CONCRETE WITHOUT QUARRIES

A BIOMIMICRY LESSON PLAN | High School
General Science and Chemistry
“The core idea is that nature, imaginative by necessity, has already solved many of the problems we are grappling with. Animals, plants, and microbes are the consummate engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth... The conscious emulation of life’s genius is a survival strategy for the human race, a path to a sustainable future. The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.”

- Janine Benyus,

*Biomimicry: Innovation Inspired by Nature*
CONCRETE WITHOUT QUARRIES

Sam Stier, Dona Boggs, and Dave Jones

Introduction

Biomimicry is an innovation method that seeks solutions to humankind’s various sustainability challenges by applying principles underlying nature’s time-tested strategies (Benyus 1997). Modern day manufacturing, for example, presents myriad challenges to environmental sustainability. Materials mined from the earth, processed using fossil fuels and hazardous chemicals, and resulting in pollutants discharged into the environment characterize our species’ dominant manufacturing paradigm. Concrete provides an illustrative case: cement used in concrete is manufactured by extracting calcium carbonate from open-pit mines, cooking the material at 2642 degrees Fahrenheit (1400 degrees Celsius), and discharging approximately 6% of humanity’s annual greenhouse gas emissions into the atmosphere.

In this science lesson plan for high school students, students learn that the prevailing manufacturing model on planet Earth—practiced by millions of other species—is one in which raw materials for manufacturing are actually acquired benignly from the environment. By emulating a physiological process used by corals to create calcium carbonate out of seawater and carbon dioxide, young people experience first-hand a cutting-edge biomimetic technology with the promise of transforming conventional concrete manufacturing into a more sustainable industry. Moreover, students learn that there is a universe of biological models around us to serve as inspiration for sustainable chemistry methods and other kinds of innovation. The lab is safe, meets national and state educational standards, can be conducted within one to two 50-minute periods without specialized scientific knowledge or equipment, and uses materials that cost less than $50 to obtain.
GRADE LEVEL | 10th – 12th

AREA | Chemistry

DURATION | Approximately one to two 50-minute sessions, longer if desired

MATERIALS |

• A source of carbon dioxide, such as dry ice (100% CO₂). Many grocery stores carry dry ice. Cost: ~$3.00 (enough for 5 groups of 4 students each).

• A source of seawater or a seawater analog. Actual seawater can be used, if available. Alternatively, a seawater mix found at any pet store for aquariums can be used. Cost: ~$4.00 (enough for 5 groups of 4 students each). A solution of calcium chloride will also work well.

• Aquarium bubbler (optional but recommended), which can be found at any pet store for aquariums. Cost: ~$0.57 each (http://bit.ly/RAYX7y); total $3.00 (to supply 5 groups of 4 students each).

• A source of sodium hydroxide (NaOH), such as household 100% lye drain opener, which can be found in grocery or hardware stores. Cost: ~ $4.00 (enough for 5 groups of 4 students each).

• Glass containers, rubber tubing, and connectors. These can be chemistry lab grade or recycled glass food jars. Rubber tubing can be found at any chemistry supply outlet (e.g., http://bit.ly/13ajSlq). Tubing cost: ~$1.30 for 2 feet; total $7.00 (to supply 5 groups of 4 students each).

• Filter paper, which can be ordered online (e.g., at Amazon.com). Cost: ~$1.99 (enough for 5 groups of 4 students each).

• Small bag of cement (e.g., Quikrete). Cost ~$8.00 (enough for 5 groups of 4 students each).

• Vinegar (optional). Cost: ~$3.00 (enough for 5 groups of 4 students each).

SAFETY |

Dry ice, cement, and sodium hydroxide should be handled with a skin barrier (e.g., gloves). Sodium hydroxide is caustic; avoid skin or eye contact or inhalation of vapors.
Main Lesson Plan Goals and Objectives

This activity addresses the following key educational themes:

1 | Conventional manufacturing methods used by humans generally start with the extraction of raw materials from the environment, using processes that result in some degree of environmental damage. These processes over time have resulted in large-scale damage to the earth’s living systems and, given the earth’s inherent limits, cannot continue indefinitely.

2 | Harm to the environment is not a necessary consequence of raw material extraction; the prevailing manufacturing model on Earth, practiced by millions of species, is actually one in which raw materials are acquired benignly.

3 | By emulating manufacturing processes widespread in the rest of the natural world, humans can transform their production methods to be more benign, and even beneficial to the environment of which humans are a part.

Standards

This activity can be used to address chemistry education standards. The list below, which is not exhaustive, is drawn from the current version of Benchmarks for Science Literacy (Standard D: The Structure of Matter), which also incorporates standards from Science for all Americans (1991) and the National Science Education Standards (1996).

- Atoms often join with one another in various combinations of distinct molecules or in repeating three-dimensional crystal patterns.

- An enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

- The rate of reactions among atoms and molecules depends on how often they encounter one another, which is affected by the concentration, pressure, and temperature of the reacting materials.
Procedure

1 | Form the students into small groups (2-4 people) and explain the procedure to them, the materials involved, and safety considerations. Assign tasks to different students within each group, so each student has a tangible role to play in the process.

2 | Use seawater or create a seawater analog mix, either from a seawater mix from a pet store, or by providing students with a pre-mixed solution, or by having them create a solution of 0.1 M CaCl₂ (i.e. 1.47 g in 100 ml). Explain to students that this solution is like the seawater that corals use and contains calcium atoms that will become part of the calcium carbonate (CaCO₃) compound they are creating.

3 | Prepare a 1M solution of NaOH (i.e. 3.99 g in 100 ml). Household lye can serve as a source of NaOH. Students should wear goggles and gloves when handling this material. Explain to students that corals get calcium to bind with carbon and oxygen by controlling the solution in which the atoms are placed, increasing the concentration of some atoms and reducing the concentration of others using special biological pumps. The sodium hydroxide acts to help do this without the special pumps used by corals.

4 | Using gloves, place a piece of dry ice in a glass jar or side arm flask and enclose with a screw-top lid or stopper through which the tubing passes.

5 | Add several drops of the NaOH solution to the seawater solution. While precipitate forms, continue adding NaOH as desired or needed.

6 | Insert tube into the container of seawater solution. White, cloudy precipitate should form immediately, falling slowly to the bottom of the container. To produce enough precipitate, run the reaction for at least 3-5 minutes. During this time, you can review with students the chemical reaction happening, emphasizing that, like corals, they are making something solid and valuable come out of simply a waste gas (CO₂) and an abundant liquid (seawater).

7 | Remove the tubing from the seawater solution and let the solution sit for a few minutes. You will see the solution clearing up at the top as the precipitate falls to the bottom. Have students write their initials on the filter paper, and then slowly pour the solution through the filter paper to collect the precipitate.¹

8 | Place the filter paper on a window ledge to dry overnight, or place in a drying oven (if available) for approximately 20 minutes. Once dry, allow students to rub the powdered calcium carbonate between their fingers.²

¹ Filtration by gravity works fine. Placing the filter paper in a büchner funnel using a vacuum filtration system will also work.

² The product may contain other compounds in addition to CaCO₃, especially depending on the seawater mixture. X-ray crystallography analysis of the product created with this lab procedure using dry ice and a calcium chloride solution yielded 100% CaCO₃.
9 | (Optional) Place a few drops of vinegar on the precipitate to help illustrate to students the presence of carbon dioxide, once sequestered in the calcium carbonate and now returning to the atmosphere.

Humans make glass by mining silicon dioxide and heating it to 1,575°C. This venus flower basket, a deep-sea marine sponge, makes its glass skeleton at ambient ocean temperatures from silicon dioxide filtered out of seawater.

Neissera meningitidis, a bacteria that can cause meningitis, is not an organism people generally appreciate. But this bacteria inspired Dr. Irving DeVoe at McGill University to develop a method of extracting precious metals out of spent mining tailings rather than have to mine virgin material.

While similar in structure and composition, plastics source their carbon predominantly from petroleum, while plants obtain it from air (CO₂). The plant kingdom served as inspiration for Dr. Geoffrey Coates of Cornell University, who recently developed a way to manufacture plastics using carbon atoms acquired from the air.
Questions

The following series of balanced chemical equations describe the reactions required to produce calcium carbonate from carbon dioxide:

1 | Bubbling carbon dioxide through water causes the formation of carbonic acid:
   \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \]

2 | The addition of the base causes the formation of sodium hydrogen carbonate and water:
   \[ \text{H}_2\text{CO}_3 + \text{NaOH} \rightarrow \text{NaHCO}_3 + \text{H}_2\text{O} \]

3 | The addition of even more base results in the formation of sodium carbonate and water:
   \[ \text{NaHCO}_3 + \text{NaOH} \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \]

4 | Finally the sodium carbonate reacts with the aqueous calcium chloride (seawater) to form the calcium carbonate that will be used in the production of cement for concrete (plus sodium chloride, or salt):
   \[ \text{Na}_2\text{CO}_3 + \text{CaCl}_2 \rightarrow \text{CaCO}_3 + 2\text{NaCl} \]

Use the reaction series above to answer the following questions:

1 | Classify each of the above reactions either as a synthesis, decomposition, single replacement, or double replacement reaction. Explain your reasoning.

   Reaction 1 is a synthesis reaction because two materials are combining to form a new material. Reactions 2, 3, and 4 are all double replacement reactions because in all three there are two exchanges of positive ions and negative ions.

2 | Assuming all the carbon dioxide reacts in the first step, if one mole of carbon dioxide is bubbled through excess water, how many moles of calcium carbonate could be produced?

   a | One mole of CO$_2$ produces one mole of H$_2$CO$_3$ and
   b | One mole of H$_2$CO$_3$ produces one mole of NaHCO$_3$ and
   c | One mole of NaHCO$_3$ produces one mole of Na$_2$CO$_3$ and finally
   d | One mole of Na$_2$CO$_3$ produces one mole of CaCO$_3$. So overall one mole of CO$_2$ produces one mole of CaCO$_3$. 

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3 | If you started with one metric ton (1000 kg) carbon dioxide, how many kilograms of calcium carbonate could be produced assuming all the carbon dioxide reacts?

\[
\frac{1000 \text{ kg CO}_2}{1 \text{ kg}} \times \frac{1000 \text{ g CO}_2}{1 \text{ mol CO}_2} \times \frac{1 \text{ mol CaCO}_3}{1 \text{ mol CO}_2} \times \frac{100.09 \text{ g CaCO}_3}{1 \text{ mol CaCO}_3} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 2275 \text{ kg}
\]

So about 2.25 metric tons of calcium carbonate can be produced from 1 metric ton of carbon dioxide!

4 | If 1138 kg of calcium carbonate are produced when one metric ton of carbon dioxide is reacted, what percent yield does this represent?

\[
\% \text{ yield} = \frac{1138 \text{ kg}}{2275 \text{ kg}} = .5002 = 50.02 \%
\]

5 | How many kilograms of calcium chloride would be required if one metric ton of carbon dioxide were reacted?

\[
\frac{1000 \text{ kg CO}_2}{1 \text{ kg}} \times \frac{1000 \text{ g CO}_2}{1 \text{ mol CO}_2} \times \frac{1 \text{ mol CaCl}_2}{1 \text{ mol CO}_2} \times \frac{110.98 \text{ g CaCl}_2}{1 \text{ mol CaCl}_2} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 2522 \text{ kg}
\]

So about 2.5 metric tons of calcium chloride are required to react completely with 1 metric ton of carbon dioxide.

**Evaluation**

In order to evaluate the effectiveness of the lesson, consider using the following questions:

1 | How would you describe what you learned from this activity?

2 | Because the Earth’s natural resources are limited, how would you describe what will happen as humans continue to consume them?

3 | What is an important difference between how humans typically acquire raw materials for cement manufacturing, and how corals do it, explored in this activity?

4 | What other materials do humans make and how do we make them? Give at least one example. What impact on the environment does each process have?

5 | For each material you mentioned in #4, try to identify an organism that makes a similar material. What impact on the environment does each organism’s process have?

6 | What is biomimicry?
References


Acknowledgements

Many individuals and organizations enabled the development of this lesson plan. The authors would like to especially thank the Ayrshire Foundation for making this work possible, as well as the Kendeda Foundation and Nathan Cummings Foundation. We would also like to thank the Calera Corporation for their generous technical advice and lab analysis assistance. Finally, we would like to thank the coral, an organism among many that continues to show our species the path towards an enduring way of life.

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