Active Problem-based Learning on Nano-amended Cement Composites for Nuclear Waste Storage for Civil and Environmental Engineering Undergraduate Students

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Introduction and Objectives

Problem-based and active learning in the classroom are increasingly important in developing the necessary critical thinking skills of an engineer [1-3]. In this project, active learning exercises are based on a problem-based learning framework called Environments For Fostering Effective Critical Thinking (EFFEC Ts), which was developed at the University of South Carolina (USC) through NSF funding [4-6]. The EFFECTs approach helps students progressively learn complex material, like nanotechnology, in an educational setting that stimulates independent thought as well as intellectual dialogue with peers and instructors. The work described in this paper is part of a larger NSF project to integrate student learning of nanotechnology across the civil and environmental engineering curriculum [7].

The problem-based learning framework is embedded with assessment instruments, such as decision worksheets, that are intended to capture student knowledge and critical thinking. This particular research project aims to assess methods for evaluating critical thinking from illustrative and written responses on worksheets completed in an engineering-focused class environment. It is proposed that this can be accomplished by: examining how students absorb, process, and apply new information through multiple iterations of similar active learning exercises, when new information is presented between each iteration; examining how group dynamics influence student responses and thinking processes through the evolution of responses from individual to team to individual; identifying factors that may influence student thinking processes during these exercises; and developing suitable performance measures. The findings will inform instructors on the effectiveness of these active learning exercises in the classroom.

This paper reports on the salient results of this two-year experience. In particular, it is discussed and demonstrated how the decision worksheets and written evidence from active learning exercises were used to extract information to help understand how students: (a) learn about and apply knowledge of new and career-relevant information; and (b) influence each other’s learning processes when confronted with a challenging yet relevant question, given the opportunity to engage in problem-based learning.

Background

During the fall 2014 and fall 2015 semesters, a two-week sequence of a civil engineering materials lab course at the University of South Carolina was dedicated to create in-class environments for student-centered, problem-based learning. The goal was to elicit critical thinking in the complex and increasingly important area of nanomaterials in civil and environmental engineering. To this end, each class of over 30 third- and fourth-year undergraduate students participated in two 1.5-hour lab class periods.
In the first lab period, referred to as Session I, the students: (a) watched and discussed three short videos illustrating the relevance of and basic concepts related to nanomaterials; and (b) estimated a solution to a driving question set in the context of nano-amended cement composites for below-ground nuclear waste storage at a local site, where leaching is of concern. The driving question was, “What is the amount, using wt% as units (i.e., percent by weight of cement), of multiwalled carbon nanotubes needed to attain at least a 20% increase in compressive strength in Type I ordinary Portland cement mortar?” This question was presented in a decision worksheet [8] that included supplemental questions designed to lead students through a progression of visualizing the problem and making educated assumptions for parameters and approximations of values needed to solve.

Students completed the decision worksheet individually, and then again in teams of four to five students. It is important to note that this sequence occurred near the end of the semester, after students had learned about Portland cement and worked with various cement-based materials, including mortar. Furthermore, students participated on the same teams throughout the semester. This means that, at the time of this exercise, students were familiar with the technical content (e.g., composition and properties of cement mortar) and with each other. Nanomaterials, on the other hand, were new to some students but somewhat familiar to others [7].

In the second lab period, Session II, the instructor presented results from ongoing research on nuclear waste storage in South Carolina. The presentation was designed to facilitate interactive lecturing, and it was coupled with intermediate breaks to conduct active learning exercises. Each exercise had a specific purpose to strengthen their understanding of fundamental concepts (e.g., particle size and proportions within the mortar microstructure, nanomaterial processing for physical and chemical compatibility with hydrated cement, and salient properties affecting strength and radionuclide retention, such as porosity). The outcomes consisted of written answers to guiding questions related to those on the decision worksheet from Session I.

**Methodology**

Research conducted thus far has encompassed two phases of a larger research project design.

Phase 1 was for evaluating illustrative responses from decision worksheets completed in Session I and active learning exercise responses completed in Session II. This has been accomplished by: (a) developing a rubric to evaluate student visualization of the nanoscale and proportions within the mortar microstructure; (b) comparing drawings from Session I and Session II using the rubric; and (c) recording results. Drawings were made in response to the prompt, “In the space below, draw a magnified view of the nano-reinforced mortar at an appropriate nanoscale. List the dimensional scale, and label all of the parts in your sketch.”

Phase 2 was for compiling and comparing data from the remaining written responses collected from the student activities. This has been accomplished by: (a) collecting data from all responses, including quantitative data from written responses and qualitative data from illustrative and written responses, using rubrics established for that purpose; (b) categorizing and arranging data; and (c) comparing data per question and per session for individual student responses and team responses.
Sketches from Phase 1 were first evaluated using the rubric developed as shown in Table 1, resulting in a broad overview of the impact of different factors throughout the activities. Schematics collected from the first worksheet and the final worksheet were scored according to this rubric to determine overall net improvement. Scores of Poor, Good, and Excellent were assigned using a photograph of the actual structure of nanotube-reinforced cement mortar as the standard.

In response to these generalized results, the initial rubric (Table 1) was refined in order to track more specific factors believed to indicate evidence of the learning process during the activities. Phase 1 sketches were then evaluated using two rubrics, one focused on student identification of salient elements in the schematic of Portland cement mortar amended with carbon nanotubes (Table 2), and one focused on student understanding of the nanoscale (Table 3). Representative examples of low-scoring and high-scoring schematics are shown in Figure 1(a) and Figure 1(b), respectively.
### Table 1. Initial Rubric for Evaluation of Schematics

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1 – Poor</th>
<th>2 – Good</th>
<th>3 – Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the sketch contain and label all reasonable and necessary elements?</td>
<td>Sketch contains one or two relevant elements, may or may not be labeled</td>
<td>Sketch contains nanotubes and a scale, along with one or two other relevant elements, most items have labels</td>
<td>Sketch contains nanotubes, all correct elements of mortar, and an appropriate scale; all elements are correctly labeled</td>
</tr>
<tr>
<td>Does the sketch represent an appropriate and reasonable configuration of elements?</td>
<td>Sketch shows elements out of proportion, unrealistic configurations, etc.</td>
<td>Most elements of sketch are proportionate, with reasonable configurations</td>
<td>Sketch offers a realistic and accurate representation that is similar to actual observations</td>
</tr>
<tr>
<td>Does the sketch demonstrate understanding of the subject matter?</td>
<td>Sketch shows little understanding, may be chaotic in nature, show inappropriate labeling or element shapes</td>
<td>Sketch shows some understanding, may have one or two errors, but clearly shows thought and planning</td>
<td>Sketch demonstrates understanding of subject matter through clear, knowledgeable, and correct drawings</td>
</tr>
</tbody>
</table>

### Table 2. Second Rubric for Evaluation of Schematics – Elements

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1 – Poor</th>
<th>2 – Fair</th>
<th>3 – Good</th>
<th>4 – Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the sketch contain and label all reasonable and necessary elements?</td>
<td>Sketch contains one or no necessary elements; no elements are labeled</td>
<td>Sketch contains at least two necessary elements; may contain one or more unnecessary elements; at least one or two elements are correctly labeled</td>
<td>Sketch contains at least three necessary elements and no unnecessary elements; at least three elements are correctly labeled</td>
<td>Sketch contains all necessary elements and no unnecessary elements; all elements are correctly labeled; sketch may offer more information through captions</td>
</tr>
<tr>
<td>Are representations of elements correct and realistic depictions?</td>
<td>Sketch shows little understanding of appropriate element shapes; may be chaotic in nature</td>
<td>Sketch shows general understanding of appropriate element shapes</td>
<td>Element shapes are mostly reasonable and realistic, with one or two errors</td>
<td>Depiction of all elements are reasonable and similar to actual photographic observations</td>
</tr>
</tbody>
</table>

### Table 3. Second Rubric for Evaluation of Schematics – Scale

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1 – Poor</th>
<th>2 – Fair</th>
<th>3 – Good</th>
<th>4 – Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the sketch contain an appropriate scale?</td>
<td>The sketch does not contain a scale</td>
<td>The sketch contains a scale, but it may be inappropriate</td>
<td>The sketch contains a reasonably appropriate scale; may attempt to label elements with reasonable sizes</td>
<td>The sketch contains an appropriate scale; may label elements with correct sizes</td>
</tr>
<tr>
<td>Are element proportions correctly represented?</td>
<td>Element proportions are inappropriate; may all be roughly the same size</td>
<td>Elements are different sizes, but still in inappropriate proportions</td>
<td>Element sizes are approaching correct proportions; may have one or two errors</td>
<td>Element proportions are appropriate, realistic, and similar to actual photographic observations</td>
</tr>
</tbody>
</table>
Prior to answering the driving question, answer the following supporting questions first.

1. In the space below, draw a magnified view of the nano-reinforced mortar at an appropriate nanoscale. List the dimensional scale and label for all of the parts in your sketch.
Prior to answering the driving question, answer the following supporting questions first.

1. In the space below, draw a magnified view of the nano-reinforced mortar at an appropriate nanoscale. Use the dimensional scale and label for all of the parts in your sketch.
During Phase 2, responses from the first individual activity and the second team-based activity were transcribed into digital records. Responses were then analyzed to determine if and how various group dynamics affected student understanding of the material. Methods utilized included identifying common words and concepts used, as well as the frequency with which these words occurred; recording frequency of various response formats; and comparing the individual and team responses to identify any patterns in the evolution of responses.

Phase 2 also involved the identification and tracking of misconceptions evident in the responses about nanomaterials and the nanoscale. More specifically, responses from Question 2 of the first and second activities were qualitatively evaluated using the rubric presented in Table 4. This particular question, which was repeated in both activities, prompts the students with “What information do you think you need to know to answer the driving question? List all of the factors and/or variables that are needed and identify which ones are the most important. For each factor/variable listed, offer a rationale for why it is needed. For example, through what mechanism/s does it affect strength enhancement?” The rubric was designed to gain an overview of the general state of student understanding of nanomaterials at the nanoscale and their relevance in the context of cement mortar. Scores of Poor, Good, and Excellent were assigned using an expert-based correct response as the standard for excellence.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1 – Poor</th>
<th>2 – Good</th>
<th>3 – Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Does the response offer a rationale?</td>
<td>Offers no rationale</td>
<td>Offers limited or shallow rationale</td>
<td>Offers in-depth rationale</td>
</tr>
<tr>
<td>Does the response provide sufficient information/fully answer the question?</td>
<td>Offers no or few parameters/questions, does not consider driving question</td>
<td>Offers some parameters, may pose questions about behaviors, may offer irrelevant information</td>
<td>Offers relevant information/parameters that are sufficient to answer the driving question</td>
</tr>
<tr>
<td>Does the response attempt to connect parameters to demonstrate how they affect answers the driving question?</td>
<td>Does not attempt to connect parameters</td>
<td>Makes some attempt to connect parameters, may make irrelevant connections</td>
<td>Connects parameters and offers in-depth demonstration of how these affect each other and the driving question</td>
</tr>
</tbody>
</table>

Table 4. Rubric for Evaluation of Written Responses to Question 2.

Results and Discussion

In Phase 1, the initial rubric was applied to generate overall scores for each illustration based on a 3x3 matrix of three categories and three ratings, as shown in Table 1. An overall poor schematic would score 3, and an overall excellent schematic would score 9. Theoretically, scores are on a scale of 0-9, since a score of zero can be assigned if schematics are missing or unrelated to the prompt. In this evaluation, scores ranged from 3-8. To determine an overall improvement score for each student, scores from the first activity were subtracted from the scores of the third and final activity. Table 5 summarizes these overall improvement scores, which range from −2 to +4, for the entire class.
While 46.9% of students failed to improve their scores, the overall positive improvement score for the class suggests some evidence of learning processes occurring during the activities. It is important to note that an average improvement of 0.94 points, on a scale of 0-9, translates to an equivalent improvement of an entire letter grade on a traditional academic grading scale (an improvement of 10.4 points on a 100-point scale).

After the initial rubric (Table 1) was redesigned to specifically evaluate elements and scale using two separate rubrics for elements (Table 2) and scale (Table 3), it was found that the sum of improvement scores for the two separate elements decreased, as highlighted in Table 6. Even though each one of the two rubrics is based on a 2x4 matrix, with a maximum of 8 points rather than 9, the range of possible scores (2-8) is the same as that for the initial rubric (3-9). Thus, the improvement scores from the initial rubric can be compared directly to each one of the rubrics in the second evaluation. The combined average of 23.0, while less than the sum of 30.0 in Table 5, still shows an overall positive improvement. Also, fewer students (37.6%) showed neutral or negative improvement, a decrease of 9.3% from the initial rubric. Students showed more improvement in identifying and labeling elements than in developing an accurate recognition of the nanoscale, with overall improvements of 9.8 and 6.2 points, respectively, on an equivalent scale of 100 points.

### Table 5. Results of Initial Schematic Evaluations.

<table>
<thead>
<tr>
<th></th>
<th>Sum of all improvement scores</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Negative improvement scores, percent</th>
<th>Neutral improvement scores, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1, initial rubric (Table 1)</td>
<td>30.0</td>
<td>0.94</td>
<td>1.64</td>
<td>15.6%</td>
<td>31.3%</td>
</tr>
</tbody>
</table>

### Table 6. Results of Second Schematic Evaluations.

<table>
<thead>
<tr>
<th></th>
<th>Elements Rubric (Table 2)</th>
<th>Scale Rubric (Table 3)</th>
<th>Combined Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of all improvement scores</td>
<td>28.0</td>
<td>18.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Mean</td>
<td>0.88</td>
<td>0.56</td>
<td>0.72</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.08</td>
<td>1.54</td>
<td>1.31</td>
</tr>
<tr>
<td>Negative improvement scores, percent</td>
<td>12.5%</td>
<td>18.8%</td>
<td>15.7%</td>
</tr>
<tr>
<td>Neutral improvement scores, percent</td>
<td>21.9%</td>
<td>21.9%</td>
<td>21.9%</td>
</tr>
</tbody>
</table>
In Phase 2, the first question posed to students was the driving question for the entire problem-based learning sequence. The driving question is, “What is the amount, using wt% as units (i.e. percent by weight of cement), of multiwalled carbon nanotubes (MWCNTs) needed to attain at least a 20% increase in compressive strength in Type I cement mortar?” Values given ranged from 0.0001 to 11 wt% for individual student responses. After each student completes an independent worksheet, teams of students collaborate to complete the same worksheet. Values for the team responses ranged from 0.05 to 2.54 wt%. Since the range decreased by 77% from the individual responses to the team responses, it seems that individual responses on the upper and lower extremes were discredited within the group discussion. None of the recommended values, in wt%, were unreasonably large, suggesting that students had some conception of nanotubes as being much smaller and stronger compared to other elements present in the cement mortar. Interestingly, four of the eight groups selected an answer for the team worksheet that was the same as one of their group member’s answers on the individual worksheet. The other four groups seemed to reach a consensus amongst themselves, but with different approaches. Two groups calculated an original value during the team exercise; one other group responded with a group consensus guess, rather than one supported with calculations. The fourth group answer was based on choosing a value that most of the team members had answered with on their individual worksheets. With just two groups providing calculations to support their answer, it is assumed that the vast majority (6 of 8 groups) chose an answer that seemed “good enough” or was convincingly proposed and defended by an individual student.

The remaining three questions on the worksheet for the first and second activities were designed to encourage critical thinking about the considerations required to answer the driving question, and ultimately, lead students to an educated estimate. Question 2, posed after students were asked to provide a sketch in Question 1, asked “What information do you think you need to know to answer the driving question? List all of the factors and/or variables that are needed and identify which ones are the most important. For each factor/variable listed, offer a rationale for why it is needed. For example, through which mechanism/s does it affect strength enhancement?” First, the format in which students gave their responses was evaluated. As shown in Figure 2, the majority of responses include both bulleted lists of parameters and questions or comments about the properties, behaviors, and interactions of certain parameters. Bulleted lists were the most common response format. Only 7% of total responses posed questions about properties and interactions as the sole response mechanism. Exceptions include a response that was phrased in two paragraphs, and a response containing a bulleted list consisting of categories of properties. These two exceptions represent specific examples of deeper thinking about how these parameters are affected by processes and interactions. Students were also tasked in the question to provide a rationale for each piece of given information and rank them in order of importance. Only 35% of individual responses and 38% of team responses were numbered or ranked according to importance. More surprising was that only 37% of team responses offered an explanation for their parameters compared to 94% of individual responses. These data suggest that students may have relied on their explanations from the individual worksheets to support their choices during group discussion, but did not reiterate those rationales on the team worksheet once the group was in agreement.
The rubric presented in Table 4 was used to qualitatively evaluate responses to Question 2. Criteria were laid out to rank responses as Poor, Good, or Excellent in three categories. The average ranking was then assigned to each response. The distributions of each average ranking for the individual and team responses are presented in Figure 3. High quality responses were considered to be those that listed relative parameters, offered a reasonable rationale for said parameters, and made an attempt to think critically about the influence of each parameter. The quality of responses decreased by 13% from individual to team responses, partly due to the lack of rationale given in team responses. As mentioned above, rationales may not have been forefront in students’ minds when completing the team worksheet, since almost all students (94%, see above) had included written justifications for their individual answers.
To achieve a reasonable answer to the driving question, one must account for just a few technical parameters. Yet a large volume of unique responses, much of it irrelevant, was evident during the evaluation of Question 2. This response behavior suggests that students lack the critical thinking skills, in concert with insufficient knowledge, to distinguish between relevant and irrelevant factors. In other words, students did not feel capable or confident enough to decide what not to write in their response. In these cases, it appears that students produced a list of all seemingly related factors to make the impression of deep thinking, when in fact it is more representative of shallow thinking. Some of the more common but irrelevant factors were associated with nuclear waste, climate and natural disasters, and material costs. In reality, these factors are unlikely to produce an effect on the strength of the cement mortar. The occurrence of these factors often persisted into the team responses.

One of the main objectives of these activities was to expose students to the size and scale of nanomaterials and how these sizes relate to more familiar materials, such as cement. Not surprisingly, a notable misconception is the true size of multiwalled carbon nanotubes. An example of this was observed in one particular schematic, in which this student visualized that a single nanotube plugs into the pore spaces between cement particles. In other words, this student depicted the pores between cement particles to be the same size as the width of the nanotubes, which were labeled as 1 nm wide. In fact, a nanotube is one to three orders of magnitude smaller than the size of these voids. Interestingly, this misconception of scale persisted in this student’s team response, which also provided the highest answer among team responses to the driving question, 2.54 wt%.

Each unique factor given in response to Question 2 was recorded, and the number of occurrences per factor was assessed. Sixty-nine unique factors were provided in response to this question, but many terms occurred just once or twice. Therefore, word clouds were created to provide a visual representation of these responses. Each word cloud shows the top 40 most frequent words offered in response to Question 2, excluding common English words, such as “the” or “and”, that occurred at least three times. Word clouds for all responses to Question 2 are presented in Figure 4(a) through Figure 4(c).

Based on the phrasing of the question, it was anticipated that words such as “strength” and “nanotubes” would appear with the highest frequencies. However, it is of interest to note that some words associated with cement mortar had higher usage rates, like “aggregate”, “density”, “pore/s” and “water”. These particular terms are significant because all four are relevant to the solution, but are not identified in the problem statement or worksheet prompts. Thus, student recognition of these concepts indicates some level of knowledge, and perhaps critical thinking, about what is needed to solve the problem. However, it can also be seen that few, if any, terms present in the word clouds are specific to nanomaterials, other than those words that were included on the worksheet, like “MWCNT”.
Figure 4(a). Word Cloud for Question 2 Overall Responses.

Figure 4(b). Word Cloud for Question 2 Individual Responses.

Figure 4(c). Word Cloud for Question 2 Team Responses.
Conclusions, Recommendations, and Future Work

One of the main objectives of Phase 1 of this project is to answer the question, How does exposure to, and subsequent learning of, new information manifest itself through student performance on questions requiring schematic responses? This requires the researcher to make a decision regarding whether to measure student performance, or student learning and academic growth. This is a complicated decision. Can it be reasonably assumed that improved student performance is equal to learning? If not, how can we detect and quantifiably measure learning and academic growth? Therefore, an assumption needs to be made in order to extract value from the data presented here.

For this project, it is assumed that improved student performance after exposure to new material indicates at least the presence of learning and academic growth. That is, students needed to absorb and apply this new information in order to give responses that increased in quality. This is, of course, not suggesting that those students who did not show improvement did not learn during the activities. It is impossible to attribute the decrease in student performance to a singular factor, but group dynamics and the design of the activities themselves may have influenced them. Considering these assumptions, rubrics were utilized to uniformly measure the change in student performance, and showed that as a class, students made encouraging progress and demonstrated some evidence of learning, equated to an approximate average of 8 points on a 100-point scale.

Although the results show that the activities brought an increase in student performance equivalent to 8-10 points, depending on the depth of evaluation, better design of the active learning environments may result in even greater increases in student performance and understanding. For example, instructing students to repeat the same worksheet from one week to the next may cause some detrimental effects on performance because of negative student attitudes. Students, not understanding the need for repetition, may put more effort into the first iteration than the second. It is possible that such behavior accounts, at least in part, for the drop in student performance as noted in the overall improvement results from the Phase 1 sketches. It is recommended that the order of activities and prompts be redesigned to facilitate student corrections and connections, rather than simple repetitions, of worksheet responses. This approach could also help students highlight their own learning.

It is also recommended that the activities be modified to encourage more academic growth in understanding the nanoscale. This was a main focus, yet it showed the least improvement in the schematic responses, indicating widespread misconception of the size of nanoparticles even after the introduction of new material. Suggestions include (1) prompting students to relate the nanoscale to a different, but more familiar, scale while equating one or more elements of the schematics to more routine objects for comparison; (2) prompting students to include the orders of magnitude between different elements in their schematics; and/or (3) requiring students to correct their responses after acquiring each new piece of information.

In regard to Phase 2 of the project, the impacts of team interactions should be further examined. One suggestion is to insert a third step between the individual and team activities, where students are paired prior to working in a larger team. This could be accomplished with simple active
learning strategies, such as the think-pair-share method. Or, a more elaborate scheme can be
developed using hands-on experiments designed such that each one of two student pairs learn
something unique, which then must be shared when the pairs form a four-person team. This
technique of pairing students can help pinpoint how specific group interactions impact responses.
Soliciting direct feedback from student groups could also be considered in evaluating team
dynamics, such as requiring students to describe the process of choosing their combined
responses.

As this is an ongoing project, the next phases will comprise the following activities.

- Tracking the evolution of responses across both sessions to evaluate depth of student
thinking by: (a) comparing individual responses from Session I, team responses from Session
I, and individual responses from Session II, to see how responses changed between each
iteration of the active learning exercises; and (b) comparing student responses during each
iteration to the information presented before each exercise (e.g., instructional videos,
research presentation) to see how much and what kind of new information was retained and
utilized.
- Categorizing thinking patterns in individual and group settings by: (a) identifying possible
factors affecting student thinking and patterns evident in team and individual responses; and
(b) developing possible indicators of critical thinking in written responses.
- Evaluating student performance based upon written responses by: (a) defining performance
measures to recognize levels of critical thinking from written responses; and (b) drawing
conclusions on the effectiveness of problem-based, active learning in the classroom and the
feasibility of evaluating critical thinking from written responses.

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