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Integrating Thematic Problem-Based Learning Modules on Nanotechnology in the Civil Engineering Curriculum

Dr. Nicole Berge, University of South Carolina

Dr. Nicole Berge received her B.S. and M.S. in Civil and Environmental Engineering from the University of South Carolina in 1999 and 2001, respectively. In 2006, she received her Ph.D. in Environmental Engineering from the University of Central Florida. From 2006 to 2008, Dr. Berge worked as a postdoctoral associate at Tufts University. Currently, she is an associate professor at the University of South Carolina.

Dr. Charles E. Pierce, University of South Carolina

Dr. Pierce is the Director for Diversity and Inclusion and Associate Professor in the Department of Civil and Environmental Engineering at the University of South Carolina. He is a USC Connect Faculty Fellow for Integrative Learning, and a Bell South Teaching Fellow in the College of Engineering and Computing. Dr. Pierce also serves as the ASEE Campus Representative for USC.

Dr. Robert Petrulis

Dr. Petrulis is an independent consultant specializing in education-related project evaluation and research. He is based in Columbia, South Carolina.

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Introduction

The rapid growth of nanomaterials within consumer products, construction materials, and other medical or electronic devices necessitates the education of engineering students on the impacts and implications of nanotechnology. For civil and environmental engineering students, in particular, it is important to understand the complex roles of nanomaterials in waste management. Nanomaterials can be incorporated to enhance concrete properties for spent nuclear waste containment, for example. At the same time, it is critical that we develop environmentally sound end-of-life management strategies for nanomaterial-laden items. To that end, students must learn about the unique aspects of fundamental nanomaterial properties (e.g., surface area, surface chemistry), as well as potential issues associated with nanomaterial disposal (e.g., transport in waste environments, health concerns).

Rather than teach a singular elective course on nanotechnology, it was decided to distribute and integrate the content across multiple courses. This paper describes the implementation of that integrated theme within a civil and environmental engineering curriculum. The integrated approach is referred to as a Nanotechnology LINK, which stands for Learning Integration of New Knowledge (Pierce and Berge 2014). The proposed benefits of this approach are that (1) student learning of nanotechnology concepts and course-specific core concepts are simultaneous and connected, such that nanotechnology is not isolated or out of context for students; (2) exposure to nanotechnology is extended over a much longer period of time, rather than concentrated in one semester, with the goal of facilitating integrative learning across courses; and (3) more students in our program are exposed to nanotechnology.

Module Development and Implementation

Problem-based learning, or PBL, was selected as the pedagogical method for introducing fundamental concepts associated with nanomaterials and applications of nanotechnology. Each PBL module was created to encompass a sequence of consecutive class periods using the Environments for Fostering Effective Critical Thinking (EFFECTs) framework developed at the University of South Carolina (USC). EFFECTs use student-centered learning strategies to promote deep learning, enhance conceptual understanding, and stimulate growth in critical thinking skills while solving a real problem. Prior to this project, a number of civil engineering EFFECT modules had been developed and implemented at USC in multiple undergraduate courses (Berge and Flora 2010; Pierce et al. 2012; 2013). While those experiences established this particular PBL framework as a successful approach for student learning (Pierce et al. 2012; 2014), it was limited in its implementation to a handful of faculty members. Furthermore, it had not been used for a thematic integration of student learning from one course to another. Here, the premise was that each PBL module would represent a signature learning experience for students in each course, where PBL was not otherwise used. The intent was to make it easily distinguishable and connected, such that students think *"this is how we learn about nanotechnology"* and *"this is what I remember about nanotechnology from other modules."*

During this project, eleven different nanomaterial-related activities were developed and implemented in eight existing civil and environmental engineering courses. Of these eight courses, three are required for all undergraduate students. The remaining five courses are technical electives. In most cases, PBL modules were designed for a two-week sequence of class periods, although some were shorter and others were longer. Implementation of these modules occurred over a three-year period.

A listing of the impacted courses and a brief description of the activities conducted within them are described below. Instructional materials associated with these modules, including worksheets and student handouts, can be found in an online library for EFFECTs located at: http://sdii.ce.sc.edu/effects/. The courses are listed in academic order, from first-year to senior year courses.

ECIV 101: Introduction to Civil and Environmental Engineering
(first year, required course)

In this course, students routinely participate in several hands-on modules to experience various aspects of civil engineering, including environmental, geotechnical, and structural engineering (Pierce et al. 2012). The nanotechnology themed module was developed for environmental engineering, for which students were asked to design a sedimentation basin for nanoparticle removal. During the first active learning exercise, students performed lab experiments to evaluate the settling velocity of various particles to obtain a relationship between velocity and particle characteristics. From this relationship, students extrapolated the settling velocity of nanomaterials. Subsequent activities concentrated on nanomaterial coagulation/flocculation to enhance particle settling and estimate particle removal efficiencies, which were followed with an introduction and discussion of Stoke's law. In a separate module, students were prompted to determine the mass of single-walled carbon nanotubes (SWNTs) needed to remove natural organic matter in a water treatment plant. To find a solution, students designed and conducted adsorption experiments. Both modules required each student to document his/her proposed solution in an individual engineering report, detailing how the results obtained from the active learning exercises were used to solve the problem.

ECIV 303: Civil Engineering Materials
(junior year, required course)

It was decided to implement a PBL module into the civil engineering materials lab course (see discussion below for ECIV 303L) rather than this course. Instead, students were exposed to nanotechnology through a student presentation completed as part of a research team assignment. This assignment required teams of seven to eight students to (1) conduct a critical review of the archival literature on a cutting-edge civil engineering material, and (2) prepare and deliver a 15-minute presentation in class at the end of the semester. In each one of two semesters, one team was designated for a presentation related to nanotechnology. In fall 2014, the designated team focused on titanium dioxide nanoparticles as a means to confer photocatalytic (self-cleaning) capabilities to concrete surfaces. In fall 2015, the designated team focused on graphitic nanoparticles (multiwalled carbon nanotubes and graphene nanoplatelets) as nanoreinforcement for cement composites. During the six weeks allotted for this assignment, each team met with the instructor biweekly to discuss the literature and assess progress. Each team was required to include the following topics in the presentation: constituents and molecular structure; relevant physical and mechanical properties; significance of the materials; applications and examples; advantages and drawbacks; attributes associated with sustainability; and proposed ideas to address outstanding issues. For the purposes of this project, the impact on the individual students in the teams conducting research on nanotechnology was higher than for the rest of the class.

ECIV 303L: Civil Engineering Materials Laboratory
(junior year, elective course)

In this lab course, students were prompted to help design nanomaterial-containing cement composites for nuclear waste storage using dry casks. To provide them with adequate background, students were assigned to view three educational videos (produced as part of this project) on nanomaterial dimensions, uses, and manufacturing. The first exercise required students to draw, as individuals and in teams, a nanoscaled view of low-porosity and high-toughness Portland cement mortar incorporating multiwalled carbon nanotubes (MWCNTs). Supplemental questions were designed to invoke student reflections on the shape and relative size of MWCNTs and cement hydrates, and how those physical relationships affect relevant mechanical properties of the nanoreinforced mortar. Student teams worked on a set of three hands-on active learning exercises using more familiar physical objects, on a larger scale, to represent MWCNTs, cement hydrates, and fine aggregate. These activities were crafted for students to gain insight into the morphology and size of MWCNTs, and how that knowledge would influence their incorporation into a fresh mortar mixture. These simple but effective hands-on activities were integrated into a research presentation on the results of manufacturing and physical testing of MWCNT-reinforced cement mortar prototypes, which were performed at USC as part of an ongoing USDOE funded project. Discussion of student learning from this PBL module can be found in Haggard et al. (2017).

ECIV 350: Introduction to Environmental Engineering
(junior year, required course)

This course was chosen as the cornerstone for this thematic curriculum project, such that nanotechnology was more fully integrated into the course objectives. In this course, there were four distinct teaching and learning opportunities embedded throughout the semester, as described herein.

1. First, nanotechnology applications and concepts relevant to environmental engineering were introduced throughout the course using interactive lectures.
2. Students completed a PBL module to design a sedimentation basin for nanoparticle removal (see prior discussion associated with ECIV 101).
3. In another module, students were asked to design a water treatment filter that would achieve the highest removal of phenol. During this active learning exercise, students designed model filtration units using plastic cups (filter housing) and Starburst® fruit chews (adsorption media) to remove the maximum amount of contaminant. The fundamental concepts/topics were adsorption processes; surface area of nanomaterials;

and the relationship between surface area and contaminant removal via adsorption.

4. All students in this course were required to create a "nanomercial" as part of a small team project. The concept was for each team to create a 3-5 minute extended public service announcement/infomercial about an environmentally relevant nanotechnology topic or problem. There were ten team videos produced, and several examples of presentation titles include: Nanoparticles Tackle Algae; Nanotechnology and Steam Generation; Nanotechnology in Concrete; Nanotechnology and Oil Spills; Solar Nanomercial; Do Your Feet Stink Too?; and Mr. TiO_2. These videos can be accessed through the project-specific YouTube channel located at: https://www.youtube.com/channel/UCLnCwjvSZgGjKWFyt_Mny4Q.

ECIV 350L: Introduction to Environmental Engineering Laboratory
(junior year, elective course)

In this lab course, students were prompted to design a water disinfection system using sunlight in the presence of TiO_2 for a small community. Bench-scale lab experiments were designed and performed by the students to evaluate the effectiveness of TiO_2 nanoparticles in the removal of total coliform bacteria. Using their removal data, students reported on and discussed whether their proposed system was designed properly to meet the recreational water quality criteria of < 1 CPU/100 mL.

ECIV 490: Introduction to Civil and Environmental Engineering Research
(any year, elective course)

This course was not designated for PBL; rather, a select group of students in this course participated in independent research associated with nanomaterials. Recipients of the Nanotechnology LINK Summer Research Fellowship were required to enroll in this course (spring 2015 and 2016) and produce a research proposal, prior to their summer research experience. More details on this research course can be found in Pierce et al. (2016).

ECIV 533: Geosynthetics and Geotechnical Design of Landfills
(junior/senior year, elective course)

In this advanced course, a PBL module was developed for students to determine if the properties of a HDPE geomembrane located in a bottom liner system of a landfill can be influenced by the presence of nanomaterials in the leachate. During this module, students performed a series of in-class activities involving: (1) physical and mechanical properties of geomembranes; (2) analysis of design case studies in which students were asked to draw schematics of the design scenarios and free body diagrams, showing all stresses acting on the geomembrane; (3) in-class team calculations to predict whether or not 100% of the antioxidants would be removed from the geomembrane if 1000 mg/L of TiO_2 were present in the leachate; (4) class discussions associated with geomembrane aging and geomembrane properties that change with time; and (5) final calculations to answer the question. The concepts emphasized within this module included physical properties and strength degradation of geomembranes; surface area of nanoparticles; and the chemical interactions between geomembranes and leachate containing nanomaterials.

ECIV 555: Principles of Municipal Solid Waste Engineering
(junior/senior year, elective course)

The PBL module for this course required students to determine the concentration of nanomaterials in landfill leachate when consumer products containing nanomaterials are known to be present in the landfill. During this module, students completed a sequence of in-class activities to identify which consumer products discarded in landfills contain nanomaterials, using the findNano mobile application; estimate the mass of different nanomaterials in the landfill; and understand processes that occur in landfills to discover how nanomaterials can transition into the landfill leachate. Embedded within these activities were the fundamental concepts/topics of nanomaterials in consumer products; concentrations of nanomaterials found in the environment; leachate volume and composition; and waste composition and generation.

Student Exposure to Nanotechnology

A significant result from this thematic curriculum project is the student exposure to nanotechnology. Approximately 70% of the undergraduate student population (259 students, over a three year period) was exposed to some aspect of nanotechnology in the civil and environmental engineering curriculum. Of these students, 40% were exposed to nanotechnology in at least two courses. A much smaller student population, on the order of 10%, was exposed to nanotechnology in at least three courses. Of these, a few students were impacted in five courses.

To gauge student perceptions of the PBL modules integrated within courses across the curriculum, an online survey was developed and distributed to 210 recipients. The target population was comprised of 183 current students and 27 recent graduates. A total of 45 responses were received, providing a yield of 21%. Of the 45 respondents, six did not recall having participated in a nanotechnology module, and eight more did not complete the survey beyond the first two questions. Thus, a total of 31 completed surveys were collected for a response rate of 15%. The most significant findings from this survey are discussed below.

- There was a general consensus that there is a desire and need for classes in nanotechnology and for that content to be incorporated into a greater number of courses. Thus, it was recognized that nanotechnology is something that civil and environmental engineering students should be learning.
- Of the nanotechnology content learned, the majority of respondents reported that the *use of nanomaterials* was the most memorable concept. Even though this represents a more general topic rather than a technical concept, it is what resonated with students. Other concepts that were reported as significant include particle surface area, material strength, and environmental implications.
- About three-quarters of the respondents indicated that the problem-based learning approaches used in the nanotechnology modules allowed them to explore the topic more thoroughly than through a lecture alone, and that engaging in these activities was similar to the work of a practicing engineer.
- Most responses also offered positive sentiment, indicating that students generally enjoyed and appreciated the nanotechnology modules. Several comments, as well as responses to specific closed-ended questions, indicated that most students appreciated the problem-

based learning structure, and these students perceived to have benefited from the hands-on, real-world nature of the in-class problems. Although most students were positive about the experiences, about one-quarter of them were neutral or negative about these experiences.

Faculty Reflections on the Integration of PBL Modules

An external evaluator conducted one-on-one interviews of the instructors for the eight courses. The following are the major conclusions associated with these interviews:

- Most students, on the order of two-thirds to three-quarters, became highly engaged in the hands-on, active learning process. Another, smaller group, was more resistant. In some cases, students in this latter group seem to be uncomfortable with the lack of problem definition and find the required conceptualization to be challenging. Others appear to be uncomfortable with working in groups, and still others prefer to sit and take notes rather than engage in the hands-on components.
- The active learning modules require a learning curve for students. Faculty reported that students who had prior experience with these in-class activities were able to engage in the process more quickly than those to whom this was new.
- Most of the instructors will continue to use this problem-based, active learning approach in their courses, albeit with modifications in some cases. Several faculty reported that the design and development of the modules is iterative, and may take several times to hone them into really effective teaching and learning experiences.

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