Infrastructure Materials
An Inquiry-Based Design Sequence

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Infrastructure materials are among the most used material on earth with concrete being used more than any other except water. Annually, over one ton of concrete is used per person on earth. The *Infrastructure Materials* module introduces students to the design of concrete materials and design with concrete materials for use in infrastructure applications: roads, bridges, buildings, dams, waterways, airport pavements, etc. The module includes a sequence of activities which enables students to discover factors critical to understanding how to design concrete and how to design with concrete. It guides students developing the realization that concrete is not a simple homogeneous material which is purchased in a sack at the hardware store, but rather a complex heterogeneous class of material with a wide range of design diversity. The activities include: a concrete hunt in which students try to identify objects which are made of concrete and the reasons why concrete was used for that application, an exploration activity which give students a chance to discover what concrete is made of and what the apparent characteristics of the material are, an activity in which students make concrete and discover that concrete gets hard because of a chemical reaction and concomitant physical changes, an introduction to fracture processes and concepts of brittle failure and reinforcing mechanics and finally a design activity which inspires the students to design, build, test and redesign a product and apply the principles of chemistry, physics and mathematics, which they explored in preceding activities. These and other activities have been modeled and field-tested in outreach programs by the Center for Advanced Cement-Based Materials (ACBM) at Northwestern University and at schools with teachers and students ranging from middle school to high school age. Infrastructure Materials is part of a larger National Science Foundation-funded program called Materials World Modules (MWM). MWM is a series of modules which introduce students to important contemporary topics in materials science. Each module is a sequence of self-contained activities which provide students with the background necessary for them to engage in inquiry through design.

Background

We are in the midst of major changes in both pre-college (K-12) and college level education. It is becoming increasingly evident that the traditional approach to teaching —wherein a teacher provides a set of stimuli and reinforcements in an effort to elicit desired responses from students— is unsuccessful in fostering understanding, synthesis, eventual application of knowledge and the ability to use information, Trowbridge and Bybee[2]. As an alternative, Trowbridge and Bybee[2] suggest an inquiry-based approach which encourages student input of creative ideas, uses alternative sources of information, uses open-ended questions, encourages students to suggest causes for events through prediction, testing of one's ideas before acceptance, challenging of the ideas of others, collecting evidence to support one's ideas and restructuring one's concepts on the basis of new evidence. The National Research Council has provided a set of standards for K-12 science education called the National Science Education Standards[3]. Among the goals set in these standards are science taught through inquiry. At the same time, Pauschke and Ingraffea[4] report that recent innovations in undergraduate education indicate trends such as emphasis on design, multidisciplinary approaches, team dynamics, hands-on design and analysis experiences, communication skills and tying theory to practice. In developing activities for our students at any level, we must strive to integrate relevant experiences which result in enduring frameworks upon which individuals can better relate to the world around them.

Infrastructure Materials[5] is an inquiry-based design sequence for high school students. The activities have been developed as part of a large-scale program called Materials World Modules (MWM) which is funded by the National Science Foundation (NSF). Under the direction of the Materials Research Center at Northwestern University, the MWM team is developing ten self-contained modules designed with the following goals consistent with the National Science Education Standards:

- Develop in students the abilities necessary to do scientific inquiry including the ability to generate questions, design and conduct scientific investigations, formulate models, analyze alternative models and communicate and defend explanations.
- Help students to understand that scientific inquiry is focused on logically consistent explanations, grounded in current knowledge and augmented by mathematics and technology.
- Provide opportunities for students to participate in iterative design wherein they identify technological problems, propose designs, choose between alternative solutions, implement and evaluate a solution, redesign the product, and communicate the problem, process and solution.
- Train students to understand the relationship between science and technology.
- Have students address and appreciate the use of science and technology to meet local, national, and global challenges, including problems of personal and community health, natural resources, environmental quality, and human-induced hazards.
- Present the technical content in historical perspective viewing the history and nature of science as a human endeavor, predicting new knowledge, supported by developing technology.

Inquiry-based learning is a process wherein students ask a question, complete an investigation, answer the question and present the results to others. Infrastructure Materials strives to achieve these goals.

It is the intention of this summary to stress the pedagogical methodology as demonstrated through the use of a case study in infrastructure materials. The MWM is a collection of ten such topical modules which include biodegradable materials, ceramics, composites, smart sensors and others which emphasize the inquiry-based approach to teaching on topics in materials science, each of which culminate in a student-directed design activity.

Baumgartner and Reiser[6] have reviewed the research-based pedegogical foundations for the MWM in detail.

Infrastructure Materials

Infrastructure is a vast topic which encompasses many aspects of our society and culture. Infrastructure materials are those materials used in the construction of the underlying foundation of our modern society, the system of roads, bridges, canals, buildings, homes, communication networks, airports, dams, utility systems, railways and much more. The activities which are part of *Infrastructure Materials* focus mainly on concrete materials. Concrete is by far the most widely used construction material and is the second most used material on earth with only water being used in larger quantities.

Activities of the Module

There are ten activities in this module supported by several additional “extension” activities and a mini-encyclopedia (minipedia).

- *Intro Activity*- This activity provides students an opportunity to test some infrastructure materials and to compare some of their qualities. The activity includes a test for impact resistance, compressive strength, abrasion resistance, and fire resistance.
- *Concrete Hunt*- In the hunt, students are asked to find examples of concrete in the structures around them. They learn what things to look for when identifying concrete. They learn the difference between concrete, cement, stone, asphalt, brick, and mortar. They come to understand that concrete is commonly used for four reasons: its strength, durability, formability, and low cost.
- *Cement – A Binder*- In this activity, students get to explore the material that holds concrete together. They mix Portland cement with water, and some rapid hardening cement with water to observe any temperature or consistency changes. It is shown that hardening is a chemical and physical change which results from the reaction between cement and water.
- *Cement - Changing the Rate of Setting*- Through discussion and a process of guided conceptual modeling, students should come to the realization that both salt and sugar somehow interfere with the hydration process altering the course of reaction.
- *Explore Making Concrete - Observations*- In this activity, students observe concrete on many levels. First, they look at a sample under a magnifying glass to identify the key components. Then, students see, and measure using a balance, the effect of mixing aggregate sizes to decrease the size of flaws in a concrete sample.
- *Explore Making Concrete - Mixing and Testing*- This is the first activity where students combine their knowledge of the ingredients of concrete, the process by which it hardens, and the ways to make it strong. They will use all the ingredients of concrete to make a sample of their own design, and another that is assigned to them. They will begin to think about how the ingredients can work together to make strong concrete.

- *Tension and Compression*- Through exploration with bending and breaking many brittle materials, students discover that concrete, like other brittle materials, is strong in compression and weak in tension.
- *Reinforced Concrete*- Here, students use their knowledge of the best concrete, and begin to add other ingredients to it to reinforce it. They discover that they can change the properties of concrete just by adding one new ingredient.
- *Fibrous Mortar*- Here students reinforce concrete using a specific kind of fiber. Students can also control the process by which they make their samples.
- *Teacher Directed Design Project*- The module culminates with a design project. Some teachers choose to give the design task. In this activity, the students are instructed to research, design, and manufacture a concrete tile which can be reinforced.
- *Student Directed Design Project*- Some teachers prefer to let their students decide on the application for which they will design their concrete. Student design projects have included foundations for buildings, garden blocks, driveways, and paperweights.

Each activity is designed around inquiry-based learning objectives and so each begins and ends with questions. Questions are used to help students get started with the activity, focus their thinking, and stimulate them to think of and pose their own questions. The module is organized so that students discover basic information through guided inquiry. This is facilitated by activities which emphasize observation and exploration through experimentation. Once the students have acquired a basic background through such activities they are then encouraged to design their own product. Some classes use a teacher-directed design project and some use a student-directed design project. In each case, the design project allows students to synthesize the knowledge, skills, and experience they have gained over the course of the module. The design project is critical to the learning process because students learn from their own questions and are encouraged to redesign after they have tested their first design.

Goals of the Module

The Infrastructure Materials module proposes two sets of goals for students. The first is a set of content objectives which students can learn by doing the included activities. These objectives are:

- cement as a binder which holds aggregate together in concrete
- aggregate and particle packing
- the effect of water on concrete strength
- chemical and physical changes which occur during curing of concrete
- the differences between brittle and ductile materials
- the way brittle materials fail
- the effect of reinforcing materials in concrete and types of reinforcement

The module also proposes to teach process skills which students can use to help in decision-making throughout their lives. These process skills are:

- generating questions for investigation
- thinking clearly and logically about scientific or technical data and information
- performing scientific experimentation

- collaboration among researchers
- self-reliance
- responsibility for own learning
- communication of learning to peers and superiors

Teaching Strategies of the Module

The module uses the following strategies:

- Development of design skills and methodologies through guided inquiry
- Motivational activities with ties to the outside-world
- Learning through observation.
- Predicting the outcome of an observation or experiment before the activity is undertaken.
- Exploration and development of basic knowledge through experimentation.
- Conducting an open-ended student directed design project.

Each activity in the module contains similar aspects when used successfully in the classroom. The activities toward the beginning of the module tend to be more directed, and the ones at the end, more open-ended. However, all the activities use each of the strategies above.

<u>Inquiry</u>
Each activity is designed to have students discover through guided inquiry those key elements about concrete which they will need to know to apply to their design projects. The approach used challenges the students to think about questions posed in the module and generate their own questions about their surroundings. Questioning strategies used in the module include helping students to identify the objectives of an activity, aiding in the synthesis of knowledge gained in each activity to the larger set of information in the whole module, applying the knowledge and skills gained in each activity to the next activity and to the students' lives outside the classroom, and facilitating students generating their own questions for observation and experimentation.

Students become aware of the content objectives of the module and their progress in meeting those objectives through the questions in each activity. For example, in *Cement-A Binder,* students are asked, "*What are the physical properties of cement?"* and *"Is the process by which cement hardens a chemical process or a physical process?"* Another example is from *Explore Making Concrete - Mixing and Testing,* when the students are asked, "*What are the components of concrete?", "What makes concrete strong?"* and *"What makes concrete weak?"* These questions relate directly to the activity the student is performing, and also directly to the content objectives of the module.

Through questions, students also begin to synthesize the knowledge they learned from the previous activities. For example, in *Tension and Compression*, students are asked, "*How would you test the strength of concrete?", "Where does concrete break when it does?"* and *"Are there brittle materials that are strong?"* To answer these questions, students must refer back to the *Concrete Hunt* and *Explore Making Concrete-Observations*. In the hunt, they saw that concrete was used in applications such as buildings and columns. Now, they can start to see that these are compressive applications, and that is where concrete is most strong. In *Explore Making Concrete*, the students observed that there are lots of tiny holes in concrete, and they start to see that these holes, or flaws are what make concrete weak in tension. By making students aware that they are building on knowledge gained throughout the module, students start to take responsibilty for their own learning.

The third questioning strategy is to apply knowledge and skills students learn in the module to life outside the classroom. For example, in *Cement-Changing the Rate of Setting*, students are asked, "*What happens to cement as it hardens?*" and *"Do you think there may be ways to alter the way cement hardens?"* In this activity, students relate what they are learning to other topics they may have studied in science classes before. Chemistry students can relate the rate of reaction in concrete to reaction rate studies they have done previously. Other students can relate this activity to studies of physical and chemical changes. When students see how the learning in this module is related to other courses of study, or to other parts of their lives, the experience becomes more real to them.

In the last questioning strategy, students are encouraged to generate their own questions. The most clear example of this is in the design activities. In both the teacher and student directed design activity, students choose their own materials, and how to use those materials. In making these choices, students see that they are capable of making informed decisions about technical data. In asking their own questions, students are aware of their own learning, and they begin to meet all of the process and content goals for the module. The process of responding to questions, and asking questions is critical for the success of the module in the classroom.

<u>Motivating the Subject</u>

Infrastructure may at first seem to students to be a dull and somewhat drab topic. Many will not even know what infrastructure means. Motivating the student early in each activity is key to getting them involved in the topic.

In the first activity, students are helped to discover what they already know about infrastructure. This makes the whole module seem more inviting and motivates the learning. Often times in science the student knows more than they think they know, however, have simply never heard those things discussed in the context of science. Students are lead to realize that infrastructure is the physical constructs of our society, the roadways, rail systems, bridges, dams, waterways, airports communication networks, buildings, homes and much more. They come to realize that infrastructure is an enormous topic of profound significance and that the materials used to construct infrastructure are many and diverse.

Motivation by connecting the students' learning to the rest of their lives happens also later in the module. For example, in the activity, *Tension and Compression* students compare concrete to other materials they know. They break and bend familiar materials like chalk, toothpicks, and paper trying to see how they are like or unlike concrete. By using familiar materials that the students already know, they see that they can connect their learning in this module to what they already know.

Finally, in the design activities, students are asked to actually construct a concrete sample which can be used in application, or a prototype of one. This helps students to see the applications of their work.

Observation

Each activity uses observation skills. For example, in *Concrete Hunt* students are asked to walk around their school campus or are taken on a field trip around town or are assigned the activity for homework. While on their hunt they are asked to identify items made of concrete, to list the function of the object, and to state why they think that concrete was used in that application. After a brief introduction to infrastructure, the activity begins by challenging the students with some questions:

What makes something concrete, rather than brick, asphalt, or stone?
Why are some things made from concrete instead of from some other material?
What are the functions of the infrastructure of our society?

The objective is to get the students thinking and to present them with questions which will make them look closely to observe differences and similarities in the materials which on every other day they would otherwise, literally, walk right over.

Predictions

A hallmark of this series of modules is the repeated use of predictions. People in our ever-more-technology-based society must learn to predict what they expect to see, then test and compare reality with prediction. Here are some of the things students are asked to predict before the *Concrete Hunt*:

What kinds of things do you think are made out of concrete?
Where might these objects be found around your home or school?
Why would you choose to build something out of concrete?

Students find that concrete is indeed different from other infrastructure materials. Concrete is everywhere, it is used to carry loads, it is used where durability and abrasion resistance is important, it is used to bond other materials together and it comes in many shapes. In short, students discover that concrete is strong, durable, inexpensive and formable.

In the series of activities which follow, students are repeatedly challenged through questions and are directed to make predictions. Another example of students making predictions occurs in *Explore Making Concrete-Mixing and Testing.* Students make concrete of different water to cement ratios. As the samples are curing, the students are asked to predict which samples will be the strongest, most durable, and easiest to break. Predictions in this module call on students to use what knowledge they already have. For learning to occur, students must see explicitly how the new information and skills fit in with what they already know. Predictions are one way that the module encourages students to see what they already know, and then, after the observations are gathered, see whether they were correct in their predictions. If not, then it is easy for them to see that they have learned something they did not know already, but did have some previous experience with.

Experimentation

From the activities leading into the teacher-directed design project and the student-directed design project, students learn through experimentation about the properties of concrete. Although some activities are more structured, the instructions are not a cookbook of what to use or how to conduct the experiment. Students need to formulate and conceptualize how to conduct an experiment which will yield the knowledge they need to answer the question which they have been asked and/or which they have asked.

An example procedure from *Reinforced Concrete* follows:

- *Choose a material to use for reinforcement for your concrete. Think carefully about how you will use this material. Mix some concrete, and set it to cure using the reinforcing material that you select. Record all your steps and your observations.*
- *Be sure to cast samples of your concrete without reinforcement to use as a control.*
- *When samples are cured to your satisfaction, you may test them. You may choose to test them as done in previous activities or to devise a different test.*
- *Compare your results with those of the rest of the class.*
- *Do not forget to make predictions.*

Note here that the students are guided in the steps of the activity but are not specifically told either what materials to use or exactly how to use them. By this point in the module, students have already mixed and worked with concrete and cement. Students no longer need to be told to add 40 grams of water for every 100 grams of cement. Through the process of guided inquiry the students begin to develop knowledge and experience about how to explore open-ended questions. They should begin to expect that they themselves will establish not only the experimental parameters for making their samples but also the parameters by which the samples will be tested. In this way, real-world scientific inquiry and design is being practiced rather than following step-by-step instructions without forethought to why they are doing what they are doing.

In the real world, scientists and engineers face open ended problems on a daily basis. For that matter, this concept extends beyond laboratory science and into daily life. To be sure, following instructions plays an important role in learning. The rather loose looking set of procedural guidelines given here, however, provide not only a very well defined set of instructions to be followed but also creates possibilities for students to direct their own inquiry and think through the design process.

Students gain a clearer understanding of the materials with which they are working while they experiment. The module encourages controlled experimentation, where students have one variable and a control for each experiment. For example, in the acitivity *Reinforced Concrete* students from different groups make concrete samples with a specific reinforcement. One group makes concrete with no reinforcement. All groups use the same mix for their concrete, so that the results can be compared across the class. By experimenting with different reinforcements, students can see the purpose of reinforcement in general and the relative benefits or drawbacks of each reinforcement tested.

Through experimentation, students also learn about the process of informed decision-making. For example, in the student directed design project, students choose their materials with which to design. Once the materials are chosen, students choose how to use each. In this process of choice, students are encouraged to try different things, varying only one thing at a time. This technique allows them to see causal relationships between the ingredients and methods they employ. In performing these choices and tasks, students begin to understand a way of making informed choices, which can be broadened to making informed choices about other aspects of their life.

Design

Student design is incorporated into all the activities in the module. At the beginning, students are asked to design ways to test materials in the *Introductory Activity*. Students are encouraged to design a mix for concrete in the *Explore Making Concrete-Mixing and Testing* activity. In *Reinforced Concrete* and *Fibrous Mortar*, students design the way their reinforcement will be set into the concrete, and the way it will cure.

The two design projects at the end of the module provide an opportunity for students to experience the design process from start to finish. In the teacher directed design activity a scenario is created in which students play the role of an applications engineer in a company. They receive some information from the company's market research group concerning tile products and a set of guidelines for formulating what is called a *high-performance tile material* from the research department. Their job is to develop a product which targets one or more of the tile markets. The following is an excerpt from the teacher-directed project:

> ***The Design Challenge - Scenario***
>
> *You are an applications engineer and you have just been given an exciting new materials system with which to work. The system allows you to make formulations of concrete using various ingredients including fibers and other reinforcements to produce high-performance concrete for production of tiles. The research team tells you that you can make tiles from Portland cement and the following ingredients in the general proportions shown below. The properties of the material may be modified depending on the formulation and, hence, targeted for specific applications. Your company's Marketing Research Department has already explored several potential commercial applications and has provided you with the following report. The cost of materials is also available from the Marketing group. Your boss has just asked you to take charge of the development project. You are to identify a product, develop the materials, produce prototypes, test the product for your application and convince the Marketing Department that your product can compete commercially. You are expected to do a rigorous review of the tile market. Consider other tile products as well including tiles for bathrooms, exterior facades and interior wall coverings as well as others you may think.*

This project immerses the students in a simulation of a real-world situation. They must research the market, consider the limitations of the materials they have to work with, design a development plan, design the test methods, produce samples and full-scale prototypes communicate the results to others and convince their peers that their product is viable.

The student directed design project is similar, however; students are given more latitude to select a product to be made of concrete. They are not restricted to a tile product or formulation guidelines. Teachers may choose to do one or both of these activities as part of the sequence.

A key element of the design project is *Redesign*. Real-world product design is almost never complete after the first prototypes are built. Revision and iteration is a method whereby knowledge is gained which leads to a vision for further improvement. After the first set of prototypes have been analyzed students are instructed to evaluate the information, compare their results with data from others to recommend improvements in their process and to produce another set of prototypes.

Following any design activity, whether it is in the design project or an earlier activity, students encounter *Reflection* questions which stretch the limits of their knowledge and challenge them to think about what they did. For example, in *Reinforced Concrete*, students are asked, *"Do you think that reinforcing the concrete will affect its ability to remain strong and durable over time?","Have your ideas changed about how to reinforce a concrete beam?"* and *"Can you think of another material or technique that you would use to improve your original design?"* In answering these questions, the student begins to make connections with other topics which are of consideration. This trains the student to think beyond the obvious, to consider many aspects and to make linkages with the bigger picture.

These teaching strategies are fundamental to the implementation of the Infrastructure Materials module in any classroom. In order for students to learn about engineering, in this case infrastructure engineering, students must do some of the engineering themselves. It is not enough to read about it in a book. The students must be actively engaged in questions, in observation, in prediction, in experimentation, and in design. The purpose of this module is not to prepare future engineers and scientists only. All people in our society need to have these skills to function in and around technology. In making informed decisions about issues from nuclear power to building a house, all citizens must be able to interpret and reason clearly about data. This module is one step toward that end.

Notes on Collaboration Between Students

Throughout the course of study students are encouraged to collaborate on projects. Interaction between teams is also encouraged. In this environment, no team of students will likely be working on exactly the same problem or will likely take the same approach to a given problem. Students are directed to consider ways to utilize the collective information to create a larger, more in-depth picture of the whole. Through communicating results between students by oral and written work, students will begin to learn from others and, hopefully, assimilate the progress of their colleagues into their research, much in the way that scientists do in academia and industry.

Notes on Assessment

The inquiry-based approach presented here can create some problems in assessment. Teachers will not be able to simply go down a list of responses from students and mark off correct and incorrect answers to canned questions. It will require more input from teachers to review the students written and oral presentations looking for the elements of scientific inquiry in the students work: ability to generate questions, design and conduct scientific investigations, formulate models, analyze alternatives and communicate and defend results. Several suggestions, paraphrased from MWM literature[7], for assessment follow:

Inquiry-based assessment: Seek to discover if the student can explain their results, right or wrong, and discuss the process by which they arrived at those results.

Traditional assessment: Have the students write traditional laboratory reports for each activity and evaluate them for format, clarity, accuracy, inclusiveness, etc.

Self assessment: Give students guidance to set their own goals. From time-to-time, review progress against these goals. At the end of the project assist the student in evaluating their own success at achieving set goals.

Science process skills: Evaluate students through observation seeking to assess for the following science process skills: observing, communicating, measuring, classifying, making and using models, recognizing space or time relationships, collecting and interpreting data, inferring, predicting, identifying and controlling variables, formulation of equations and hypotheses, and making operational definitions.

Portfolio assessment: All students should be maintaining detailed logs of their work. This can be used as a portfolio of their activities through which teachers can assess progress and skill competencies.

Notes on Module Development

The Infrastructure Materials module has been developed over a period of two years involving engineering researchers at Northwestern, education researchers at Northwestern, and high school teachers. This development team wrote the activities based on engineering knowledge and practice, and on available materials and expertise at middle schools and high schools. One of the unique parts of the development team is the inclusion of people from so many different areas. The education researchers were able to lend a great deal to the educational philosophy presented in the modules; the engineers were able to provide vast amounts of technical resources; the high school teachers were able to provide an idea for what was realistic in a high school. The module is currently in the publication process.

The module has been extensively tested by seven teachers and more than 300 high school students. It was instructive for the development team to see what the testing teachers needed more information on, and what they were able to fit into their existing curriculum. Most teachers chose to use the activities in one hour blocks every day for about two weeks. This allowed them to do about five of the activities leading up to the design activities. The activities were revised to reflect input from the teachers at pilot sites and the responses of students to the activities.

Summary

The design projects are self-contained inquiry-based activities. By the end of the sequence students have experienced and hopefully learned key skills used in both scientific inquiry and design engineering. The sequence focuses on observation, experimentation and design. In these activities, students must conceptualize the problem, ask questions, focus on a goal, design experiments, collect and analyze the information and communicate the results to others.

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