials are incorporated into construction products, even less information is provided, and the complexity of the construction product supply chain has been identified as a contributor to the poor availability of information to product users (BiPRO, 2013; López de Ipiña et al., 2015). It is essential that those who conduct risk assessments in construction are able to rely on the data provided, and to be confident that data sheets are comprehensive, accurate, and based on the most current findings regarding nanomaterial hazard. There is published guidance on the preparation of such safety data sheets for nanomaterials (ISO, 2012), but current evidence suggests that this guidance is rarely, if ever, followed.

Given that better information sharing is unlikely to be driven by changes to legislation in the short term, certainly in the UK, it can only happen if manufacturers take such action independently. Indeed, there is a strong argument that they have a moral duty to do so, to ensure that their products can be used safely. Responsible Research and Innovation is an EU approach which expects business to work with researchers and the public to ensure that the needs of all parties are aligned (Sutcliffe, 2011). There is evidence that some companies recognise this responsibility. For example Bayer (who developed 'Baytubes', one of the early CNT products) states on its website, 'we assess the possible health and environmental risks of a product along the entire value chain. This starts with research and

⁶ <http://www.anec.eu/attachments/ANEC-PR-2016-PRL-001.pdf>

development and continues through production, marketing and use by the customer through to disposal'.⁷ In reality it is difficult to evaluate how companies make judgements, and how they balance the legal and social responsibilities with accountability to their shareholders. For example, an Australian/American company has started trialling CNT-enhanced concrete in construction projects including a length of road surface on an American interstate highway. The company reports that it has resolved health and safety concerns through the inclusion of the CNTs in a liquid admixture and by using only a low percentage in its product⁸. This in itself is not evidence that the material will be safe at various stages of use, although further information may become available before the product reaches commercialisation.

Increased knowledge

The principle here is that we need to know much more: there are several important aspects to this, including further study of the toxicology of specific nanomaterials, especially those which are most likely to be used in products (or are already being used). A second area, as discussed above, is research to identify the particular characteristics which make nanomaterials more or less safe, so that the general principles can be used to understand the risks of a wider range of materials. A third area, which builds on this, is to find ways to design nanomaterials which are intrinsically safer, by making chemical or structural alterations which reduce the potential for health risks (Bussy et al., 2012; Costa, 2014). This 'safer by design' approach is in line with current best practice in risk management in construction more widely (Behm, 2005), and is an important focus for European funding, through projects such as Prosafe and Nanoreg II.

In addition to research on the hazards from nanomaterials, further research is required on the potential for exposure for those working in construction and demolition. Such research is difficult to plan due to the uncertainties about where nanomaterials are being used. In addition, there are substantial challenges associated with the measurement of nanoparticle release: traditional occupational hygiene methods are often inappropriate or inadequate. Nevertheless, it is important that research is undertaken which assesses potential exposures from real construction products during standard building processes. For those working in demolition additional testing is required which includes weathering and life cycle approaches combined with assessment of the impact of the destructive processes used in this field

Much of the ongoing research to improve the knowledge base with regard to the risks from nanomaterials is publically funded; the EU spent around €5bn on nanotechnology research for the period 2002-2013, including a range of studies specifically addressing health and safety concerns (e.g. Scaffold, NanoMicex, Sanowork, Marina and NanoReg), and further projects are ongoing under the Horizon 2020 programme.⁹ The United States committed €15bn over a similar period. Funding research in this way ensures a degree of neutrality and also means that results can be shared widely. However, there is also scope for private

⁷ <http://www.bayer.com/en/product-stewardship.aspx>

⁸ <http://www.edenenergy.com.au/pdfs/6afaf9eddd984d978e3e7cd605545531.pdf>

⁹ <http://www.nanosafetycluster.eu/>

organisations such as manufacturing companies to undertake research. This has the advantage for companies that they do not need to disclose confidential data regarding the composition of their products. It also ensures that testing, whether toxicity or exposure based, can be based on real products, which are not always available to independent researchers, particularly prior to commercial release. However, companies may be unable or unwilling to commit the necessary resources for testing until they are confident that a product is commercially viable. There is some evidence from France, where companies are required to characterise in detail the nanomaterials in their products, that this could adversely affect the innovation and development of nanomaterials (RPA et al, 2015); some suppliers are reportedly seeking to avoid using nanomaterial based products in order to avoid costly or complex processes. Additionally, where costs are incurred by organisations, they will inevitably be passed on to customers. This has particular implications for the adoption of nanomaterials in construction given the high volumes of materials used and the strong focus in the industry on price and value.

Living with uncertainty

The reality is that nanomaterials are already being used despite incomplete knowledge regarding their risks and it is inevitable that the use of nanotechnology will continue to develop ahead of detailed information on the hazards of specific materials. Steps therefore need to be taken to minimise any potential for harm until the knowledge base 'catches up' with usage. This is illustrated on figure 1 by a bar (rather than an arrow), as it relates to measures needed to cope with the current situation rather than to progress. A key current measure is the adoption of a precautionary approach, advocated by the HSE in the UK and similar bodies elsewhere (HSE, 2013). This recognises that limited (or no) evidence of harm is not the same as evidence that no harm will occur, and therefore protective measures should be taken where there is uncertainty.

Where insufficient evidence exists to accurately judge the hazard from a particular product or material, exposure control is essential to manage risk. There are, of course, significant hazards already present in the construction industry, including silica dust, sensitising agents and solvents, which require good exposure controls. Standard measures such as ventilation, extraction and dust suppression systems, high standards of hygiene and welfare, and provision of suitable protective clothing and equipment when necessary are the most effective route to protect against both the known and the unknown hazards in the industry; ensuring these are robustly implemented must be a high priority regardless of the introduction of new materials.

Centralised risk assessment and recommendation is important to help constructors make good decisions. For example, Scaffold is a large European project which has assessed the potential for exposure to nanomaterials during construction and maintenance tasks, and is expected to publish an on-line tool specific to the use of such products shortly.¹⁰

However, there are additional steps that individual designers, specifiers or constructors can consider. First, they should ask challenging questions of their

¹⁰ <http://scaffold.eu-vri.eu/>

suppliers, particularly where materials have been introduced with novel or improved properties. As discussed above, this will encourage suppliers to develop a better understanding of the products that they sell and to ensure that safety data sheets for nanomaterials are comprehensive and accurate. Such questioning is particularly important for materials which are fibre based, as adequate risk assessment is not possible without consideration of the dimensions and other properties of these materials.

Secondly, contractors should keep accurate records of the products used in their buildings; this could be done using the health and safety file required under the UK's Construction (Design and Management) Regulations (2015), or by including material details in BIM (Building Information Modelling) representations of new buildings. This will make risk assessment easier for those who modify or demolish the buildings in future years, by which time it is likely that more detailed information about toxicity will be available.

Looking more closely

A final consideration relates to the 'unknown unknowns,' and the need for strategies to expose this lack of knowledge so that it can be managed. It may also be useful to reflect on whether more is often known than is admitted. For example, asbestos was used for many years in construction, promoted as a miracle material, supposedly with little understanding of its toxicity. However, there is evidence that it was recognised as being dangerous by the late 19th century (Gee and Greenberg, 2001); and that by the early 20th century those working with it were being refused health insurance (Hoffman, 1918). Its toxic properties therefore were not unknown: rather they were unproven, and perhaps insufficient attention was paid to those who tried to raise concerns. Epidemiological evidence of problems continued to be published through the middle part of the twentieth century (Doll, 1955; Selikoff et al., 1964), but bans on the use of asbestos were not implemented until the 1980s. Clearly, the benefit of hindsight makes this picture much clearer than it was at the time; but more willingness to challenge the status quo might have reached a similar conclusion rather earlier.

Conclusions

In this research, we have drawn together the key literatures on the use of nanomaterials in construction. This has been supplemented by interviews with those working with or supplying such products across the industry, to provide up-to-date information regarding the extent of knowledge in this area within the industry. By considering these findings within a framework of knowns and unknowns we have been able to demonstrate the areas where intervention is most needed, and how this might be driven.

As nanotechnology has advanced over the last 15-20 years and new developments continue, the information needed to adequately assess and manage the associated risks has failed to develop at the same rate. Those working with these new materials have to make decisions regarding risk management, but inevitably do so based on incomplete information. Such decisions have to balance potential benefit with

possible risk; a concept that society is familiar with in many situations. Drugs with severe side effects are approved, but only for use in life threatening diseases; the armed forces prepare their recruits for battle situations using rigorous training methods unlikely to be considered acceptable in other sectors. In construction, these judgements are also made – paint with a slightly higher level of toxicity (for example one based on VOCs) might be justified if it lasts twice as long as a lower risk product, and thus would delay the need for repainting, thereby reducing risk overall.

Similar judgements are important with nanotechnology. Nanomaterials certainly offer potential benefits - for example reduced environmental impacts from the use of concrete, improved energy efficiency from thermally insulated windows, and reduced vibration exposure through the use of self-compacting concrete. However, these need to be balanced against the possible risks and this is proving challenging. Nanosilver for example, has antimicrobial properties and is used to reduce infection in health care environments. However, there is also evidence of environmental effects as a consequence of its toxicity to microbes, and concerns that it may encourage the development of resistant microorganisms (Maillard and Hartemann, 2013). It is therefore argued by some that its use should be limited until further information is available (SCENIHR, 2014). In the meantime, however, its widespread use continues in consumer products (such as washing machines, socks and house paints for example) despite the benefits being relatively low.

Asbestos provides historical evidence of failing to balance benefits and risks – a Lancet article from 1967 argued that ‘it would be ludicrous to outlaw this valuable and often irreplaceable material in all circumstances (as) asbestos can save more lives than it can possibly endanger’ (Gee and Greenberg, 2001). This highlights the danger that excitement and enthusiasm at the properties of a new material might forestall rational consideration of the risks that it may also bring. Som et al (2014.) have recommended that development of new products should only proceed where benefits outweigh risks; and that where risks are high, development should not generally proceed, no matter how great the benefits. However, detailed risk assessment is difficult for nanomaterials given the incomplete nature of the evidence base.

The lack of robust toxicological data notwithstanding, the far greater problem is the failure to use the information which is available. Good communication is critical. Our study found examples of information sharing up and down the supply chain, between designers, clients, contractors and subcontractors. However, the literature suggests that this does not always occur (Briscoe and Dainty, 2005) and our study also found that the sharing of information through the supply chain between product manufacturers, suppliers and users in relation to nanomaterials was particularly poor. Developers of new materials must therefore take responsibility for ensuring that the potential risks of products are properly evaluated and kept under review as new data emerges, and that this information is adequately shared with end users. Again, there are both risks and benefits here: the benefits being improved transparency, which enables better risk management and will also facilitate applied research. The risks relate to commercial sensitivities, with companies understandably protective of their intellectual property and perhaps also nervous of

sharing information which may frighten their customers unnecessarily. These concerns will need to be addressed if information sharing is to increase.

Responsibility also lies with those working throughout the construction industry to ask questions of those who supply them with products. This is familiar territory - construction is recognised as being a conservative industry, and this relates in part to the recognition that buildability, building quality and product longevity are essential. Construction is accustomed to asking difficult questions or to resisting new innovations in order to avoid the possible hazards or unpredictability of the unfamiliar (Harty et al., 2007). However, designers and contractors cannot ask the right questions if they do not realise that they are working with new products; a questioning approach can only go so far if there is uncertainty about what should be questioned.

Many of the principles discussed in this paper in relation to nanotechnology will apply to other innovations in construction. For example, new products such as MDF and other composite materials have been widely adopted in recent years in areas where wood, stone or metal would traditionally have been used, and in each case have been taken into widespread use before formal guidance was available. The historical examples of asbestos, and lead in paints, supposedly miracle materials, confirm that this is not a new phenomenon. Where knowledge is incomplete, pragmatic decisions, made to proceed anyway, must ensure that precautionary measures are in place and pay due respect to the potential benefits and risks. At the same time, steps to reduce what is unknown must include a combination of increasing the knowledge available, and making far better use of what is already known. In managing the challenges of the unknown, as in so many things, communication is key.

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