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PERSPECTIVES

# Toward responsible development and effective risk management of nano-enabled products in the U.S. construction industry

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**Abstract** The global construction sector is experiencing major improvements to building materials used in large quantities through commercial applications of nanotechnology. Nano-enabled construction products hold great promise for energy efficiency and resource conservation, but risk assessments lag as new products emerge. This paper presents results from an inventory, survey, and exposure assessment conducted by the authors and explores these findings in the broader context of evolving research trends and responsible development of nanotechnology. An inventory of 458 reportedly nano-enabled construction products provided insight into product availability, potential exposures, and deficiencies in risk communication that are barriers to adoption of proactive safety measures. Seasoned construction trainers surveyed were largely unaware of the availability of nano-enabled construction products. Exposure assessment demonstrated the effectiveness of ventilation to reduce exposures during mechanical abrasion of photocatalytic tiles containing titanium dioxide ($TiO_2$). Dissociated particles of $TiO_2$ just above the nanoscale (138 nm) were detected in the debris collected during cutting of the tiles, but measurements were below recommended exposure limits for $TiO_2$. Exposure assessments remain scarce, and toxicological understanding primarily pertains to unincorporated nanomaterials; less is known about the occupational risks of nano-enabled construction products across their life cycle. Further research is needed to characterize and quantify exposure to debris released from nanocomposite materials for realistic risk assessment, and to ascertain how nanocomposite matrices, fillers, and degradation forces interact to affect release dynamics. Improving risk communication strategies and implementing safe work practices will cultivate responsible development of nanotechnology in construction, as will multidisciplinary research efforts.

**Keywords** Construction industry · Nanomaterials · Exposure assessment · Risk communication ·

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## Introduction

A broad range of engineered nanomaterials (ENMs) and nanoscale modifications of internal and surface structures have been used to enhance conventional materials used in the construction industry with novel or augmented macroscale properties (Ge and Gao 2008; Hanus and Harris 2013; Pachego-Torgal et al. 2013; Mora 2007; Rana et al. 2009; Zhu et al. 2004). Lee et al. (2010) reviewed these innovations, noting that the remarkable benefits to be gained through applications of nanotechnology in construction may be offset by concerns over human and environmental exposure to ENMs across the life cycles of these materials. A recent policy analysis highlighted gaps in the U.S. regulatory oversight across the life cycle of ENMs, finding that the largest gaps occur at post-market stages and at points of ENM release (Beaudrie et al. 2013). Challenges identified in the analysis included high scientific uncertainty and lack of information on environmental effects, health and safety risks to workers, and basic product data.

The Project on Emerging Nanotechnologies (2013) provided insight into nano-enabled construction products used by consumers but excluded commercial and industrial products for professional use. Efforts to gauge actual use of nanoproducts in the European construction industry in 2009 identified 94 products, representing a relatively small niche market comprised primarily of coatings, cement, and concrete (Broekhuizen et al. 2011; Broekhuizen and Broekhuizen 2009). Surveys conducted as part of that research revealed that 80 % of workers' representatives and 71 % of employers' representatives were unaware of the availability of nanomaterials and whether these materials were actually used on their jobsites. Through telephone surveys, Bekker et al. (2013) found construction to be among the Dutch industrial sectors producing or applying manufactured nanomaterial-enabled end products with the highest degree of market penetration. Currently, very little is known about the availability and actual use of ENMs in the U.S. construction industry, and level of awareness pertaining to these materials among U.S. construction industry stakeholders is unknown.

Many facilities have opted to take proactive measures to identify and control potential exposures to ENMs in the workplace (Methner 2010), but lack of basic product data may be a barrier for U.S. construction contractors that choose to do the same. Currently, no U.S. regulations require manufacturers of nano-enabled products to identify ENMs on product labels or Safety Data Sheets (SDSs), and ENMs can be designated as proprietary. Conversely, some construction products marketed as 'nano' do not contain ENMs (Broekhuizen et al. 2011; Jones et al. 2015). SDSs for ENMs have been characterized as inadequate from a risk communication perspective (Eastlake et al. 2012), and further loss of information down the production chain can occur (Broekhuizen et al. 2011). Considering all of the above, hazard communication for ENMs in commercial products may be inconsistent and has not been evaluated for nano-enabled construction materials in the marketplace.

Assessing potential risks associated with use of ENMs in construction will require improved understanding of the release of ENMs from host matrices and the potential for exposures to occur across the life cycle of nanocomposite materials (Ging et al. 2014; Lee et al. 2010). In construction, exposures to ENMs may occur during installation, repair, renovation, demolition, and disposal of nano-enabled construction materials. A recent examination of the International Council of Nanotechnology environmental and health literature database revealed that only 0.8 % of studies examined release of ENMs from nanocomposites compared to 83 % that assessed the intrinsic hazards of nanomaterials (Froggett et al. 2014). The authors identified 10,000 publications, of which fifty-four deliberately investigated release from solid, non-food nanocomposites. Less than half of the fifty-four studies involved some form of machining induced release, and only five investigated machining induced release of nanoscale titanium dioxide (nano-$TiO_2$).

All five studies compared sanding dust released from paints doped with engineered nanoparticles (ENPs) to sanding dust released from conventional paints (Gohler et al. 2010; Golanski et al. 2011; Koponen et al. 2009, 2011; Saber et al. 2012), demonstrating only subtle differences in the dust released from nano-$TiO_2$-doped versus conventional coatings. ENPs remained embedded in the paint matrix, and unagglomerated $TiO_2$ ENPs were not detected in the dust. Koponen et al. (2009, 2011) attributed the dominant source of nanoparticles to the motor from the sanding machine. Saber et al. (2012) performed toxicological assays of the dust obtained, concluding that addition of ENPs did not increase the potential of sanding dust to cause inflammation, oxidative stress, or DNA damage. Subsequent in vitro (Kaiser et al. 2013) and in vivo (Smulders et al. 2014) toxicological experiments also suggested that paints containing ENPs do not pose an additional acute health hazard to humans compared to conventional counterparts.

Although these initial findings are encouraging with regard to occupational health, ENMs can be used in a wide variety of construction applications involving different host matrices and nano-fillers, both of which are theorized to influence release of ENMs and subsequent exposure (Duncan 2015). Given the scarcity of ENM release and exposure studies that are directly applicable to construction, further investigation of these topics is warranted.

Evaluating the effectiveness of protective measures to minimize exposure to ENMs in construction may be equally important. Research conducted in laboratories and production settings indicate that both respirators and engineering controls are effective in mitigating exposure to ENMs (Brochot et al. 2012; Methner 2008, 2010; Rengasamy and Eimer 2011; Shaffer and Rengasamy 2009). Determining whether exposure controls used in construction are equally effective is needed to foster safe handling of ENMs by construction workers who may be wary of novel materials, for which the risks to human health are not fully understood.

Despite tremendous growth of nanotoxicological publications in the past 15 years, conflicting results and methodological shortcomings hamper a clear understanding of potential human health risks posed by ENMs (Krug 2014). Valsami-Jones and Lynch (2015) asserted that mechanistic understanding of nanotoxicity remains limited and that there is no simple correlation between toxic responses and predictors of toxicity, such as nanoparticle size. Risk assessment for this broad class of materials defined only by size is complicated by the plethora of variations in nanoparticle size, morphology, surface structure, and other characteristics of ENMs that are theorized to modify toxic responses.

Despite these uncertainties, the emergence and rapid expansion of the field of nanotoxicology suggest growing concern over the safety of ENMs. As a result of increased surface area, ENMs can be more biologically reactive than larger particles of the same composition on an equivalent mass basis. Fractions of inhaled ENMs can translocate to the brain (Oberdörster et al. 2004) and the circulatory system, accumulating in secondary tissues and organs, where micron-sized particles cannot (Kreyling et al. 2013).

At present, there are no enforceable occupational exposure limits in the United States for ENMs specifically, though other existing standards may apply. A 2012 workshop on strategies for setting occupational exposure limits (OELs) for ENMs found broad agreement that OELs need to be established before occupational health effects potentially become manifest, but the participants also identified significant barriers to doing so (Gordon et al. 2014). To our knowledge, only two benchmarks for occupational exposure to ENMs have been established by the U.S. federal agencies to date.

The National Institute for Occupational Safety and Health (NIOSH) established a Recommended Exposure Limit (REL) of 2.4 mg/m$^3$ for fine $TiO_2$ and 0.3 mg/m$^3$ for ultrafine (including engineered nanoscale) $TiO_2$, as time-weighted average (TWA) concentrations for up to 10 h per day during a 40-h work week (NIOSH 2011), reflecting size-dependent health concerns. Ultrafine $TiO_2$ was determined to be a potential occupational carcinogen, but fine $TiO_2$ was not classified as such, citing insufficient data (NIOSH 2011). The NIOSH REL for carbon nanotubes (CNTs) and carbon nanofibers (CNFs) recommends that exposures should be kept below 0.001 mg/m$^3$ of respirable elemental carbon as an 8-h TWA (NIOSH 2013). Researchers from the Finnish Institute of Occupational Health suggested a more restrictive 8-h OEL of 0.1 mg/m$^3$ for nano-$TiO_2$, a fiber-based OEL for CNTs/CNFs of 0.01 fibers/cm$^3$, and an 8-h OEL for the respirable fraction of amorphous silicon dioxide of 0.3 mg/m$^3$ (Stockmann-Juvala et al. 2014).

Maynard et al. (2006) commented, "In what may be unprecedented pre-emptive action in the face of a new technology, governments, industries, and research organizations around the world are beginning to address how the benefits of emerging nanotechnologies can be realized while minimizing potential risks." Responsible development of nanotechnology, as paraphrased above, continues to be an important underlying theme of research (Balbus et al. 2006; Hutchison

2008; Iavicoli et al. 2009; Roco 2005; Schulte et al. 2014; Som et al. 2013). The earliest and most extensive societal exposures to ENMs are likely to occur in the workplace (Schulte et al. 2008), and many facilities have chosen a proactive approach to eliminate or minimize occupational exposure to uncharacterized ENMs (Methner 2010). Despite this departure from historical norms, some have looked to late lessons learned from a history of innovation and questioned whether enough is being done to avoid repeating mistakes of the past (Hansen et al. 2008; Hansen and Gee 2014).

In construction, historical use of novel materials in the built environment has resulted in unintended consequences. Renovation and demolition of structures containing lead, polychlorinated biphenyls, and asbestos, for example, continue to cause adverse health effects among workers, decades after initial use. Analogous scenarios are foreseeable if exposure to ENMs in construction proves to be hazardous.

The construction industry merits careful consideration. ENMs have the potential to become ubiquitous in the built environment and can be incorporated into materials used in high volumes, such as cement. Nanocomposites in the built environment may be subject to environmental degradation for extended periods of time, which may precede mechanical forces applied to these materials during routine construction activities. This may be a cause for concern because the interplay of factors that influence release of ENMs from composite materials is not well understood. Recent research indicates that photodecomposition, thermal degradation, and hydrolysis can affect both the dispersion and release of ENMs embedded in nanocomposite matrices (Duncan 2015). Few studies have addressed how ENMs may change when they are incorporated into and released from products, and toxicological research to date primarily pertains to 'as manufactured,' unbound ENMs (Nowack et al. 2012; Mitrano et al. 2015). Transformations that occur as ENMs are used in, and released from products can determine whether exposures occurring upon release consist of a more or less diverse set of ENMs in comparison to the 'as manufactured' ENMs initially incorporated into the host material, which has direct bearing on their potential toxicity (Mitrano et al. 2015). It becomes clear that exposure assessments are needed to characterize and quantify forms of ENM released from nano-enabled products to provide critical input for realistic toxicological assessment of exposures to ENMs that are likely to occur in construction.

The construction industry encompasses many different trades, work activities, and materials, resulting in a broad diversity of occupational exposures. In 2010, over 50 % of construction workers reported that they were regularly exposed to vapors, gas, dust or fumes at work twice a week or more, which was more than double that of all industries combined (CPWR 2013). Construction workers, representing only 5–6 % of the non-farm labor force, account for half of all occupational cancers (Liss et al. 2010). Occupational guidance for working with ENMs has initially been geared toward manufacturing and laboratory settings, where processes tend to be stable. Construction sites are dynamic. Conditions, employees, processes, and materials change frequently, making it more challenging to identify potential ENM exposures, particularly for work performed decades later on existing structures.

Addressing the occupational health risks of emerging nanotechnologies in the construction industry now will be important to safeguarding the health of these workers in the future; however, the knowledge gaps identified above are significant barriers to this process, more specifically:

1. What types of ENMs and nano-enabled construction products are currently available in the U.S. marketplace?
2. What is the extent of hazard communication for these products?
3. Are industry stakeholders aware of the availability and occupational health and safety aspects of these products?
4. In what form are ENMs released from nano-enabled construction products during routine construction activities across the life cycle of these products?
5. Do exposures to ENMs in construction exceed Recommended Exposure Limits?
6. Are conventional control methods effective in reducing exposures to ENMs?

The overarching objective of this manuscript was to provide a broad perspective on responsible development of nanotechnology in construction by beginning to address the knowledge gaps outlined above. Answering these basic, fundamental questions will be essential to responsible development of nanotechnology in construction.

Objectives of the research were to:

1. Assess the availability of nano-enabled construction products in the U.S. and extent of hazard communication for these products by leveraging online product information to create an inventory of nano-enabled construction products (knowledge gaps 1–2).
2. Evaluate awareness and perceptions of nanotechnology among a group of construction health and safety trainers (knowledge gap 3).
3. Characterize release of ENMs, quantify exposure versus RELs, and measure effectiveness of controls in a case study of photocatalytic roofing tiles (knowledge gaps 4–6).

## Methods

### Inventory

A new and independently conducted inventory of construction products in the marketplace reported to be nano-enabled (www.nano.elcosh.org) was created using extensive web-based searches and monitoring relevant listservs, RSS feeds, construction industry trade publications, media articles, peer-reviewed literature, and social media. Nanotechnology nomenclature used in this paper refers to the definitions set forth by the International Organization for Standardization (ISO/TS 80004-1:2015), with the exception of the term 'nano-enabled,' which is used in a generic sense to refer to products meeting the inclusion criteria specified below. The inventory will continue to be updated on a regular basis and resides within the Electronic Library of Construction Occupational Safety and Health (eLCOSH), a site created in 2000 and maintained by CPWR—The Center for Construction Research and Training. Toward a more comprehensive inventory, broad inclusion criteria were applied, accounting for the frequent lack of information concerning applications of nanotechnology (e.g., manufacturers reporting use of 'nanotechnology' without further explanation).

The majority of products were included on the basis of manufacturer claims that used the term 'nano': reference to a product as a 'nanocomposite' or 'nano-coating,' reported use of nano-objects, and other specific references to use of nanotechnology. A small number of products were included on the basis of equivalent claims provided by sources other than the manufacturer, such as trade journals and peer-reviewed literature. A limited number of products were included based upon manufacturers' claims of photocatalytic properties or use of the term 'nano' in the product name. Products were only included if use of nanotechnology appeared plausible. The rationale for including each product was provided in the open-access online inventory.

Our population of interest, the construction industry and its workers, was defined using the 2007 North American Industry Classification System and the 2010 Standard Occupational Coding system. Products that could potentially be found on a construction jobsite were included in the inventory. The inventory was primarily aimed at identifying prototypical building materials for end-users, such as cement, but some cross-cutting products were also included (e.g., a diesel additive used in construction machinery). Products in their unfinished form were also included if deemed applicable to construction (e.g., raw material additives designed for paints and coatings).

Both nanostructured products and products with incorporated ENMs were included because reliable information to make this distinction was not always available. The inventory was neither designed to be comprehensive nor to provide definitive proof of the use of ENMs. SDSs, Technical Data Sheets, and product websites were thoroughly reviewed to record the following information for each product:

- brief description of the product from the manufacturer or distributor,
- typical usage or substrate,
- reported use of nanotechnology (chemical composition, size, and morphology of ENMs when available),
- rationale for inclusion in the inventory,
- name and location of the manufacturer or distributor (USA location recorded if provided),
- availability of SDSs online, and
- URLs from where the information was obtained.

### Trainer survey

A written survey was administered to trainers from construction trade unions attending a nanotechnology workshop as part of a Trainer Enhancement program conducted in 2013 by CPWR—The Center for Construction Research and Training and the National Institute of Environmental Health Sciences. The same survey was administered during a health and safety meeting in 2014 to a group of apprenticeship trainers from the Operative Plasterers and Cement Masons International Association. The eleven-item survey (Online Resource 1) was designed to gauge perceptions and level of knowledge relating to use of nanotechnology in the construction industry. The survey protocol was approved by CPWR's Institutional Review Board prior to use.

## Case study

A case study of BoralPure™ Smog-Eating Tiles was used to investigate potential mechanically induced release of nano-$TiO_2$ from a cementitious composite with a surface coating of photocatalytic $TiO_2$. According to the manufacturer, a 2000-square foot roof of BoralPure™ Smog-Eating Tiles can oxidize the same amount of nitrogen oxide as a car produces from being driven up to 10,800 miles via $TiO_2$-induced photocatalysis over the course of a year. Hashimoto et al. (2005) identified the use of nanoscale $TiO_2$ as an important requirement for successful photocatalytic decomposition of pollutants, and it was therefore hypothesized that the tiles contained nano-$TiO_2$. Product literature and calls to the manufacturer did not reveal the size of the $TiO_2$ contained in, or added to the tile. Bulk characterization of the tile was performed.

Representative portions of the tile were sheared and placed onto a carbon-taped stub, then carbon coated. The photocatalytic surface of the sample was then analyzed by a Tescan scanning electron microscope equipped with a Gresham light element detector and an IXRF digital imaging system (EDS). One sample of the tile was examined in cross section using a back scattering electron imaging system (BSE). EDS was performed to verify the elements present, and then BSE was utilized to map the $TiO_2$ particles embedded in a matrix of calcium aluminum silicate, with the aim of determining the size of the $TiO_2$ particles present in the sample.

A pilot study was conducted to assess the suitability of the exposure assessment protocol, particularly the appropriate selection of tools and equipment. Nonetheless, useful data were generated during the pilot. The tiles used were 33 × 42 × 3 cm with three holes partially drilled through one end by the manufacturer. The pilot was conducted outdoors in Laurel, Maryland on the parking lot of a roofing company that provided technical guidance and tools. Personal and area air samples were collected while a tradesperson performed the following: (1) made repeated shallow cuts through the surface layer of the tile using a Rigid angle grinder (Ridge Tool Company, Elyria, OH) with a 7-inch diameter, 1/8 inch thick masonry circular cut-off blade with a 5/8 inch arbor with diamond knockout, (2) drilled holes with a 14.4 volt, XRP DeWalt cordless electric drill (DeWalt Industrial Tool Co., Baltimore, MD) using a 5/16th inch masonry bit and (3) nailed roofing tiles onto a simulated roof. Samples were collected with no controls in place and also with local exhaust ventilation (LEV) supplied by an Ermator S26 vacuum (Pullman Ermator, Tampa, FL) and CutBuddie tool shroud (Dust Technologies, South Price, UT) attached to the angle grinder. The Ermator has a maximum air flow of 258 cubic feet per minute (cfm), a cyclonic pre-separator, a main filter with collection efficiency greater than 99.5 % and a high efficiency (HEPA) filter with 99.97 % efficiency. The tradesperson who performed all of the work had decades of experience in construction and wore a full-face powered air-purifying respirator, Tyvek suit with hood, and ear muff hearing protection.

Five sampling stations were established around the work to attenuate the effect of wind, which is historically out of the west. Wind velocity was measured with a TSI VelociCheck (TSI, Incorporated, Shoreview, MN). Four stations, positioned at the cardinal points of the compass, had identical sampling media: 37-mm diameter, closed-face cassettes containing 5-micron porosity, pre-weighed, polyvinyl chloride (PVC) filters (Bureau Veritas, Novi, MI) placed at breathing zone height on sampling stands approximately four feet from the work and attached by Tygon tubing to high volume samplers (Reliance Electric, Gallipolis, OH) calibrated to draw between 4.0 and 4.5 liters per minute. These cassettes were analyzed for total dust by NIOSH Method 0500 and for $TiO_2$ by NIOSH Method 7300. One additional station was established with a 0.45 micrometer porosity mixed cellulose ester filter held at breathing zone height in a 25-mm cassette (Zefon International, Ocala, FL) for transmission electron microscopic analysis.

Two personal sampling pumps (Escort Elf, Zefon International, Ocala, FL) were worn by the test subject at waist level connected by Tygon tubing to a sampling train affixed in his breathing zone. Each pump pulled air at 2.5 L per min in conformity with the ISO/CEN particle size-selection criteria through a SKC respirable dust aluminum cyclone holding a 37 mm, 5-micron porosity, pre-weighed PVC filter supported by a backup pad in a three-piece filter cassette. The cassettes were analyzed for $TiO_2$ by NIOSH Method 7300 and for respirable dust by NIOSH Method 0600. Real-time industrial hygiene data were collected with a TSI P-Trak Ultrafine Particle Counter Model 8525 (TSI Incorporated, Shoreview, MN). All pumps were calibrated before and after sampling using an electronic dry piston primary flow meter (DryCal DC-Lite; Bios International Corp., Butler, NJ). Temperature and relative humidity were measured with a TSI Q-Track.

Sampling was conducted at the stations for each of the following activities in the order listed:

1. Background concentrations with no activities;
2. Running the angle grinder and electric drill without doing any work to determine the type and number of particles generated by the equipment;
3. Making shallow cuts in the roofing tiles with LEV operating;
4. Making shallow cuts in the roofing tiles with no LEV;
5. Drilling holes in the tiles; and
6. Nailing tiles to a 4 ft. by 8 ft. sheet of ¾ inch plywood positioned horizontally and attached to a structure created with 2 × 4 lumber and angled at approximately 65 degrees.

Three area samples from the pilot were analyzed via transmission electron microscopy (TEM). The TEM protocol included manual counting and sizing of approximately 100 $TiO_2$ structures per sample with elemental analysis performed by EDS.

A second sampling session was conducted with adjusted protocols informed by the pilot study. Although the outdoor pilot represented the more likely exposure scenario, we sought to replicate the results in a chamber where extraneous particles were eliminated. We also sought to decrease variability by increasing the sample size of measurements taken during cutting of the tile, which was deemed to be the only task in the pilot worthy of further examination. A different cutting tool and blade were selected that were capable of cutting completely through the tiles to better represent typical performance of the task.

The second sampling session was conducted inside an environmentally controlled chamber in October of 2013 in Columbia, Maryland. The 2900 ft.[3] chamber was capable of providing 18.6 air changes per hour through a HEPA-filtered ventilation unit with a nominal volumetric flow rate of 900 cubic feet per minute, although the unit was not operated during each sampling run. Following each run, the chamber was purged with the HEPA-filtered ventilation unit until particle number concentrations measured by the TSI P-Trak returned to initial background levels. The tests were conducted with the same test subject wearing the same personal protective equipment. Only cutting of tiles was conducted for this session using a Bosch saw (Robert Bosch, LLC, Farmington, MI) holding a 12-inch blade. LEV was again provided by an Ermator S-26 HEPA vacuum. Five stations were established, similar to the outdoor protocol, around the test subject with high volume samplers set at approximate breathing zone height (Fig. 1). Four stations collected total dust samples on 37 mm PVC filters following NIOSH Method 0500. One station collected particles for TEM analysis, using a 25 mm 0.45 porosity mixed cellulose ester filter held in a conductive cowl following a

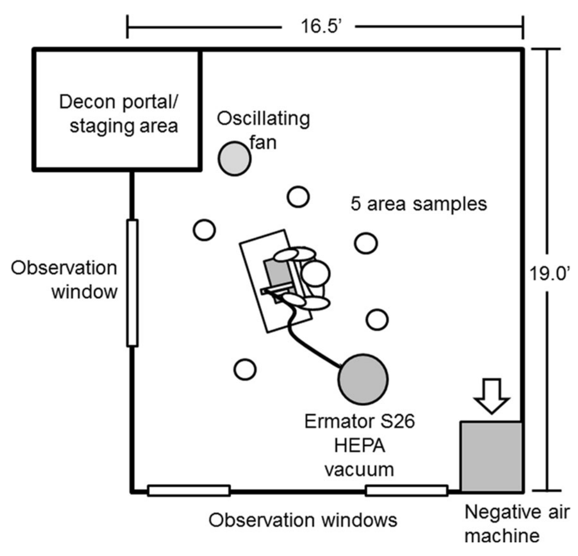


**Fig. 1** Diagram of the environmentally controlled chamber showing positions of the five area samples, oscillating fan, negative air machine, test subject, and saw with vacuum attached

modified NIOSH 7402 method. Samples were also collected for $TiO_2$ analysis by NIOSH Method 7300, as recommended in the NIOSH Current Intelligence Bulletin (NIOSH 2011). Two personal samples were collected in the breathing zone of the test subject during each run and analyzed by NIOSH Method 0600 for respirable dust.

### Analytical methods

All samples were sent under a chain of custody to Bureau Veritas North America, Inc., (BVNA), a microscopy laboratory accredited by the American Industrial Hygiene Association and the National Institute of Standards and Technology under the National Laboratory Voluntary Laboratory Accreditation Program. BVNA followed standard NIOSH protocol for analyses, as indicated above, except for the analysis of $TiO_2$ by TEM. For $TiO_2$, the sample filters were prepared by the TEM direct air method, without plasma ashing, as per NIOSH 7402. Portions of each sample filter were affixed to glass slides and treated with filter clearing solution (35 % dimethyl formamide, 15 % glacial acetic acid, and 50 % deionized water). Filters were then carbon coated and placed onto three 200-mesh copper grids for TEM analysis. Sizing and elemental identification of particles and structures in the released debris were performed using a Philips CM-12 transmission electron microscope and an IXRF digital imaging system. A minimum of ten grid openings or 100 structures or particles, whichever came first, were analyzed. Length and width of $TiO_2$ particles and debris fragments containing $TiO_2$ were measured at magnification of $\times$15,000 or higher. Dissociated particles were differentiated from agglomerates or aggregates at magnifications greater than $\times$31,000.

### Statistical analysis

Univariate methods were used to generate descriptive statistics for the inventory, survey, and exposure data. Normality of measured concentrations of airborne $TiO_2$ and respirable dust was assessed using Shapiro-Wilks tests and quantile–quantile plots. Heteroscedasticity was assessed using homogeneity of variance tests and the folded F statistic. Two-sample independent $t$ tests were used to examine differences in mean exposure concentrations according to the presence of engineering controls for normally distributed data satisfying the assumption of equal variances. In the case of unequal variances, the Satterthwaite approximation was used. All statistical analyses were performed using SAS 9.2 (SAS Institute Inc. 2011).

## Results

### Inventory

As of March, 17, 2015, the open-access inventory (www.nano.elcosh.org) featured 458 construction products in the marketplace reported to be nano-enabled, i.e., those satisfying inclusion criteria outlined above (CPWR 2014). The inventory lists a single company for each product, such that 126 companies were identified as manufacturers or distributors of the 458 products. Manufacturers were listed by default. Of the 126 companies, close to three-quarters (73.8 %) provided a United States address or specified that their products are sold in the USA. For the remaining companies, product availability in the United States could not be confirmed. Online SDSs were obtained for most products in the inventory ($N = 256$, 55.8 %). SDSs for remaining products did not appear to be available online. Notably, products designated as articles do not require SDSs under OSHA's Hazard Communication Standard, 29 CFR 1910.1200.

Twenty-six categories of products were identified (Fig. 2). Coatings comprised the bulk of the inventory ($N = 266$, 58.1 %) and included primers, surface sealants, penetrating sealers, varnishes, lacquers, and paints for interior and exterior surfaces. Coatings in the inventory were marketed as one or more of the following: icephobic, oleophobic, hydrophobic, wear and abrasion resistant, smog-eating, pollution reducing, self-cleaning, photocatalytic, anti-corrosive, fire retardant, bactericidal, anti-ultraviolet, anti-glare, anti-fog, anti-graffiti, sound reducing, highly insulating; or mold, algae, and efflorescence inhibiting. Mineral surfaces (cement, concrete, stone, brick, masonry, terrazzo, travertine, etc.) were the most frequently recommended substrates for coatings, whereas the second largest category of coatings were those designed for a wide range of substrates (e.g., metal, wood, glass, plastic, or cement). Cement,

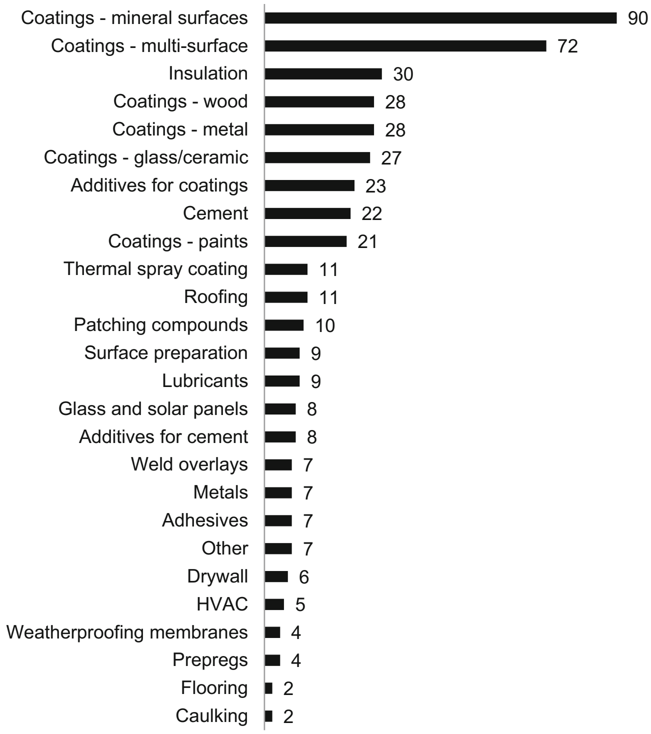


**Fig. 2** Number of construction products marketed as nano-enabled by product category[a] ($N = 458$)

[a] 'Other' category includes: magnesium nanoparticle boiler additive, CNT-enhanced fiberglass, CNT epoxy, anti-fog film for glass (e.g. protective eyewear), CNT conductor for electrical power distribution, coating for lead abatement, coating for vinyl composition tile

insulation, and additives for coatings were the most frequently identified products, aside from coatings.

Information provided by manufacturers and distributors via product websites, brochures, technical data sheets, and SDSs was often limited regarding use of nanotechnology. Table 1 illustrates information obtained regarding applications of nanotechnology for products in the inventory. Nanomaterial chemical composition was specified for less than half of products ($N = 208$, 45.5 %), for which 29 broadly defined chemical compositions were reported. Nanomaterial composition was partially specified for approximately 16 % of products. For over one-third of products in the inventory, no further information on nanomaterial composition was obtained beyond reported use of 'nanotechnology,' 'nanofibers,' 'nanotubes,' 'nanomaterials,' or 'nanoparticles.' A limited number of phone calls to manufacturers yielded no additional product information than what was publicly available online. The most frequently reported nanomaterials were polymers, $TiO_2$, silica polymorphs, zinc oxide, and carbon nanotubes.

Specifics of nanomaterial composition (e.g., size, morphology, surface characteristics, and commercial source) were infrequently reported, making linkage to existing nanomaterial registries infeasible in most cases. For example, rarely did companies differentiate anatase versus rutile forms of nano-$TiO_2$ used in products, and nanomaterial size was frequently unspecified for products purported to contain nano-objects.

## Trainer survey

All 79 trainers present at the time of survey administration opted to participate. Participants self-identified with 22 different construction trades; masons, plasterers, and carpenters comprised the majority of those surveyed (58 %). On average, the group reported having $30.5 \pm 9.4$ years of trade experience and $13.3 \pm 7.8$ years of training experience. Respondents hailed from diverse locations across the United States.

Less than half of respondents (48 %) were aware that construction products containing nanomaterials are commercially available in the USA, and only 13 %

**Table 1** Reported nanomaterial composition of nano-enabled construction products in the inventory ($N = 458$)

| Reported nanomaterial composition | Products (N) | % |
|---|---|---|
| Specified | 208 | 45.5 |
| Aluminum oxide | 8 | 1.8 |
| Austenite | 1 | 0.2 |
| Boehmite | 1 | 0.2 |
| Calcium hydroxide | 1 | 0.2 |
| Carbon | 4 | 0.9 |
| Carbon nanotubes | 12 | 2.6 |
| Cerium oxide | 4 | 0.9 |
| Diamond | 1 | 0.2 |
| Lithium | 8 | 1.8 |
| Magnesium | 1 | 0.2 |
| Multiple[a] | 10 | 2.2 |
| Nanoscale pores | 17 | 3.7 |
| Polycarbon | 51 | 11.1 |
| Polycarbonate | 1 | 0.2 |
| Polysiloxane | 3 | 0.7 |
| Silane | 2 | 0.4 |
| Silica | 21 | 4.6 |
| Silica fume | 2 | 0.4 |
| Silicone | 3 | 0.7 |
| Siloxane | 6 | 1.3 |
| Silver | 9 | 2.0 |
| Titanium dioxide | 22 | 4.8 |
| Titanium nitride | 2 | 0.4 |
| Tungsten carbide | 4 | 0.9 |
| Tungsten disulfide nanofullerenes | 3 | 0.7 |
| Zinc oxide | 11 | 2.4 |
| Partially specified | 72 | 15.7 |
| Acrylic | 3 | 0.7 |
| Acrylic-urethane | 1 | 0.2 |
| Ceramic | 5 | 1.1 |
| Crystal | 2 | 0.4 |
| Fluorochemical | 1 | 0.2 |
| Nanostructured | 27 | 5.9 |
| Oxide | 11 | 2.4 |
| Polymer | 22 | 4.8 |
| Unspecified | 178 | 38.9 |
| Nanofibers | 1 | 0.2 |
| Nanomaterials | 15 | 3.3 |
| Nanoparticles | 76 | 16.6 |
| Nanotechnology | 70 | 15.3 |
| Nanotubes | 1 | 0.2 |
| Photocatalytic materials | 5 | 1.1 |
| Reference to 'nano' | 10 | 2.2 |

[a] Multiple category applies to products for which more than one nanomaterial chemical composition was reported, including the following not shown elsewhere in the table: graphene nanoplatelets, nanoemulsion of paraffin, nanostructured emulsion of silicon, electrically conductive transition metal oxy-nitride

knew of a nano-enabled product being used on an actual construction job site (Table 2). Nano-enabled products reportedly used on job sites were specified to be insulation, plastering, and cement-based materials. The vast majority indicated that they had not addressed nanotechnology during worker training, and only three participants were aware of any existing Recommended Exposure Limits (RELs) for nanomaterials. Following the survey, respondents were informed of existing RELs and instructed how to train workers on safe practices related to use of nano-enabled products on job sites.

Responding to three questions with a 7-point Likert scale, close to three-quarters of trainers surveyed (73 %) felt that uncontrolled occupational exposures to certain ENPs likely pose a significant health risk to construction workers (slightly agreed, agreed, or strongly agreed). Roughly 41 % agreed to some extent that application of nanotechnology in construction has the potential to provide significant environmental and public benefit. Almost half (48 %) felt that application of nanotechnology in construction has the potential to significantly harm the environment.

## Case study: release of $TiO_2$

An SDS for Boral concrete tiles indicated that the tiles are predominantly composed of Portland cement (20–40 % by weight) and silica sand, quartz (40–75 % by weight). Titanium dioxide (CAS # 13463-67-7) was listed as 0–2 % by weight. SEM analysis of the roofing tile surface revealed the presence of $TiO_2$ particles embedded in a matrix of calcium aluminum silicate (Fig. 3). The smallest $TiO_2$ particles detected on the surface of the tile by SEM had diameters between 100 and 200 nm, though most were sized at approximately 500 nm. Without plasma

**Table 2** Union construction trainers' responses to five survey questions addressing awareness and use of nanotechnology in construction

| Survey questions | Response frequency | | |
|---|---|---|---|
| | Yes | No | No response |
| Prior to this enhancement, were you aware that nanotechnology has been applied to construction materials? | 41 (52 %) | 38 (48 %) | – |
| Prior to this enhancement, were you aware that construction products containing nanomaterials are commercially available in the USA? | 38 (48 %) | 41 (52 %) | – |
| Have you ever seen first-hand a construction product incorporating engineered nanotechnology or a construction product marketed with the word 'nano'? | 12 (15 %) | 68 (82 %) | 2 (3 %) |
| Are you aware of any instance where a nano-enabled product was used on a construction job site? If so, please specify the type of product and application | 10 (13 %) | 68 (86 %) | 1 (1 %) |
| Have you addressed nanotechnology in any training you have conducted? | 9 (11 %) | 70 (89 %) | – |

ashing, it could not be determined if nanoscale $TiO_2$ was present below the surface of the tile.

TEM analysis of air samples collected while cutting into the surface of the roofing tile outdoors revealed many particles of aluminum, iron, and silicon in the released debris. In some instances, $TiO_2$ particles were covered with any or all of the aforementioned particles. $TiO_2$ was only detected in two of the three area samples submitted for analysis. Most of the $TiO_2$ analyzed by TEM was bound in debris matrices (58.9 %), while the remainder (41.1 %) was dissociated from the matrix (Fig. 4). Dissociated $TiO_2$ particles detected in the released debris were mostly spherical (85.5 %), though some were oblong (14.5 %), with sizes ranging from 138 nm in all dimensions to 4.14 µm in length and 2.07 µm in width. Only four dissociated $TiO_2$ particles <200 nm were detected. All four were spherical with diameters of 138 nm and were only present in the area sample collected while LEV was being used. The smallest dimensions of debris fragments or dissociated particles examined by TEM were most frequently between 200 and 300 nm (Fig. 4). The number of debris fragments or particles per cubic centimeter of air was one order of magnitude lower for the sample

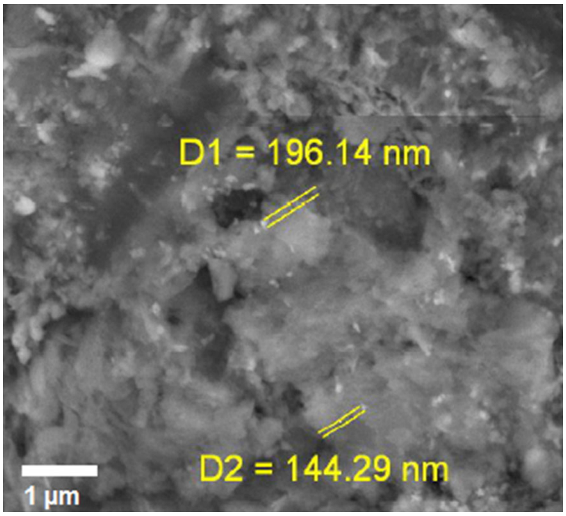


**Fig. 3** SEM image of a cross section of BoralPure™ Smog-Eating Tile at ×16,000 magnification showing $TiO_2$ particles with diameters between 100 and 200 nm embedded in a matrix of calcium aluminum silicate

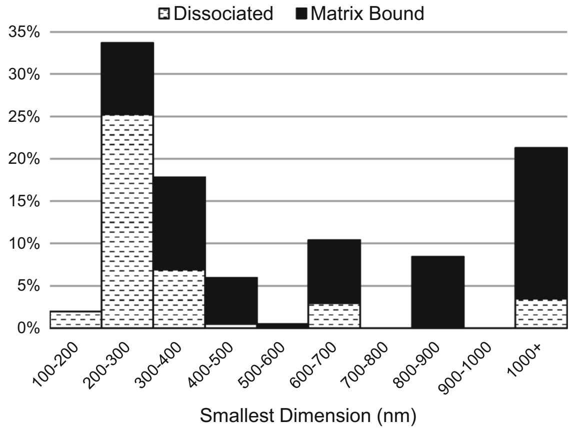


**Fig. 4** Size distribution of debris captured while cutting into the surface of the tiles outdoors. Area air samples were analyzed using TEM and EDS following NIOSH 7402 (modified). A total of 202 structures or particles were sized and analyzed. Dissociated particles of $TiO_2$ ($N = 83$, patterned fill) and debris fragments containing $TiO_2$ particles ($N = 119$, black fill) are shown as a percentage of the total number of structures analyzed ($N = 202$)

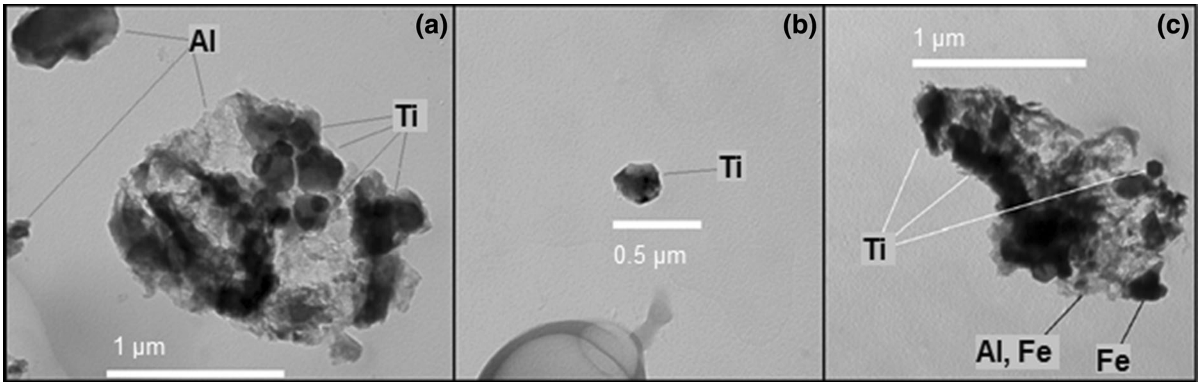


**Fig. 5** TEM images at ×31,000 magnification of released debris captured during cutting of the roofing tile. **a** debris fragment captured while sampling outdoors, **b** dissociated $TiO_2$ particle captured while sampling outdoors, **c** debris fragment captured while sampling in the chamber

collected with LEV (3/cm$^3$) compared to the sample collected without LEV (37/cm$^3$), as determined by TEM.

In contrast, only agglomerates or aggregates containing $TiO_2$ were detected via TEM analysis of the debris released while cutting through the roofing tiles in the environmentally controlled chamber. Ten debris fragments containing $TiO_2$ were analyzed, ranging from 280 × 210 nm to 1.74 × 1.53 µm. In comparison to the pilot, the smallest dimensions of these structures were primarily greater than 1 µm (40 %) or between 200 and 300 nm (30 %). The debris was composed of $TiO_2$, aluminum, iron, calcium, and silicon. Representative photomicrographs of the released debris are presented in Fig. 5.

## Case study: exposure assessment and effectiveness of controls

The task-based acute exposure measurements obtained during outdoor sampling were unlikely to result in time-weighted average exposures exceeding the American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TLV) of 3 mg/m$^3$ for respirable dust or the NIOSH REL of 0.3 mg/m$^3$ for ultrafine $TiO_2$. The highest personal breathing zone measurements were 2.7 mg/m$^3$ for respirable dust and 0.047 mg/m$^3$ for $TiO_2$; a full workday generating these peak exposure levels would not exceed the aforementioned OELs. Peak exposures occurred during cutting of the tiles. Breathing zone exposures were substantially higher than area exposures. Half of personal breathing zone samples were below detectable limits for respirable dust (<1.4 mg/m$^3$) and $TiO_2$ (<0.057 mg/m$^3$). Excluding non-detects, mean concentration in the personal breathing zone was 1.56 ± 0.81 mg/m$^3$ for respirable dust and 0.034 ± 0.014 mg/m$^3$ for $TiO_2$.

In contrast to making repeated cuts into the surface of the tile outdoors, cutting completely through the tiles in the environmentally controlled chamber generated excessive amounts of visible dust (Fig. 6). LEV was an effective means of controlling exposures, resulting in statistically significant reductions in the mean concentrations of respirable dust and airborne $TiO_2$ (Table 3). Reductions in mean exposure concentrations by use of LEV were 95 % or greater, but exposures to respirable dust in the chamber still exceeded the ACGIH TLV when controls were in use. Despite extraordinary levels of dust, mean concentrations of airborne $TiO_2$ (Table 3) were below the NIOSH RELs for fine (2.4 mg/m$^3$) and ultrafine (0.3 mg/m$^3$) $TiO_2$.

Real-time concentration measurements of submicron particles (20–1000 nm) for drilling and nailing of the tiles outdoors were similar to measured concentrations when no activities were performed or when tools were idling (Fig. 7). Mean concentration of submicron particles per cubic centimeter (pt/cc) while cutting with LEV (9135 ± 9200) was roughly three times higher than when the angle grinder was idling (3153 ± 4014) but 94 % lower than cutting without LEV (160,900 ± 92,152), though individual measurements varied considerably.

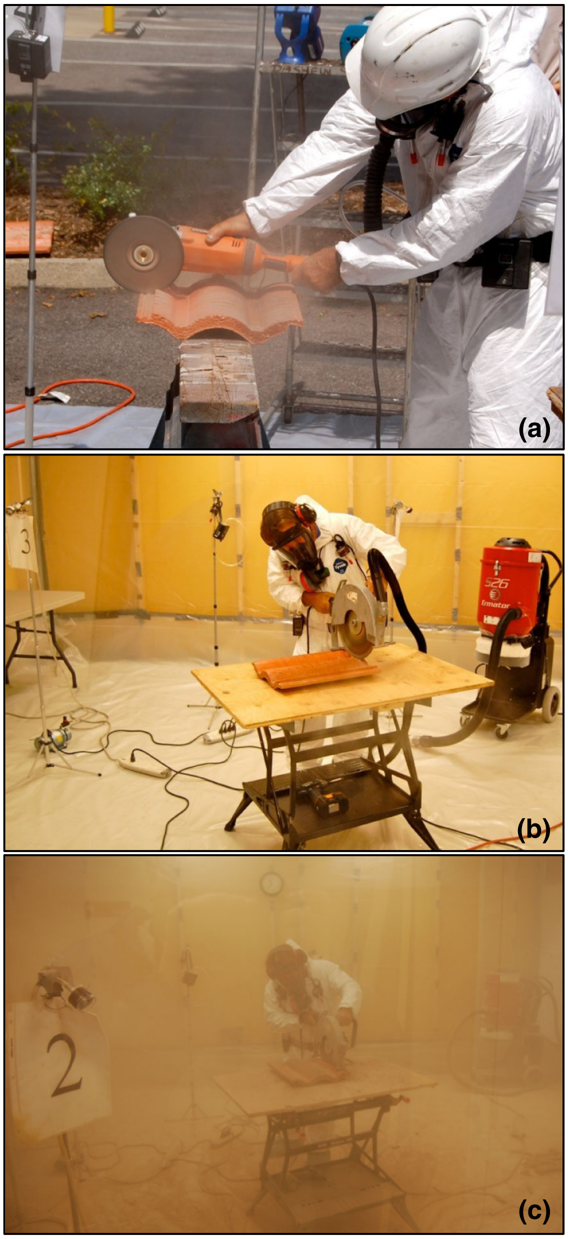


**Fig. 6** **a** Making repeated shallow cuts into the surface of the tiles outdoors without LEV, **b** cutting straight through the tiles in the environmentally controlled chamber with LEVM, **c** cutting straight through the tiles in the chamber without LEV

Real-time particle counts obtained while sampling in the chamber are not presented since they exceeded the upper detection limit of the instrument (500,000 pt/cc). There was no precipitation while sampling outdoors, and measurements of wind, temperature, and relative humidity were within normal ranges.

## Discussion

### Inventory

Construction products reported to be nano-enabled are becoming more widely available in the U.S., seemingly moving beyond the niche market in Europe described by Broekhuizen et al. (2011). Insulation, cement, and particularly coatings remain the most commonly reported applications in construction, but new product types have emerged. The Project on Emerging Technologies (2013) featured 1824 consumer products as of this writing, including 87 construction materials, and has frequently been cited as evidence of the diffusion of nanotechnology in daily life. The inventory of nano-enabled construction products described here includes information on 458 products, identifies over two dozen ENMs reportedly used in these products, and provides similar evidence of the diffusion of nanotechnology in construction. Although the current inventory is focused on professional applications, there is clearly overlap with consumers, for whom regulations and availability of personal protective equipment will differ. Aside from the trainer surveys, actual product use was not directly assessed. Some products in the inventory were only available by custom order; others were carried by major nationwide retailers.

The inventory of nano-enabled construction products is not comprehensive but provides insight into potential exposures, reported applications of nanotechnology in construction, and the associated benefits and risks. Each product in the inventory is purported to have novel or augmented properties, some of which may benefit society substantially through energy and material resource conservation, for example. Concrete is the most widely used construction material on earth (Pachego-Torgal et al. 2013), and $CO_2$ emissions associated with concrete production constitute an estimated 6–7 % of the planet's total $CO_2$ emissions (Shi et al. 2011; Habert 2013). Positive impacts on climate change are possible with buildings constructed with nano-enabled concrete that will last much longer because of greater density and intrinsic self-monitoring and self-healing capabilities (Pachego-Torgal et al. 2013). Self-cleaning surfaces may be important for water conservation, CNTs are being used to improve power distribution, and nanostructured insulation has improved energy

**Table 3** Measured concentrations of airborne titanium and respirable dust while cutting the tiles in an environmentally controlled chamber

| Analyte | Sample type | Without LEV | | With LEV | | LEV efficacy | |
|---|---|---|---|---|---|---|---|
| | | N | Conc. mg/m$^3$ (mean ± SD) | N | Conc. mg/m$^3$ (mean ± SD) | Reduction (%) | *P* value |
| Titanium | Area | 12 | 2.0 ± 0.37 | 15 | 0.11 ± 0.03 | 95 | <.0001* |
| Titanium | Personal | 6 | 0.34 ± 0.08 | 8 | ND[a] | – | – |
| Respirable dust | Area | 12 | 675.0 ± 107.2 | 15 | 19.8 ± 6.2 | 97 | <.0001** |
| Respirable dust | Personal | 6 | 81.2 ± 22.3 | 8 | 4.4 ± 0.75 | 95 | 0.0004*** |

Mean concentrations and standard deviations expressed as mg/m$^3$ are presented for samples taken with or without the use of local exhaust ventilation (LEV). Two-sample *t* tests were used to assess reductions in mean concentration by use of LEV

[a] Samples were below limits of detection, which ranged from 0.038 to 0.040 mg/m$^3$

* $t$ value = 17.18, $df$ = 11, ** $t$ value = 21.14, $df$ = 21, *** $t$ value = 8.43, $df$ = 5

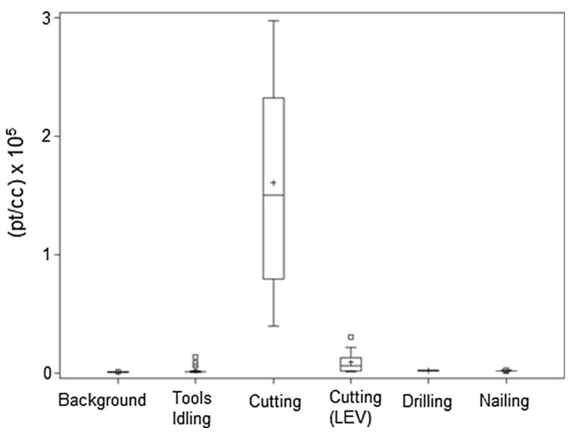


**Fig. 7** Boxplots of real-time particle concentrations measured while sampling outdoors. Measurements were obtained with no activities performed (background), with power tools idling, and during cutting, drilling, and nailing of the tiles. Cutting was also performed with use of local exhaust ventilation (LEV). Samples collected at one minute intervals are shown as number of particles (20–1000 nm) per cubic centimeter (pt/cc) × 10$^5$. Interquartile ranges and medians are denoted by the boxes, with plus symbols denoting mean concentrations

efficiency in buildings. The list of benefits continues, but reaping the benefits of nanotechnology in construction while promoting its responsible development requires that risks associated with nano-enabled construction products are further evaluated and communicated to users of these products. A first step toward minimizing risk would be to enable workers to determine if they are handling materials that contain ENMs.

Findings from the inventory suggest that a lack of transparency regarding use of nanotechnology in construction products appears to be the norm. The Project on Emerging Nanotechnologies (2013) implemented a classification system that "provides a subjective confidence level in the 'nano' claims gathered for each [consumer] product." Using this system, only 34 'nano' claims could be verified (1.9 %) and only 11 could be extensively verified (0.6 %). For the current study, basic information, such as nanomaterial chemical composition, was frequently absent from SDSs and other product literature or designated as proprietary. Information provided to users of nano-enabled construction products may be frequently insufficient to determine whether a product contains potentially hazardous ENMs, if the application of nanotechnology in the product is likely benign, or if the product is marketed as 'nano' but does not contain ENMs.

Several studies have examined SDSs for ENMs and found them inadequate. A review of 49 SDSs collected by NIOSH showed that one-third did not identify nanoscale components, and only 6 % provided cautionary language about using occupational exposure limits for macroscale materials (Lippy 2009). The author recommended that OSHA require all ENMs to be identified on SDSs and that conditional language should be included explaining the inadvisability of using Permissible Exposure Limits for the bulk form of the material. NIOSH also reviewed SDSs collected in 2010–2011 and reported that 67 % provided insufficient data to communicate potential hazards of

ENMs (Eastlake et al. 2012). Only 18 % of SDSs examined by researchers in Australia provided "reliable information to appropriately inform an occupational risk assessment" (Safe Work Australia 2010). Most recently, Lee et al. (2012) evaluated 97 SDSs and reported that 85 % "did not provide any nanomaterial-specific data and the data used for hazard classification of the nanomaterials were mostly derived from non-nanoscale material data." The authors developed an ISO technical report that provides guidance on preparing SDSs (ISO/TR 13329:2012).

The ISO report takes a precautionary approach and recommends providing SDSs for all ENMs, even if the macroscale form of the material is not considered hazardous. The report also suggests physical and chemical characteristics that should be included in SDSs (size, agglomeration state, surface area, dustiness, etc.). Broad adherence to these recommendations would mitigate deficits highlighted above. Guidance for managing risks of ENMs emphasizes the first and pivotal step of obtaining reliable hazard assessment data (Schulte et al. 2008; NIOSH 2009). If SDSs and product literature remain the primary tools for identifying ENMs in the workplace, the underpinning of effective hazard assessment and risk management is threatened.

Grieger et al. (2015) developed one of the first relative risk ranking tools for nano-enabled applications to improve risk-based decision making, and implemented the tool in a case study of Army materiel or equipment. The researchers identified 1596 occupational scenarios by simultaneously accounting for ENM characteristics and applications. Lubricants, coatings, and paints were among the applications identified, suggesting utility of this approach for construction. The breadth of ENM usage in construction likely correlates to a large number of potential exposure scenarios, as was the case with the Army. Grieger et al. found that "data gaps and uncertainties were extremely prevalent across most, if not all, identified ENMs and Army materiel," a limitation that would likely apply to the construction industry as well.

The multiyear European SCAFFOLD project recently concluded, generating numerous reports on innovative strategies, methods, and tools for occupational risk management of manufactured nanomaterials in the construction industry (López de Ipiña et al. 2015). One of the reports discusses the utility of an open-source control banding tool, Stoffenmanager Nano 1.0, for risk assessment and management of ENMs in construction (Väänänen et al. 2014). The report emphasizes lack of nanomaterial-specific information on SDSs as a major barrier to effective risk assessment and management: "often the MSDS [material safety data sheet] does not contain any information about possible nanoparticles in the product… it is quite difficult for the person carrying out the risk assessment to know if a product contains nanoparticles or not." In four of six case studies, it was determined that no ENMs were present in the products tested, despite employers' beliefs that they were using 'nanoproducts.' Another challenge for the tool was similar hazard classification of nanomaterials, yielding similar risk estimates in every case. The authors concluded that one main advantage of the tool is that it forces employers and workers to study SDSs, obtain additional product information, and consider how products are handled.

The title of a manuscript by Jones et al. (2015) succinctly summarizes the challenge: *Nanomaterials in construction and demolition—how can we assess the risk if we don't know where they are?* These researchers, funded by the Institute of Occupational Safety and Health in the United Kingdom, have employed electron microscopy to characterize and confirm the presence of ENMs in potentially nano-enabled construction products, thus far finding dissimilarities in real-world applications versus those reported in the academic literature. Subsequent research for the project aims to evaluate release of ENMs during demolition and recycling at the end of the product life cycle.

In light of these prior research efforts and results from the inventory presented here, we conclude that it is exceedingly difficult at present to ascertain the extent to which ENMs are actually being used in the U.S. construction industry. The inventory sheds light on 458 reportedly nano-enabled construction products but may overestimate or underestimate the extent to which ENMs are being applied in construction due to voluntary labeling requirements. Hazard communication regarding potential occupational health risks of ENMs for these products is generally poor, and chemical composition of ENMs is frequently unreported or difficult to ascertain.

These findings elucidate challenges faced by researchers and construction contractors alike. From an ethical perspective, U.S. workers have a legal right to know what hazards are present at the workplace and how to protect themselves. Although ENMs are not well-characterized hazards, RELs and OELs for ENMs have been established, and there is broad consensus that occupational exposures to ENMs should be minimized; however, this study demonstrates that construction contractors are not afforded the necessary information to act upon these recommendations in a consistent manner. Uncertainty about the actual presence and the characteristics of ENMs used in products exacerbates toxicological uncertainty, thereby diminishing the utility of risk ranking or control banding tools, such as the Stoffenmanager Nano 1.0. Exposures to construction debris containing ENMs may occur, in lieu of clear and actionable guidance that identifies high-risk scenarios where protective measures may be warranted.

Testing well-characterized nanocomposite materials created in the laboratory has clear advantages but may not be representative of nano-enabled products used in the field. Exposure assessment using real-world materials will add value to a realistic risk assessment paradigm, but these efforts are hindered by a lack of basic product information. The onus may fall upon researchers to characterize ENMs used in commercial materials, but methods to do so, such as electron microscopy, are costly to employ on a wide scale and may be unwarranted when ENMs are not present in a given material. Ascertaining the types and quantities of ENMs used in construction should be a rudimentary step in the risk assessment process, but there is currently minimal understanding in this regard. The inventory presented here begins to fill this void, but a clear picture of the actual use of ENMs in construction has yet to be obtained.

## Trainer survey

Given the state of hazard communication described above, it follows that most of the seasoned construction health and safety trainers we surveyed were not aware that construction products containing nanomaterials are being sold in the U.S., akin to low levels of awareness among European construction industry stakeholders reported 4 years prior (Broekhuizen et al. 2011). The survey results further indicate that nano-enabled construction products are being used on the U.S. worksites. It should be noted that the trainers we surveyed typically work in training facilities as opposed to actual construction sites but interact with many workers from the field. Perceptions regarding benefits and risks of nanotechnology in construction were mixed and should be interpreted cautiously, given that nearly half of respondents were unaware that nanotechnology has been applied to construction materials.

The survey results are not representative of the U.S. construction industry as a whole but are the only published data in this regard to date. Increasing knowledge and understanding of nanotechnology among construction industry stakeholders will facilitate (1) informed decision making regarding use of nano-enabled products and safe work practices, (2) reduction of confusion and unfounded beliefs (e.g., all ENMs are inherently hazardous), and (3) improved understanding of the benefits of nano-enabled technologies in construction. Effective risk communication is challenging; an uninformed workforce may be subject to avoidable risks, but causing undue alarm may stifle innovations that benefit society. For example, broad references to 'nanomaterials' without sufficient context can convey a relatively homogeneous class of materials. Even considering a 'specific' ENM, such as CNTs, only multiwalled-CNT-7 has been classified as possibly carcinogenic to humans by the IARC (Grosse et al. 2014), and modifications of CNTs to improve safety by manufacturing design are possible (Gilbertson et al. 2015).

Six years ago, Simons et al. (2009) called for the immediate development of nanotechnology risk communication and dissemination strategies. The authors discussed some of the challenges of engaging a general public with limited technical understanding of nanotechnology, suggesting that it will be important for targeted risk communication strategies to distinguish fields of application and bolster comprehension of nanotechnology. In construction, potential for exposure to ENMs will be a function of application (e.g., type of host matrix and nanofiller), work processes (e.g., spraying, cutting, installation, engineering controls), and other factors, such as weathering.

There is almost no evidence that the recommendations of Simons et al. (2009) have been embraced by the U.S. construction industry. To the contrary, approximately half of the experienced construction health and safety trainers we surveyed were unaware of the use of nanotechnology in construction. Greater familiarity with nanotechnology must precede any understanding of potential health risks among construction industry stakeholders. One of the authors of the current manuscript co-wrote guidance for training workers about the risks of nanotechnology (Kulinowski and Lippy 2011), but very little training curricula have been developed for workers in the U.S. The European Trade Union Institute, however, through a European initiative called Nanodiode, produced guidance on informing workers and a series of presentations aimed at workers, covering the potential risks of nanomaterials and how to prevent exposures (http://www.nanodiode.eu/publication/presentations/).

Without a complete understanding of risk, training must employ a precautionary approach and should, in the opinions of the authors, seek to increase awareness, introduce basic concepts of nanotechnology, describe limitations of current understanding, acknowledge the benefits of nanotechnology, and emphasize the effectiveness of control technologies and respiratory protection. CPWR has produced a Hazard Alert in English and Spanish that covers these concepts (www.cpwr.com/publications/nanomaterials).

## Case study: release of $TiO_2$

Findings from the case study support a limited body of research suggesting that exposures to ENMs in construction are likely to consist of matrix bound or agglomerated ENMs; dissociated ENMs released from matrices upon mechanical abrasion have been detected infrequently and in low numbers in prior studies (Froggett et al. 2014). Only four dissociated particles of $TiO_2$ <200 nm were detected in the debris released during cutting of the roofing tiles. The particles were spherical with diameters of 138 nm, which falls into the ultrafine size range of 1–150 nm cited by the IARC (International Agency for Research on Cancer 2010; Linak et al. 2002). It should be considered that the 100 nm cutoff for nanomaterials is not a health-derived upper limit and potential health effects exist along a continuum in relation to particle size. Even so, a small fraction of near nanoscale, dissociated $TiO_2$ particles released from the tile seemed unlikely to correspond with significantly increased hazard potential.

In accordance with prior studies examining release of $TiO_2$ ENPs while sanding paints (Gohler et al. 2010; Golanski et al. 2011; Koponen et al. 2009, 2011; Saber et al. 2012), our results suggest that most of the $TiO_2$ particles released during cutting of the tiles, were either protruding from or embedded in the roofing tile debris fragments. Similarly, SEM analysis of samples taken during drilling of mortar containing nano-$TiO_2$ as part of the aforementioned SCAFFOLD project did not detect dissociated particles of nano-$TiO_2$ in the personal breathing zone (Vaquero et al. 2015). For the current case study, dissociated $TiO_2$ particles just above the nanoscale range were only observed in the dust collected during the outdoor pilot, whereas only larger agglomerates or aggregates containing $TiO_2$ primary particles were observed in samples collected indoors. Several interpretations may account for this apparent discrepancy: (1) a different blade was used while sampling outdoors, and increased contact was made with the surface of the tile, where $TiO_2$ was concentrated, increasing the likelihood of detection; (2) dissociated $TiO_2$ was also released while cutting indoors but not detected in a limited number of heavily loaded TEM samples; (3) ambient airborne $TiO_2$ particles were present when sampling outdoors.

The latter appears to be the least likely explanation. Background concentrations of $TiO_2$ prior to sampling were below detectable limits when no activities were being performed (<0.016 $mg/m^3$) and when tools were powered on and off prior to sampling (<0.013 $mg/m^3$), however analytical methods to quantify trace amounts of nanoparticles from environmental samples are absent (Varner et al. 2010), and limited quantitative information is available on nano-$TiO_2$ in ambient air within or surrounding nano-$TiO_2$ production facilities (U.S. EPA 2010), so we cannot entirely exclude the possibility of environmental artifact. Notably, the sampling was not conducted near a nano-$TiO_2$ production facility. The first and second explanations appear more plausible. Similarities in size and morphology of dissociated $TiO_2$ particles to those observed in larger debris fragments support the conclusion that dissociated $TiO_2$ was released from the tile.

Emphasis has been placed on whether ENMs released from products remain matrix bound or if they are released as unbound particles. This is a meaningful distinction, considering that agglomeration state can be an important determinant of nanoparticle induced toxicity (Noel et al. 2013), however the question of whether inhaled agglomerates are dispersed in the lung may be equally critical for risk assessment in the construction industry. It is logical to assume that ENMs tend to lose their toxic potential after being encapsulated in a matrix, but further research into the biological fate and transport of ENMs released from nano-enabled products may be required to validate this assumption.

Dipalmitoyl phosphatidyl-choline, the main component of lung surfactant, does not appear capable of splitting the bonds between $TiO_2$ aggregates and agglomerates (Maier et al. 2006), and a review by Levy et al. (2012) did not find evidence that commercially produced carbon black is likely to disperse when in contact with lung fluid. On the other hand, in vivo studies of single-walled (Shvedova et al. 2012) and multiwalled (Mercer et al. 2013a, b) CNTs do provide indirect evidence of deagglomeration in the lung over time and translocation to systemic organs, suggesting potential slow-release of more bioactive structures following deposition of agglomerated nanoparticles in the lung (Castranova et al. 2014). These findings may have important implications for exposures to ENMs that are likely to occur in the construction industry.

Further investigation is therefore warranted to evaluate release of ENMs from commercially available construction products during routine work activities. The vast majority of existing nanotoxicological publications concern 'as manufactured' ENMs, which have yet to be incorporated into end user products. Initial risk management has primarily taken place in locations such as laboratories and production facilities, where occupational exposure to unincorporated or 'raw' ENMs can occur, but the nanotechnology risk assessment paradigm may be shifting. Recognizing that incorporation of ENMs into various matrices can drastically affect their physicochemical properties and that toxicological understanding in this regard is lacking, researchers have employed a life cycle perspective to evaluate exposures and toxicity associated with nano-enabled products (Pirela et al. 2015b; Sotiriou et al. 2015). Examples of this approach include studies of printer-emitted particles related to use of ENMs in toners, which have been associated with adverse effects both in vitro (Pirela et al. 2015a; Lu et al. 2015a; Khatri et al. 2013b) and among human volunteers (Khatri et al. 2013a).

Another research priority for nanocomposite materials used in construction is to investigate how environmental degradation impacts release and toxicity of matrix bound ENMs. To our knowledge, very few studies to date have taken the comprehensive approach of evaluating the toxicity of debris released from nanocomposite material subjected to mechanical forces after weathering, which could be a common foreseeable scenario in construction.

Ging et al. (2014) used an in vivo *Drosophila* ingestion exposure model for toxicity testing of mortar-ground epoxy composites containing 1 % by mass multiwalled carbon nanotubes (MWCNTs), following 1560 h of UV exposure. They observed enhanced concentration of CNTs at the surface of composites following UV exposure but did not observe a significant increase in toxicity relative to mortar-ground particles from epoxy without nanofiller, positing that the latter finding may be due to the fact that most CNTs in the abraded samples remained embedded in the matrix. The findings are applicable to construction, but the most concerning toxic effects of CNTs are associated with inhalation exposure (Donaldson et al. 2013; Osmond-McLeod et al. 2011; Poland et al. 2008; Shvedova et al. 2014; Takagi et al. 2008) versus ingestion, and nanocomposites in the built environment will be subjected to multiple degrading forces over the course of decades versus months.

Importantly, Ging et al. (2014) have provided a valuable conceptual framework that includes important life cycle considerations for realistic risk assessment of ENM exposure in the construction industry. Two review papers suggest avenues for further inquiry and provide a detailed overview of the current understanding of ENM release dynamics, also pointing out the need for standardized and validated methods (Duncan 2015; Froggett et al. 2014). Improved understanding of ENM physiochemical transformations as they are incorporated into and released from products as well as improved understanding of their toxicokinetics may also be critical to evaluating the risks posed by exposure to ENMs in construction.

## Case study: exposure assessment

Industrial hygiene measurements for the current observational study suggest that workers would not be exposed to $TiO_2$, nanoscale or otherwise, in excess of the NIOSH RELs as a result of cutting of the roofing tile we tested under similar conditions. Cutting tile in the environmentally controlled chamber generated levels of respirable dust beyond what would be expected on a typical outdoor roofing project, but measured air concentrations of $TiO_2$ remained relatively low. This finding is consistent with the low percentage by mass concentration (0–2 %) of $TiO_2$ indicated on the SDS. In general, cutting of roofing tiles is typically performed outdoors and is the more likely scenario, whereas performance of the task indoors can be considered a worst-case exposure scenario.

The results cannot be generalized to cutting of the tiles following environmental degradation, which could potentially affect release of ENMs and subsequent exposure. The NIOSH REL pertains specifically to inhalation exposures, but other exposure routes, such as oral or dermal, may be important to consider. ENMs may be capable of penetrating flexed or damaged skin (Mortensen et al. 2013; Schneider et al. 2009), which is not uncommon among construction workers. Potential for concurrent exposure to ENMs in construction should also be noted. Numerous materials are present on actual jobsites. Separate work activities performed on multiple nano-enabled materials on a construction site could result in numerous points of ENM release and greater cumulative exposure to different types of ENMs.

Studies of occupational exposure to nano-$TiO_2$ in construction are limited but have thus far shown exposures to be below proposed or existing occupational exposure limits or reference values. Dylla and Hassan (2012) assessed exposure to nano-$TiO_2$ during laboratory-simulated construction activities involving weighing and mixing of photocatalytic mortar powders and aqueous solutions, and during field application of a photocatalytic spray coating on asphalt. They observed increased exposure to nanoparticles under both scenarios, relative to controls, but were unable to positively identify airborne ENMs by TEM. Broekhuizen et al. (2011) determined that exposure to nano-$TiO_2$ during outdoor application of a self-cleaning coating was well below precautionary nano reference values. Both studies noted difficulties in distinguishing ENPs from naturally occurring and incidental nanoparticles. The SCAFFOLD project included assessment of occupational exposure to nano-$TiO_2$ across the life cycle of depollutant mortars used in construction: nano-$TiO_2$ manufacturing, mortar manufacturing, mortar application, sol–gel spraying, machining tasks, and demolition (Vaquero et al. 2015). The highest exposures were observed for cleaning activities during nano-$TiO_2$ manufacturing and during spray application of depollutant coatings, though occupational exposure to nano-$TiO_2$ was below 0.3 $mg/m^3$ for all measured scenarios.

As opposed to nano-specific risk, exposure to crystalline silica (40–75 % by weight) during cutting of the tiles likely posed the greatest occupational health risk in the case study. Adverse human health effects resulting from exposure to $TiO_2$ have not been demonstrated, whereas occupational exposures to respirable crystalline silica in the construction industry and the associated human health effects have been well documented, including exposure to silica during roofing tile installation (Hall et al. 2013). Estimates suggest that 3600–7300 new cases of silicosis may be occurring annually in the United States (Filios et al. 2015; Rosenman et al. 2003). The hazards posed by silica exposure are well understood, and resources were not devoted to quantifying silica exposure in our case study. A limitation of doing so is that we were unable to address the possibility that incorporation of nano- or near nanoscale $TiO_2$ impacted the release of fracture-activated, respirable quartz. The case study should not be viewed as a comprehensive risk assessment of working with the tiles; this initial research was exploratory in nature to assess potential release of nano-$TiO_2$ from the tile and the effectiveness of controls. Ideally, nano-risk assessment in construction should consider risks posed by ENMs in relation to conventional hazards, and the novelty surrounding ENMs should not overshadow or usurp well-characterized hazards in the industry, such as silica. For the current case study, the low percentage by weight (0–2 %) of nano- or near nanoscale $TiO_2$ in the tile seemed unlikely to significantly increase the hazard potential posed by $TiO_2$ while working with the tiles under similar conditions, considering the current understanding of the risks posed by exposure to silica and $TiO_2$.

Further research on occupational exposure to ENMs in construction should consider additional exposure scenarios and the effects of weathering, host matrices, and nano-fillers on the potential for ENM release. Risks posed by ENMs may differ on a case-by-case basis in construction, considering, for example, the types and quantities of ENM in a product. Unfortunately, findings from the inventory indicate that it can be difficult to ascertain the types and quantities of ENMs being used in existing products.

The question remains as to whether or not the use of ENMs in construction significantly augments existing risks faced by construction workers. Cement has been described as the oldest nanomaterial, and despite over a 100 years of systematic research, its nanostructure and atomic arrangement are still not fully understood (Ridi et al. 2011). Millennia ago, ancient Romans made use of naturally occurring nanoparticles in the form of volcanic ash–lime mortar to build concrete structures that have stood the test of time (Jackson et al. 2014). More recently, it was observed that over 90 % of the total particle number concentrations measured during construction refurbishment activities consisted of nanoscale particles (Azarmi et al. 2015), suggesting that exposure to nanoscale debris may be a common occurrence in construction, even when nano-enabled materials are absent. Occupational exposure to CNTs has received significant attention, yet Kolosnjaj-Tabi et al. (2015) reported that their findings "strongly suggest that humans are routinely exposed to CNTs." They discovered that particulate matter from the lungs of asthmatic Parisian children was primarily composed of anthropogenic MWCNTs that were similar to synthetic MWCNTs and to MWCNTs detected in Parisian vehicle exhaust and dust, ambient air samples in the USA, and spider webs in India. These findings beg the question: do exposures to ENMs differ from exposures to naturally occurring or incidental nanoparticles and non-engineered nanoscale debris released from conventional construction materials?

Historical studies of ultrafine particles (UFPs) provide insight into this question, suggesting that risk assessment for emerging ENMs is urgently needed (Oberdörster et al. 2005). The novelty of risks posed by ENMs can be attributed to the fact that, "newly engineered NPs [nanoscale particulates] that are products of nanotechnology have changed the abundance, chemical composition, and physical characteristics of very small particulates in potential workplace and environmental exposures" (Hubbs et al. 2011). Researchers have compared the toxic potential of UFPs versus engineered or manufactured nanomaterials experimentally (Lu et al. 2015b; Xia et al. 2006) and more broadly via literature reviews (Madl et al. 2014; Shannahan et al. 2012;). While both similarities and differences have been observed, mechanistic understanding remains incomplete. Usage, application, and physiochemical properties of nanomaterials can affect their hazard potential; therefore characterization of the physiochemical characteristics of nanomaterials in human exposure settings is needed (Madl and Pinkerton 2009). To this end, characterizing debris released from both nano-enabled and conventional construction products will provide realistic parameters for toxicological inquiry to better understand the risks faced by construction workers.

## Case study: effectiveness of controls

The case study also demonstrated the effectiveness of engineering controls. Industrial hygiene measurements, TEM observations, and real-time particle counts of submicron particles (20–1000 nm) illustrated the effectiveness of LEV in reducing exposure to particles of all sizes during the tasks performed, just as prior research has shown reductions in crystalline silica exposure by use of LEV under similar working conditions (Flynn and Susi 2003; Meeker et al. 2009; Shepherd et al. 2009; Carlo et al. 2010). Exposure controls such as ventilation, process changes, and enclosures can be effective methods of controlling exposure to ENMs in manufacturing and production settings (Heitbrink et al. 2015; Methner 2008, 2010), and prevention of occupational exposure to welding fumes, which are partially comprised of incidental nanoparticles (Brand et al. 2013; Pfefferkorn et al. 2010), has also been demonstrated (Flynn and Susi 2012; Lehnert et al. 2012; Meeker et al. 2010; Susi et al. 2000; Blade et al. 2007).

In general, nanoparticle emissions are easier to identify and control in closed settings, such as factories, compared to dynamic worksites in construction. For example, the LEV system we used would prove impractical on steep-pitched roofs, considering working surfaces and the need to hoist and lower materials during measurement, marking, and cutting of tiles. Measuring and cutting of tiles is commonly performed on the rooftop itself to save time in an industry where production pressures are common. When engineering controls are impractical, personal protective equipment is an option. Respirators can effectively reduce exposure to nanoparticles (Brochot et al. 2012; Rengasamy and Eimer 2011; Shaffer and Rengasamy 2009) but do not prevent bystander exposures and should be used as a last resort, according to the hierarchy of controls.

Evaluating the efficacy of protective measures to reduce exposure to ENMs in construction will encourage safer use and adoption of nano-enabled products and may mitigate health concerns in the face of toxicological uncertainty. Further research considering alternative control measures, such as wet cutting methods, and different exposure scenarios will be beneficial. In some cases, reducing exposure to ENMs in construction may not require additional action on the part of contractors. If control measures are already in place to prevent other exposures, such as exposure to silica in our case study, exposures to ENMs may simultaneously be prevented. In this sense, ENMs may provide additional incentive to reduce exposure to vapors, gases, dusts, and fumes (VGDF) in construction. Many conventional construction materials already pose a risk to workers prior to the addition of ENMs. Nearly one in five cases of chronic obstructive pulmonary disease (COPD) was attributable to construction-related exposures in a case–control study, and a combined measure of all VGDF exposures was a strong predictor of COPD risk (Dement et al. 2015). Unfortunately, control measures are not always implemented in practice (Deurssen et al. 2015). Research demonstrating the effectiveness of controls to reduce ENM exposure will be beneficial, as will intervention strategies that increase implementation of safe work practices to prevent occupational exposures to VGDF, including those containing ENMs.

## Environmental impact

The focus of this manuscript has been occupational exposure to ENMs among construction workers, but nanotechnology risk assessment in a broader sense can be viewed as a public health issue encompassing multiple disciplines, where life cycle considerations are critical. Construction dust containing ENMs can drift into public spaces, potentially exposing non-working populations. Dust settles and is transported by runoff into aquatic ecosystems, where toxicity of ENMs in plants and microorganisms is a concern (von Moos and Slaveykova 2014). ENPs in paints and coatings are predicted to have the potential to contaminate drinking waters in low concentrations (Tiede et al. 2015), and it was recently observed that exposing bacteria to low, sublethal concentrations of silver nanoparticles resulted in enhanced formation of protective biofilms and upregulation of antibiotic resistance genes, suggesting the potential for accelerated biocorrosion and biofouling of water infrastructure systems and heightened bacterial pathogenesis and virulence, which could pose a risk to public health (Yang and Alvarez 2015). To what extent will ENMs used in construction contribute to inputs of ENMs to ecological systems?

Aside from renovation and demolition, other pathways by which ENMs in construction materials may flow to the environment include recycling, landfilling, and incineration. Unlike manufacturing plants, most construction sites do not have dedicated waste treatment facilities and are not subject to similarly stringent regulations. Moving down the supply chain, responsibility for SDSs may change, and the ability to identify environmental inputs via SDSs may decrease. Put into context however, naturally occurring nanoparticles are ubiquitous in nature (Hochella, Jr. et al. 2008), and releases of ENMs to the environment are believed to be a much less common occurrence than releases of incidental and naturally occurring nanoparticles (Wiesner et al. 2009). Still, quantitative understanding of nanoparticles in the environment is limited and new analytical methods are needed (Varner et al. 2010).

New analytical methods will also help validate environmental modeling efforts, for which major data gaps on the production, application, and release of ENMs have been limiting factors (Gottschalk et al. 2013). Despite these barriers, researchers have been successful in using bottom-up, semi-quantitative methods to estimate environmental flows of ENMs in construction and demolition waste in Switzerland (Hincapié et al. 2015). Focusing on paints, they found that most ENMs contained in paints in Switzerland enter recycling or landfill waste streams, and only a small fraction is incinerated. They estimated annual use of ENMs in paints in Switzerland to be 14 tons of $TiO_2$, 12 tons of $SiO_2$, 5 tons of ZnO, and 0.2 tons of Ag.

We are not aware of similar environmental modeling efforts considering construction and demolition waste containing ENMs in the U.S., though ENM production estimates provide some insight. For example, Keller and Lazareva (2014) estimated that the U.S. is responsible for 50 % of ENM production worldwide and consumes 10–12 % of all ENM-containing products, based on population. They estimated that the U.S. production of nano-$TiO_2$ was between 41,750 and 44,000 metric tons per year for all market segments. Silica fume, used as a highly reactive pozzolan for high performance concrete, makes for an interesting comparison. Also known as 'microsilica,' silica fume is a by-product of the ferrosilicon industry and has an average particle diameter of about 100 nm (U.S. EPA 2008), and can therefore be classified as an incidental nanomaterial. Global production of silica fume was estimated by the American Concrete Institute to be 900,000 metric tons annually, of which more than 120,000 metric tons were used in concrete worldwide (U.S. EPA 2008). According to the Silica Fume Association, the U.S. production of silica fume in 2004 was between 100,000 and 120,000 metric tons, of which 83,000 were used for cement or concrete; less than 16,000 metric tons were estimated to be landfilled in the U.S. in 2006 (U.S. EPA 2008). Considering that ENMs can be incorporated into construction materials used in high volumes that are subject to mechanical force and environmental degradation, it will be important to investigate the environmental fate and transport of ENMs used in construction to evaluate their full life cycle impacts.

## Conclusions

Determining the types and quantities of ENMs used in construction is required for effective risk assessment and proactive risk management, but there is currently minimal understanding in this regard. Over 450 commercial construction products are reported to be nano-enabled, but verifying the presence of ENMs in these products proved difficult without further testing, which poses a challenge to risk assessors and employers. Cement, insulation, and coatings in particular comprised the bulk of the nano-enabled product inventory. Of the 26 ENMs reported to be used in nano-enabled construction products, polymers, $TiO_2$, silica polymorphs, zinc oxide, and carbon nanotubes were most frequently reported. In most cases, specific chemical composition of ENMs could not be determined via SDSs, technical data sheets, and product literature available online, which can mitigate the effectiveness of hazard banding approaches. Types and quantities of ENMs used in construction remain unclear; greater clarity in this regard is needed to foster responsible development of nanotechnology in construction.

The survey of construction health and safety trainers suggests that familiarity with nanotechnology in the construction industry may be limited. Risk communication and dissemination strategies in the construction industry are therefore needed. The authors recommend that these efforts should seek to increase awareness, introduce basic concepts of nanotechnology, describe limitations of current understanding, acknowledge the benefits of nanotechnology, and emphasize the effectiveness of control technologies and respiratory protection.

The case study provides additional support for a limited but growing body of evidence, suggesting that ENMs released during construction activities tend to be bound to the host material or agglomerated. We were unable to determine if nanoscale $TiO_2$ was present in the roofing tile or in the dust generated during machining of the tiles, although a small number of unbound $TiO_2$ particles just above the nanoscale range were detected in the dust. Engineering controls effectively reduced exposures, and exposures to $TiO_2$ were below the NIOSH RELs, even while generating excessive levels of dust in a closed environment. We concluded that the presence of nano- or near nanoscale $TiO_2$ in the tile was unlikely to significantly increase hazard potential posed by $TiO_2$ under similar conditions, with the caveat that we did not investigate whether the presence of $TiO_2$ influenced the release of fracture-activated quartz. Additionally, multiple points of ENM release could be present on an actual jobsite. Even so, the high percentage by weight of crystalline silica in the tile was deemed to pose the greater occupational health risk, given the current level of understanding.

Numerous avenues of research were identified as essential to responsible development of nanotechnology in construction. Evaluating the effectiveness of control technologies in construction will foster safer use of nano-enabled products and negate toxicological uncertainty. Studies that characterize and quantify exposures to ENMs in construction will establish realistic parameters for toxicological inquiry, particularly those considering the effect of environmental degradation and physiochemical transformations of ENMs across the life cycle of nanocomposite materials. Research into the biological fate and transport of ENMs may also be crucial to evaluating the risks faced by construction workers exposed to agglomerated ENMs. Further investigation of incidental and naturally occurring nanoparticles will provide baseline knowledge to assess the novelty of risks posed by

ENMs and how exposures to ENMs may or may not differ from historical exposures to nanoscale particulate. Finally, potential ecological impacts of ENMs used in construction will be important to assess, given the unique nature of construction work and the potential for ENMs to become ubiquitous in the built environment. The breadth of research needs to be addressed underscores the value of a multidisciplinary approach, such as bridging toxicological and exposure sciences, to ensure responsible development of nanotechnology in the construction industry.

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**Compliance with ethical standards**

The Institutional Review Board of CPWR—The Center for Construction Research and Training approved the survey and exposure assessment activities conducted as part of this research. The authors declare that they have no conflict of interest.

**Conflict of Interest** The authors declare that they have no conflict of interest.

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