TEACHER INSTRUCTIONS

Glass Bead on a Wire

Objective: To demonstrate that glass can be a 'phase of matter' rather than a particular material and to examine the unique ability of glasses to absorb other ions during thermal treatments.

Background Information: Glasses are amorphous solids, meaning that they have no long-range order of their atoms. Crystalline materials have an orderly arrangement of atoms within their structure (Figure 1). Several materials that can be used to create a glass begin as a crystalline or semi-crystalline material. This indicates that glass can, at times, be a 'phase of matter' rather than just a particular material.

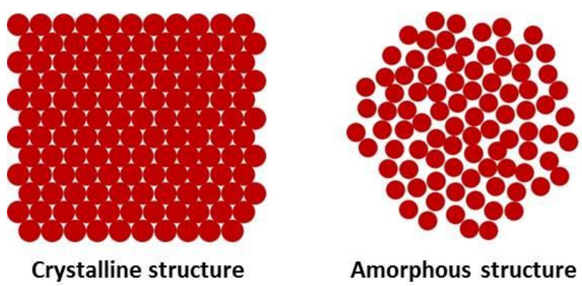

Figure 1. Crystalline and amorphous atomic arrangements

For example, Borax crystals are typically found deep in the ground and are mined as large 'chunks' (Figure 2(a)). Borax is actually sodium borate decahydrate ($Na_2B_4O_7 \cdot 10H_2O$). These chunks can be ground into a powder, which is sold in many grocery and convenience stores as a natural laundry booster that helps clean your clothes (Figure 2(b)). The powdered form of Borax is also a crystalline material, although the crystals are much smaller than the Borax that was originally mined.

Figure 2. (a) Borax crystals as mined in California and (b) powdered Borax crystals typically purchased as a household laundry booster.

The natural form of Borax contains a large amount of water, which is held in the crystalline structure of the material. When Borax is heated to temperatures high enough to start removing this water, the crystalline arrangement of the atoms in Borax begins to change. The Borax crystals will begin to swell as the water is being removed from the crystalline structure and then shrink as the water is being boiled off from the heat. This removal of water causes the crystalline structure of Borax to lose its orderly arrangement of atoms, leaving a transparent, glassy solid behind.

Powdered Borax crystals can be changed to a glassy form by heating with a Bunsen burner or a propane torch. Most Bunsen burners have the ability to control gas and air flow into the burner, which subsequently control the height and intensity of the flame produced. The oxidizing region of the Bunsen flame is produced with very high amounts of oxygen. This corresponds to the outer region of the Bunsen flame as this portion of the flame is in contact with high amounts of oxygen from the air. If the burner is turned up 'roaring hot,' this flame is a purple color (Figure 3). The reducing region of the flame is produced with low amounts of oxygen. This corresponds to the inner region of the Bunsen flame. If the burner is turned up 'roaring hot,' this flame is a blue color (Figure 3).

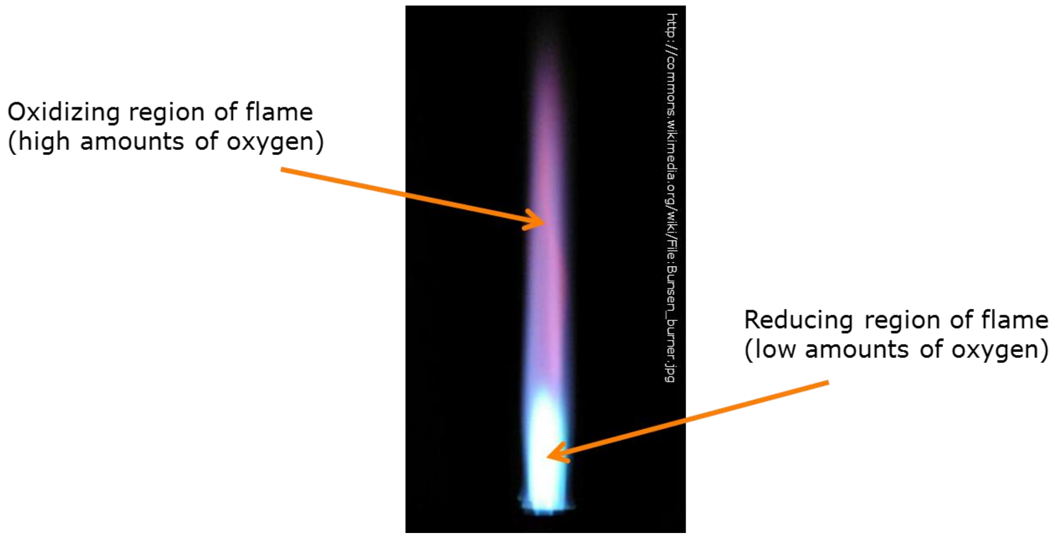

Figure 3. Bunsen burner flame with oxidizing and reducing regions

When heating powdered Borax, the transition of its atomic arrangement from crystalline to amorphous as the water is being removed during heating allows for metal ions to be substituted into the Borax atomic structure and form bonds with the oxygen atoms. The amount of oxygen available when this takes place (dependent on what part of the Bunsen flame you are using for heating) also affects how the metal ions will be incorporated in the structure and bond with oxygen atoms, which ultimately determines the color of glass that will be formed during this process. Borax glass is normally colorless, but different metal ions can be added to it during heating to produce different colors (Figure 4). See the Introductory Presentation for examples of how this phenomenon is used in real-world applications.

Figure 4. Borax beads formed with copper wire (blue bead) and nichrome wire (green bead)

Lab Description: In this lab, students will use copper and nichrome (nickel-chrome) wire to perform a Borax bead test and determine what color beads are produced from each type of wire under different heating conditions. The bead test has traditionally been used to test for the presence of certain metals. The Borax bead test is one of the oldest versions of the bead test and was developed by Jöns Jacob Berzelius in 1812! The Borax bead test consists of making a small loop at the end of a wire and heating it in a Bunsen flame until red hot. The loop is then dipped in powdered Borax and placed back in the Bunsen flame. The solid powder adheres to the hot wire and swells up as it loses its water of crystallization (the water found in the crystalline framework of a material – without this water, Borax cannot maintain a crystal structure). It then shrinks, forming a transparent glass-like bead. The bead's color is dependent on the metal ions that were present in the wire.

Keywords:

Amorphous: non-crystalline solid that lacks a long-range order of atoms

Oxidation: addition of oxygen to a material

Reduction: removal of oxygen from a material

Borax bead test: heat-induced transition of Borax from a crystalline state to an amorphous state that is typically used to test for the presence of certain metals

Water of crystallization: water that is incorporated in the crystalline structure of a material

Materials List:
Items provided in the kit
20ft Copper wire (18 gauge)
20ft Nichrome wire (20 gauge)

Items to be purchased/provided by the teacher
Powdered Borax (available for purchase as a laundry booster from stores such as Wal-mart®)
Bunsen burners (preferably should have one burner for every student, but students can share if needed)
Pliers/tongs/corks (need something for students to use to hold their wire while heating)
Watch glass or heat-resistant container , e.g. short water glasses or ceramic bowls (need one per table – several students can share one container)
Plastic sandwich baggies - OPTIONAL (needed if students want to take home their wires/beads)

Safety Precautions: Safety glasses should be worn during this lab. The wires will get very hot when placed in the Bunsen burner flame. Use pliers/tongs/corks to hold the wires while heating. Borax is toxic to humans if ingested in large quantities, so students should avoid skin contact with the powder to reduce the risk of accidental ingestion. The glass beads can fall off the wire, so caution students not to 'flick' the wire when they have a hot bead.

Instructions:

1. Cut 2 pieces of copper wire and 2 pieces of nichrome wire, each about 12 cm long.
2. Place a small amount of Borax (about a teaspoon) in a watch glass or other heat-resistant container.
3. Use the pliers to form a small loop on the end of each wire. The loop should be slightly larger than the eraser on the end of a pencil (Figure 5).

Figure 5. Wire with an appropriate size loop formed at one end

4. Using a Bunsen burner, heat the loop at the end of one of the copper wires until it gets red hot. Be sure to use the pliers to hold the wire while heating. Be sure that the Bunsen burner is turned up 'roaring hot' – you should be able to clearly see the reducing region and oxidizing region of the flame.
5. Dip the hot end of the wire into the Borax.
6. Carefully heat the Borax on the wire until it is melted and the loop fills in by placing the loop in the purple-colored outer flame (also called the oxidizing region of the flame). When the bead has a transparent color with very few air bubbles, you may add more Borax if you would like to make a larger bead. This process can be repeated to form a spherical bead if desired, but it is also ok to make a flat bead (this typically only takes one Borax treatment). This bead should have a sky blue color.
7. Repeat steps 4-6 with the other copper wire, but during step 6, hold the Borax-covered wire loop in the blue inner flame (also called the reducing region of the flame). Keep it red hot for 10-15 seconds, then cool it for 10 seconds by lowering it into the darker blue flame just above the Bunsen. The color of this bead should be red.
8. Repeat steps 4-6 with one of the nichrome wires. The bead produced should be a shade of green. Nichrome wire is typically composed of nickel, chromium, and sometimes a small amount of iron. Nickel produces a bead that is red to violet in color when heated in the oxidizing portion of the flame. Chromium produces a yellowish-green bead, and iron a yellowish-orange bead. Depending on how much of each element is present in the wire, the color of the bead will vary.
9. Repeat steps 4, 5, and 7 with the other nichrome wire. The bead produced should be a shade of green as well. Nickel turns grey when heating using the reducing flame. Chromium turns green, and iron turns green as well. Depending on how much of each element is present in the wire, the shade of green will vary.
10. Once you are satisfied with the size and color of the bead, allow the bead/wire to cool completely before placing the bead/wire in a plastic bag to take home with you.
11. You can try to remove the beads from the wire by reheating the bead and then plunging the loop into cold water. This works best with spherical beads.

Demo Delivery Hints:

1. It can be difficult to create a bead that is actually spherical. Many times, it is just easier to try to fill in the loop with the glass. Students tend to use too much Borax when trying to make a large bead and they don't take the time to get all of the gases (bubbles) out. This makes the bead look like a gray, foamy blob. Patience is required to successfully make a

large, colorful bead. However, a spherical bead can be made if a student is patient and gradually adds more Borax while heating thoroughly in-between each addition.

Figure 6. Beads that have a gray, milky color rather than a transparent, bright color due to the gas bubbles that remain trapped in the amorphous Borax

2. Borax is a deca-hydrate, which means there is a lot of water vapor to drive off as the Borax melts. This process can take quite a bit of heating and patience to get all of the bubbles out of the glass. Students often get impatient and take the wire/bead out of the flame every few seconds to check it. It will take longer to get good results this way – the wire/bead needs to be left in the flame in order for the reaction to properly occur.
3. The Borax glass beads are hygroscopic, meaning that they will absorb moisture from the air. As a result, the beads will become 'cloudy' after several days or weeks. The bead can be reheated to drive off the moisture and return the color clarity to the bead.

Troubleshooting:

1. If the loop is too large, the melted Borax can fall or drip from the loop. Be sure to keep the size of the loops just a little larger than the end of a pencil eraser.
2. It is possible to heat the wire for too long in the flame. In this case, the wire will melt. Care should be taken to monitor how long the wire glows red hot while it is in the flame.
3. At times, students may get impatient and not take the time to melt the Borax crystals completely. This will affect the color of bead that they are able to obtain. Encourage them to be patient when forming their bead.

Cleanup/Replacement parts: Turn off the Bunsen burners and allow them to cool completely before putting them away. Allow all the wires and beads to completely cool. Students should place the beads/wire in a plastic baggie to take home. Place any unused wire back in the kit. When it is time to replenish the wire supply, copper and nichrome wire can be ordered from a variety of suppliers, such as McMaster Carr (http://www.mcmaster.com). It is recommended that 18 gauge copper wire and 20 gauge nichrome wire be used for this lab. Dispose of any unused powdered Borax that has been removed from the original container. The original container of Borax can be stored for further use as long as it is kept dry. Powdered Borax is commonly available at Wal-Mart® under the name '20 Mule Team Borax'.

TEACHER DISCUSSION QUESTIONS

Glass Bead on a Wire

Discussion Questions to Ask Before the Demo

1. What is an amorphous solid, and what is a crystalline solid?

   Discussion: Crystalline solids have an orderly arrangement of atoms, while amorphous solids have no long-range order of atoms (see Figure 1 in the Teacher Instructions).

2. Can crystalline materials become amorphous? Why?

   Discussion: Ask this question to see what the students will say. Regardless of whether they answer yes or no, ask them why they think their answer is true. Try to facilitate as much discussion about this as possible. Essentially, this lab is transforming a crystalline material into an amorphous material using thermal treatment. Many students will not think this is possible because it seems that the crystalline structure should always be crystalline (and for many materials, it is). Most crystalline materials, such as metals, retain their crystalline atomic structure during heat treatment. Some movement (rearranging) of atoms or dislocations can occur, but the overall crystalline structure is still preserved. However, materials like Borax have the ability to move from a crystalline structure to an amorphous structure during heat treatment due to water removal from the atomic structure that rearranges the atoms. Quartz sand (i.e. silica) is a key ingredient in commercial glass production and undergoes a similar crystalline to amorphous transition during heat treatment.

3. What are the two parts of a Bunsen flame and why are they different?

   Discussion: Most Bunsen burners have the ability to control gas and air flow into the burner, which subsequently control the height and intensity of the flame produced. The oxidizing region of the Bunsen flame is produced with very high amounts of oxygen. This corresponds to the outer region of the Bunsen flame as this portion of the flame is in contact with high amounts of oxygen from the air. If the burner is turned up 'roaring hot,' this flame is a purple color. The reducing region of the flame is produced with low amounts of oxygen. This corresponds to the inner region of the Bunsen flame. If the burner is turned up 'roaring hot,' this flame is a blue color.

Discussion Questions to Ask During the Demo

1. Ask students to identify the oxidizing and reducing region of their Bunsen flame.

   Discussion: The oxidizing region (outer part of the flame) should be a purple color, and the reducing region (inner part of the flame) should be a blue color. By asking this question, you also ensure that the students have the appropriate amount of gas and air flow for their Bunsen flame. Having the gas/air flow too low will result in a flame that is yellow, and flow that is too high will result in a flame that is just blue and makes a loud roaring sound.

2. Before testing the first copper wire, ask students to make a prediction about what color bead they think they will get.

   Discussion: Students will most likely pick something close to the original color of the copper wire, or you will get a range of color guesses. This is to be expected, and part of what makes this lab fun is that the color of the bead does not correspond to the original color of the wire, but to the metal ion and amount of oxygen that transitions into the structure of the Borax during heating. This is next to impossible to guess, unless it is just a lucky guess. The point is to facilitate discussion about what the students have seen and what they think is going to happen.

3. Before testing the second copper wire, ask students to make a prediction about the color of bead they think they will get from this wire. Emphasize that they are going to be heating this bead in a different region of the Bunsen flame.

   Discussion: Students will most likely be stumped this time. After making the first bead, they will realize that the color of the bead doesn't have anything to do with the original color of the wire. Some will probably guess the same color as the first bead, but some of them will try to figure out how heating the bead differently is going to impact the color. Encourage discussion, and the fact that there is not necessarily one right answer. No two students are going to heat the bead exactly the same which means that some of the beads may be varying shades of the same color or a different color altogether.

4. Before testing both of the nichrome wires, ask students to make a prediction about the color of bead that they think they will get.

   Discussion: By this point, they will have seen the influence of different heating methods on the color of bead, but now they are switching to a completely different kind of wire. Color guesses will most likely be all over the place. Students most likely will not guess the colors correctly. That's ok, the point is to facilitate discussion about what they have seen and what they think is going to happen.

Discussion Questions to Ask After the Demo

1. Ask the students what they learned about the Borax bead test.

   Discussion: Emphasize why the Borax is able to incorporate metal ions into its atomic structure during heating (see explanation in the Background Information section about transition between crystalline and amorphous solids due to water loss during heating). Emphasize that the color of the bead is due to the type of metal ion and the amount of oxygen (aka the part of the Bunsen flame used for heating) that can be incorporated into the Borax atomic structure. This is why the copper wires produced different color beads than the nichrome wires, and also why a single type of wire could produce two different colors of beads depending on how it was heated. There are many other metals that can be tested using this type of bead test. Each produces a different color of bead. Searching 'Borax bead test' on the internet will provide charts of the various metals and corresponding color of bead that is produced. Feel free to expand this lab to include other metals, especially if you have older students that can perform these heating steps more efficiently and quickly than younger students.

STUDENT LAB HANDOUT

Glass Bead on a Wire

Introduction: Glasses are amorphous solids, meaning that they have no long-range order of their atoms. Crystalline materials have an orderly arrangement of atoms within their structure. Several materials that can be used to create a glass begin as a crystalline or semi-crystalline material. This indicates that glass can, at times, be a 'phase of matter' rather than just a particular material.

Lab Description: In this lab, you will use copper and nichrome wire to perform a Borax bead test and determine what color beads are produced from each type of wire under different heating conditions. The bead test has traditionally been used to test for the presence of certain metals. The Borax bead test is one of the oldest versions of a bead test and was developed by Jöns Jacob Berzelius in 1812! The Borax bead test consists of making a small loop at the end of a wire and heating it in a Bunsen flame until red hot. The loop is then dipped in powdered Borax and placed back in the Bunsen flame. The solid powder adheres to the hot wire and swells up as it loses its water of crystallization (the water found in the crystalline framework of a material – without this water, the Borax cannot maintain a crystal structure). It then shrinks as the water is burned off from the heat, forming a transparent glass-like bead. The bead's color is dependent on the metal ions that were present in the wire.

Keywords: amorphous, oxidation, reduction, Borax bead test, water of crystallization

Materials List:
Bunsen burner
Pliers/tongs (something to hold the wires while heating)
Copper wire
Nichrome wire
Watch glass containing powdered Borax
Plastic baggie

Safety Precautions: Safety glasses should be worn during this lab. The wires will get very hot when placed in the Bunsen burner flame. Use pliers/tongs/corks to hold the wires while heating. The glass beads can fall off the wire, so do not 'flick' the wire while the bead is still hot and in a molten state. Borax is toxic to humans if ingested in large quantities, so do not play with the Borax powder.

Instructions:

1. Cut 2 pieces of copper wire and 2 pieces of nichrome wire, each about 12 cm long.
2. Use the pliers to form a small loop on the end of each wire. The loop should be slightly larger than the eraser on the end of a pencil.
3. Place a small amount of Borax (about a teaspoon) in a watch glass or other heat-resistant container.
4. Using a Bunsen burner, heat the loop at the end of one of the copper wires until it gets red hot. Be sure to use the pliers to hold the wire while heating. Be sure that the Bunsen burner is turned up 'roaring hot' – you should be able to clearly see the reducing region and oxidizing region of the flame.
5. Dip the hot end of the wire into the Borax.
6. Carefully heat the Borax on the wire until it is melted and the loop fills in by placing the loop in the purple-colored outer flame (also called the oxidizing region of the flame). When the bead has a transparent color with very few air bubbles, you may add more Borax if you would like to make a larger bead. This process can be repeated to form a spherical bead if desired, but it is also ok to make a flat bead (this typically only takes one Borax treatment).
7. Repeat steps 4-6 with the other copper wire, but during step 6, hold the Borax-covered wire loop in the blue inner flame (also called the reducing region of the flame). Keep it red hot for 10-15 seconds, then cool it for 10 seconds by lowering it into the darker blue flame just above the Bunsen.
8. Repeat steps 4-6 with one of the nichrome wires.
9. Repeat steps 4, 5, and 7 with the other nichrome wire.
10. Once you are satisfied with the size and color of the beads, allow the beads/wire to cool completely before placing the beads/wire in a plastic bag to take home with you.
11. You can try to remove the beads from the wire by reheating the bead and then plunging the loop into cold water, but this usually only works with spherical beads.

Clean Up: Turn off the Bunsen burners and allow them to cool completely before putting them away. Allow all the wires and beads to completely cool before placing in a plastic baggie to take home with you. Dispose of any extra Borax remaining in the watch glass, and rinse the watch glass with soap and warm water.

STUDENT QUESTION HANDOUT

Glass Bead on a Wire

1. Compare the nichrome and copper wires. What is different about them? What is the same?

2. Draw a picture of the Bunsen flame. Where is the oxidizing region of the flame? The reducing region? Why are these two regions different?

3. What happens to the Borax when it is heated on the hot wire? Why?

4. What color bead did you make when heating the copper wire and Borax in the oxidizing flame? The reducing flame? Why are these two different?

5. What color bead did you make when heating the nichrome wire and Borax in the oxidizing flame? The reducing flame? Why are these two different?

6. Compare the bead colors obtained from the copper wire vs. the nichrome wire. Are they different? Why?

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TEACHER INSTRUCTIONS

Engineered Concrete: How Would You Design a Composite?

Objective: To demonstrate how preparation (design) of a material can affect the final material properties and to provide an introduction to composites.

Background Information: Portland cement is a ceramic material that forms the main building block of concrete. When water is mixed with Portland cement, it forms a strong bond with the cement particles and starts to cure. Curing means that the water does not evaporate, but becomes part of the hardened cement – the water and cement particles become locked together in an intertwining matrix. This matrix will gradually harden over time to form a solid material which is typically called cement paste (due to the fact that only water and Portland cement were used to create it). Addition of other items such as sand, rock, or fibers, to the cement paste while it is being mixed creates a composite material. The addition of sand, rock, or fibers provides reinforcement, and the cement paste provides a way of bonding the materials together. Cement paste containing sand is typically referred to as mortar. Cement paste containing sand (i.e. fine aggregate) and rock (i.e. coarse aggregate) is typically referred to as concrete.

Composite materials, such as mortar and concrete, exhibit characteristics different from the characteristics of the individual materials used to create the composite.

The final material properties of the composite are dependent on how much of each individual material is used in the composite (i.e. quantity of sand/rock vs. quantity of Portland cement vs. quantity of water). For concrete, adding too much reinforcement will cause the material to be very weak since there will not be enough cement paste to hold the composite together. Likewise, adding too much or too little water will also affect the concrete since there must be just the right amount of water in the composite to react with all of the Portland cement. Scientists and engineers must carefully plan how much of each material will go into a composite to make sure that the composite will have the final material properties needed for a given application.

When initially designing a composite, the appropriate amount of each material to add is often unknown. Scientists and engineers often create the first mix design (indicates the quantity of each component to add) based on how the individual components behave. As previously discussed, a composite has characteristics different from the characteristics of the individual materials used to create the composite, so this first mix design is really just a hypothesis, or educated guess, about what should go into the composite. The results of the first mix design are examined, and then the mix design is tweaked to create a second mix design (which hopefully performs better than the first). This second mix design is then tested, and the process is repeated until the desired material properties are achieved. When designing a new material, one rarely gets the mix design right the first time! It usually takes multiple iterations to achieve the desired properties for a specific application or material. This design process is an integral part of developing new composites to meet the challenges of our ever-changing world.

There are many examples of composites in our everyday lives. Wood is a natural composite composed of cellulose fibers in a matrix of lignin, a natural glue-like material. Wood is also sensitive to water. Wood has the ability to absorb water into its cells, which will make the material softer and more pliable (e.g. soggy wood that has been exposed to water has a different texture and strength than dry wood). Man-made composites include rubber tires, fiberglass, and concrete. Most car tires are composed of rubber reinforced with fibers. Rubber keeps the pressurized air in the tire, and the fibers provide the strength needed to sustain the stresses imposed on the tire by the road as the car is being driven. Fiberglass is also a very common composite that is used in a wide variety of materials such as boats, automobiles, bathtubs, and surfboards. Fiberglass is created by embedding fine glass fibers in a plastic matrix (e.g. epoxy or polyester). The most commonly used man-made composite is concrete. Concrete, like most composites, has the ability to be designed for different applications based on the type and quantity of reinforcement material that is added to the composite (e.g. steel rebar or fibers for tension reinforcement). See the Introductory Presentation for additional examples of real-world applications involving composites.

Lab Description: In this lab, students will design and make a reinforced Portland cement paste. There are numerous ways to run this lab. The main idea is for students to experience the composite design process. At least two mix designs (iterations) should be used to allow students to:

1. Hypothesize about the quantity of each component that should be added to the cement paste.
2. Test how well their first hypothesis worked.
3. Refine their design based on the results from step 2 to make a second mix design.
4. Test their second mix design and evaluate the results.

If time allows, you can have students perform more than two iterations of their mix design. Also, there are multiple ways to set-up the iterations that the students will perform. For example, you can have students experiment with different w/c ratios for the first iteration and different amounts of reinforcement for the second iteration. As an alternative, you could also have students add a set amount of reinforcement for the first iteration, and allow them to choose how much reinforcement to add for the second iteration. You will need to decide what is appropriate for your class. Generally, older students can handle changing multiple components (e.g. adjusting w/c ratio in the first iteration and reinforcement in the second iteration), while younger students tend to do better with adjusting just one component (e.g. keeping the w/c ratio constant and adjusting the amount of reinforcement added for both iterations). For this set of instructions, the more complex example (changing multiple components) has been explained, but the instructions are written in such a way that it should be easy to update for different iterations. For both iterations, students will mix a reinforced cement paste and allow it to cure in a mold. The reinforced paste will be allowed to harden overnight and form cement 'pucks'. The pucks will be tested by dropping them from a height of at least 15 feet.

Keywords:

<u>Portland cement</u>: fine powder composed primarily of ground clinker (mostly ground limestone)

<u>Concrete</u>: composite material composed of Portland cement, water, and aggregate

Composite: a material that is composed of 2 or more materials and has different properties from the original materials
Design: a plan for how to prepare a material or a method for combining the materials in a composite (% of each material that should be added, how to combine the materials, curing conditions, etc.)
Reinforcement: material that is typically added to another material to give it improved mechanical properties (e.g. addition of steel rebar or fibers to concrete)

Materials List:
Items provided in the kit
10 Plastic measuring spoons
1 Mass balance

Items to be provided by the teacher/school
Portland cement – need 200g of cement per puck if using Styrofoam bowl molds,100g per puck if using the PVC pipe molds (Portland cement can be purchased from a local hardware store in a variety of sizes, 20lb bag = 9000g cement = 45 pucks)
Disposable plastic cups (Solo cups or a cheaper equivalent) – need 8-10 cups for every group
Styrofoam bowls (12oz) or PVC pipe (3" diameter) – need 2 bowls or 1 pipe mold per student
Duct tape – only needed if using the PVC pipe molds
Vaseline – only needed if using the PVC pipe molds
Q-tips – only needed if using the PVC pipe molds
Popsicle sticks/plastic spoons or knives (something to stir the paste) – need 2 per student
Plastic wrap (Saran™ wrap or cheaper equivalent) – 1 roll should be more than enough
Permanent marker (Sharpie® or cheaper equivalent)
Plastic sandwich bags – OPTIONAL (needed if you want to store the cracked pucks after testing)
Latex/Non-latex gloves – OPTIONAL (for students to wear while mixing the cement if desired)

Items to be provided by the students
Reinforcement items

Safety Precautions: Short-term skin exposure to Portland cement is not harmful, but students should avoid skin contact if possible. The Portland cement will be a very fine powder. Care should be taken when transferring the powder from the bag to the plastic cups to keep from generating a dust cloud. If a cloud occurs, allow the powder to settle and then wipe it up with a damp paper towel. Students should wash their hands immediately after handling the cement paste, before it has time to harden. If desired, have students where latex gloves (or non-latex if allergies are an issue) to prevent skin exposure.

Instructions:
1. A few days before the lab, split the students into groups of 3 and have them discuss what reinforcement item(s) they want to bring for their group.
2. On the day of the lab, have each student prepare a Styrofoam bowl or PVC pipe mold so that it is ready for the cement paste:

a. If using Styrofoam bowls, have students use a ruler to measure ¾" from the bottom of the bowl on the slanted portion of the bowl and mark it with a pen. Measure this in several places and then use the marks to draw a line around the inside of the bowl. Students will pour cement paste into the bowl until reaching the line. This will create pucks that are approximately the same thickness. The thickness of a puck is influenced by the amount of each component added to the paste, and pucks of different thickness may perform differently due to geometry rather than the components added to the puck. Figure 1 shows pucks that were made with no regard to the thickness. It can clearly be seen that for the same amount of cement, adding different amounts of water can significantly influence the thickness of the puck. It is expected that the thicker pucks will perform better simply due to the added mass (i.e. a thicker object is usually harder to break than a thinner object of the same material). This is why it is important to specify the same thickness for all of the pucks.

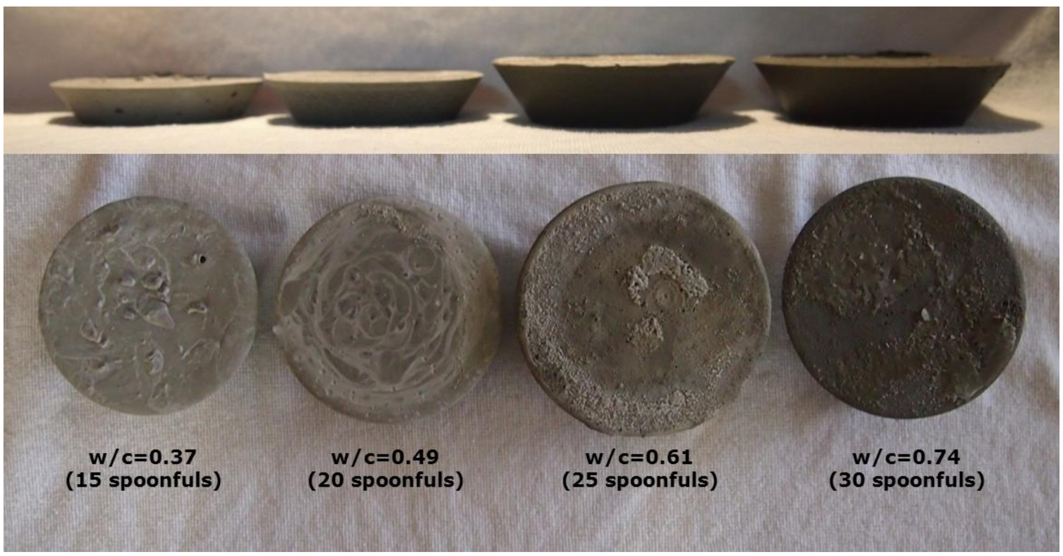

Figure 1. Influence of w/c ratio on the thickness and color of the cement puck

b. If using PVC pipe molds, you will need to cut the PVC pipe into 1" thick sections prior to beginning the lab. Each student will need one pipe mold. It is sometimes possible to ask your local hardware store to make the cuts for you (some charge a minimal fee for each cut and some will make the cuts for free if you purchased the pipe there). If you cannot find a hardware store to make the cuts, it is recommended that you use a miter saw to make the cuts. ***Note:*** If you do not have experience with a miter saw, DO NOT attempt to use one on your own for the first time. Pipes can be difficult to cut due to their rounded shape. Find someone with experience on a miter saw, and ask them to make the cuts for you or to teach you the proper technique for using the saw to make this type of cut.

   To prepare the 1" sections as a mold, layer duct tape (sticky side up) in a square that is approximately 5" x 5". Press the 1" pipe section into the mold as shown in

Figure 2. Be sure that the tape sticks to the edges of the pipe. Using a Q-tip, coat the inside of the pipe and duct tape with Vaseline to prevent the cement paste from sticking to the mold.

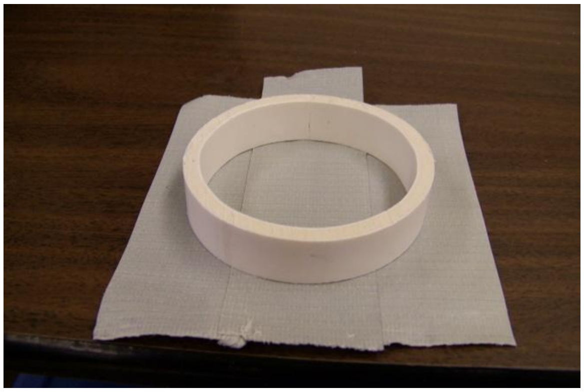

Figure 2. PVC pipe mold

3. Have each student measure 200g (100g if using the PVC pipe molds) of cement powder into a plastic disposable cup (you can also have this pre-measured for each student if access to a mass balance is limited).

4. For every group of 3 students, provide a plastic disposable cup full of water, 3 plastic measuring spoons, and 3 water to cement (w/c) ratios. Choose a low, average, and high w/c ratio so that students will be able to evaluate the effect of different amounts of water on their reinforced cement paste. For example, w/c ratios of 0.3, 0.5, and 0.8 work well for this part of the lab.

5. The w/c ratio can be calculated from the following equation:

$$w/c = \frac{mass\ of\ \ water}{mass\ of\ \ cement} = \frac{\#\ of\ \ spoonfuls \times 4.93cm^3 \times 1g/cm^3}{200g}$$

   The volume of the white measuring spoon is 4.93 cm^3 and the density of water is 1 g/cm^3. Give students the volume of the spoon and the density of water and ask them to figure out how many spoonfuls of water should be added to their cement powder to get each of the 3 w/c ratios you specified in step 2. Encourage them to work with their group to do this, without your help.

6. Once the calculations for the amount of water to add have been completed (and checked by you for each group), decide on the amount of reinforcement to add to the pucks. For this first iteration, it is recommended that you set the amount of reinforcement in terms of a mass basis or a volume basis. For example, tell each group to add 5g of their reinforcement item (mass basis) or 2 spoonfuls (volume basis – use the measuring spoons included in the kit to keep a consistent measurement for each group). You can let the students discuss this and settle on the number as a class (the class should come to a consensus on **one** number, e.g. 2g), or you can just decide for them. Sometimes, the mass vs. volume choice will depend on the reinforcement items that the students choose to bring in (this is why it is a good idea to have the students decide what to bring *before* the

lab so that you have a chance to evaluate what they will be using). Items like rice are very easy to measure on both a mass and a volume basis, but items such as glass fibers are easy to measure by mass and difficult to measure by volume. Also keep in mind when using the mass basis that items can vary drastically: 5g of rice vs. 5g of glass fibers is going to be very different in terms of volume, and it could be difficult to incorporate that volume into a single cement puck.

7. Have each group measure out the specified amount of reinforcement item decided in step 6. Each group should repeat the measurement 2 more times so that they have reinforcement items measured for 3 pucks. ***Note:*** Asking the students to pre-measure their reinforcement item before mixing gives you a chance to see for each group what they will be adding to their puck in terms of mass/volume. You can check and see if this is a reasonable amount to add. If it's not, this is your chance to increase or decrease the amount the class is using (e.g. if you specified for them to add 5g of their item – say, feathers, for example – to the puck but then realize that this is a very large amount, you could decrease the amount for the class to add to 2g). Try to be sure that the amount you ask the groups to add is reasonable for all reinforcement items that were brought in.
8. Have the groups start mixing their pucks. Each group should be making 3 pucks (1 per student). Each puck should have the same amount of cement and reinforcement item and different amounts of water (the 3 w/c ratios specified in step 4).
9. Measure the appropriate amount of water for each puck into a plastic disposable cup.
10. Using the cup of pre-measured cement powder, slowly add some of the cement powder to the water. Caution students not to 'dump' a large amount of cement powder into the cup as this usually creates a small dust cloud.
11. Stir the mixture with a popsicle stick until well blended.
12. Continue adding cement powder and stirring until all of the powder has been added and the mixture is well blended.
13. Once each mix is well-blended, have students decide how to add their reinforcement item. Depending on what item is being added, it may be easier to pour the item into the cup containing the cement paste and mix it with a popsicle stick. The item can also be placed in the mold and the paste poured over the top (this can also be done in layers – add some paste, add some reinforcement, add some paste, add some reinforcement, etc.). Encourage the groups to discuss which method they should use and why. ***Note:*** Some reinforcement items naturally lend themselves to one method or the other. This step is to get students to think about how they are actually making their puck in addition to what is included in it.
14. Record on the data sheet the method used for incorporating the reinforcement.
15. Once each student is satisfied with their method choice, have them add their reinforcement item and get their paste into a Styrofoam bowl/PVC pipe mold with as little sloshing as possible. If using the bowl, be sure to remind them to fill only to the marked line and then discard any leftover paste. If using the PVC pipe mold, fill the mold to the top of the pipe and discard any leftover paste.

16. Have students comment on any differences among their group's reinforced cement pastes – was one paste runnier than the other, did the reinforcement stick out of the top, etc.
17. Cover the top of the bowl/mold with plastic wrap and allow it to cure overnight.
18. The following day, de-mold the cement paste pucks by gently pulling on the sides of the Styrofoam bowl to loosen the bond between the paste and bowl. Place your hand over the top of the bowl and turn it over. Most of the time, the puck will fall out of the bowl. If it does not, start tearing pieces of the bowl away in large chunks until the puck can be removed. If using the PVC pipe molds, remove the duct tape from the bottom of the mold and gently push the puck out of the mold. The Vaseline should prevent the puck from sticking.
19. Label each puck with the student's name and w/c ratio using a permanent marker.
20. After all of the pucks are de-molded, have students comment on any differences that they notice about the color or texture of the pucks.
21. Drop the pucks from a height of at least 15 feet. The top of a set of bleachers works well as long as the puck can fall on a hard, solid surface. The second floor or roof of a school building or a tall play set will also work. The pucks should be dropped in an 'upright' position (how they were poured in the bowl/pipe mold). Try to drop the pucks as evenly as possible – as if you were dropping a bowl full of oatmeal and want it to land in an upright position so that nothing spills. Have students stand in a semi-circle at least 15 feet away from the point of impact so that everyone can see what is happening. Figure 2 shows pucks with different w/c ratios after dropping from a height of at least 15 feet.

w/c=0.25 (10 spoonfuls)	w/c=0.37 (15 spoonfuls)	w/c=0.49 (20 spoonfuls)	w/c=0.61 (25 spoonfuls)

Figure 2. Pucks with different w/c ratios after dropping from a height of at least 15 feet.

22. After each puck is dropped, have the students record on their data sheet what happened to the puck (did it crack into lots of pieces, a few pieces, stay in one piece, etc.). Have the students describe what the fracture surfaces look like (is the reinforcement sticking out of the cross-section or sheared off, is the reinforcement spread throughout the cross-section or clumped up in one section, etc.). It can also be helpful to take a picture of the puck after it is dropped so that you can distinguish differences between how the pucks performed.

23. Have the student whose puck was dropped pick up the pieces so that the site is ready for the next puck to be dropped. You can also have the student place the pieces of their puck in a plastic baggy so that they can compare all of the pucks after the testing is finished.
24. Have each group compare the performance of their 3 pucks. Encourage them to discuss which w/c ratio worked best for their reinforcement item. Also have them discuss what they thought about the quantity of reinforcement added – was it too much? Too little?
25. Ask each group to share with the class which w/c ratio worked best and what they thought about the quantity of reinforcement used.
26. Next, as a class, discuss the performance of the different groups. ***Note:*** In step 24, the groups are evaluating the effect of w/c ratios, while in this step, the class is discussing the influence of different reinforcement items as well as the w/c ratio.
27. For the second part of the lab, allow each group to decide their own mix design. Encourage them to evaluate the puck results from their group as well as the overall class results when deciding how much water and reinforcement to add to their second puck. Remind them that they must keep the amount of cement powder the same (to ensure that they make enough paste to fill the mold). Since there are 3 students in each group, you can allow them to make 3 different pucks (i.e. they will have 3 attempts to adjust the water/reinforcement to make a better puck) or ask them to agree on one mix design and only make one puck per group. Do what works best for the time constraints in your classroom.
28. Repeat steps 9-23 and again discuss the results within the group and together as a class.

Demo Delivery Hints:

1. Cement paste is very easy to remove from desks and skin when it is still wet (it will wipe off with a damp paper towel), but more difficult to remove once it has dried. Providing each group with some damp and dry paper towels during the lab will help them keep their hands and the lab area clean. If students have a large amount of wet cement paste on their hands, have them wipe their hands on a paper towel before washing their hands in a sink. Large amounts of wet cement paste can harden in the pipes of a sink and will cause clogging (small amounts will generally wash down without any trouble).
2. During the first part of the lab, the lower w/c ratios may be more difficult to stir. Encourage students to stir for several seconds each time they add cement powder to make sure that they are allowing time for everything to mix well. The 0.3 w/c ratio can be especially difficult. This mix requires quite a bit of stirring, but will eventually take on the consistency of thick toothpaste. Encourage the students mixing this w/c ratio to be patient and to continue stirring.
3. Plastic cups are used for mixing the cement because it is more difficult to poke holes in this type of cup when stirring compared to a Styrofoam or paper cup (Styrofoam also tends to slough off in small amounts when gouged with a popsicle stick). However, a Styrofoam bowl tends to provide a better mold since it is somewhat slick and does not have ridges to stick to the cement paste. It is also much easier to de-mold since Styrofoam tends to easily break into pieces. Styrofoam cups generally do not work well as well as the bowls for molds since the cups tend to slough off in small pieces and are

more difficult/messy to demold from the pucks. Feel free to experiment with other types of cups/bowls (e.g. paper cups that are waxed on the inside).

4. Two different mold options are provided in this lab. The Styrofoam bowls are very easy, but they do have a trapezoidal cross-section due to the slanted edges of the bowl. This can create some effects during dropping (depending on how the puck lands) that depend more on the geometry of the bowl than on the components in the composite. The PVC pipe molds do not have this geometry issue, however, there are some additional costs and prep work associated with initially preparing this type of mold. You need to select what works best for your time and financial constraints. ***Note:*** The amount of cement specified in the Student Lab Handout is currently written for the Styrofoam bowl option. You will need to decrease the amount of cement used per puck to 100g if using the PVC pipe molds.
5. Before performing the drop test, it is often fun to have each student stand on their puck to see if it can hold their weight. Most pucks will be able to withstand this weight.
6. To help contain the pucks when they are dropped, open both ends of a large cardboard box and stand it upright in the 'landing zone'. This will help contain the pieces of the puck when it hits the ground while still allowing the puck to hit a hard surface.
7. For younger students, it may be better to perform this lab by keeping the w/c ratio constant for all pucks and only changing the amount of reinforcement added. It is still recommended for you/the class to specify a single amount to be added by every student for the first iteration (e.g. 2g) and then allow each student the freedom to choose the amount for the second iteration. This allows them multiple iterations to adjust one component of the composite and look at the corresponding results, which is a simpler exercise than adjusting two components and analyzing the results.

Troubleshooting: In some cases, the Styrofoam bowl may stick to the cement puck, especially if a lot of cement paste was sloshed up on the sides of the bowl. Using a butter knife to pry the Styrofoam bowl away from the cement puck can help break the bond between the bowl and cement.

Cleanup/Replacement parts: Dispose of the plastic cups, popsicle sticks, Styrofoam bowls, and crushed cement paste pucks in the trash. If using the PVC pipe molds, wipe off the Vaseline with a damp paper towel. Dry the pipe molds and store them for later use. The plastic measuring spoons should be washed with soap and warm water, dried, and returned to the kit for later use. The balance should also be wiped down with a damp paper towel and returned to the kit. The Portland cement, plastic cups, Styrofoam bowls, and Popsicle sticks will need to be replaced before the lab is run again. All of these items can be purchased at local grocery and hardware stores. If you have Portland cement left over, this can be stored in a sealed container for further use. If the Portland cement begins to get clumpy, then new Portland cement should be purchased.

TEACHER DISCUSSION QUESTIONS

Engineered Concrete: How Would You Design a Composite?

Discussion Questions to Ask Before the Demo

1. Why do you think it is important for scientists and engineers to be able to control the design of a material?

   Discussion: See the information in the Background Information section of the Teacher Instructions.

Discussion Questions to Ask During the Demo

1. When students are adding water during the first part of the lab, have them discuss the differences that they see in the cement paste mixture of their group.

   Discussion: The low w/c ratio mixture will be very thick and difficult to stir. It should have a darker gray color compared to the higher w/c ratios. The high w/c ratio mixture will be very runny, almost like water. It should be a light gray color. The average w/c ratio will be somewhere between these two, both in color and texture. It is important for students to make these observations as they will be completely on their own in designing the second mix design. The first part of this lab provides the opportunity for them to make some conclusions on how water affects the texture of the paste and how this translates to performance.

2. During the first part of the lab, have students discuss how each puck performed after it was dropped.

   Discussion: Ask them general questions about how it broke. Did it shatter into lots of little pieces? Break into several large pieces? Did it break at all? Ask them why they think the pucks performed differently from each other? Assuming that each puck is dropped in a similar fashion, the main difference in the pucks is going to be w/c ratio and the reinforcement item used. For pucks with very low w/c ratios, strength will be lower due to the increased number of air voids in the paste. It is usually difficult to distribute reinforcement evenly in this type of paste which may also cause defects in the paste. For pucks with high w/c ratios, the strength will also be lower. The ratio of water to cement in this type of puck is so high that when the cement starts to mix with the water, there is not enough cement available to make a strong hydration product. This is similar to adding too much water to a Kool-aid mix. If you start with a set amount of Kool-aid powder and add the amount of water called for on the container, your Kool-aid will taste just right. If you add double the amount of water, your Kool-aid will taste very weak because there is not enough Kool-aid powder available to mix with that amount of water. This type of cement also generally has a hard time bonding to the reinforcement item because it is already weak. The average w/c ratio puck tends to work the best. However, if students bring in a reinforcement item that can absorb water, this will affect how the pucks perform. Encourage the students to think about why the puck performed the way it did. Have them examine the fracture surfaces for clues on how the reinforcement helped or hindered the puck.

3. After all the pucks have been tested, have students discuss which puck was the best.

   Discussion: Encourage students to discuss why this puck worked well – was it the reinforcement item itself, or the quantity of reinforcement added vs. the amount of water and cement in the puck?

4. Have students discuss what they plan to try for their second mix design based on the discussion from Questions 2 and 3.

   Discussion: Encourage students to discuss what they want to try and why. Have them discuss this within their group first, then as a class. Ask them how they decided on the quantity of water and reinforcement item to add. Have them record their reasoning on the Student Question Handout.

5. During the second part of the lab, have students discuss how each puck performed after it was dropped.

   Discussion: This is a similar discussion to Question 2, but emphasize whether what they changed from the first mix design was successful in improving the puck. Also encourage them to justify why their puck improved. If their puck did not improve, ask them what they would do differently the next time to try to get better results.

Discussion Questions to Ask After the Demo

6. What was the influence of the w/c ratio on the strength of the puck?

   Discussion: Pucks with very low or very high w/c ratios will perform worse than pucks with average w/c ratios (see reasoning in Question 2).

7. What was the influence of the reinforcement items on the strength of the puck?

   Discussion: This will vary depending on what items students bring in. Choose the items that performed the best and the worst and discuss with the students why they think this happened. Was too much of the item added? Were the item and cement able to bond together? Was the size of the reinforcement item too large compared to the size of the puck? Fibers or fiber-like reinforcement tends to perform the best. In real-world applications, fibers are added to concrete because they can be randomly distributed throughout the cement matrix. This means that the fibers are found in all different orientations throughout the matrix. When loading the concrete, the fibers are able to absorb many different kinds of loadings because of the different orientations. Steel rebar is another type of reinforcement that is traditionally used in concrete. Rebar typically runs only in one or two orientations in the matrix. It is too big and too thick to be randomly distributed throughout the matrix. As a result, the rebar only helps reinforce the concrete when loads are applied in a certain direction. In addition, the rebar is quite large and not very flexible compared to fibers. Therefore, de-bonding sometimes occurs between the concrete and the rebar during loading. This leads to cracking of the concrete and allows water to penetrate into the matrix, which starts corroding the steel rebar. Fibers can be made from a variety of materials (most of which are non-corrosive) and tend to be much smaller and flexible, so de-bonding is more difficult.

8. How important is it for scientists and engineers to be able to control the design of the material?

   Discussion: Based on the results of the lab, stress that it is important for scientists and engineers to be able to control the design of a material. This lab demonstrated that the amount of water and the amount of reinforcement added can affect the strength of a cement puck. It sometimes takes multiple iterations of tweaking the amount of materials included in order to optimize the ideal composite. Scientists and engineers routinely do this to develop materials for new applications. It is important to choose the materials that go in a composite with an understanding of the influence of each individual material on the final composite material properties. Many times, scientists and engineers can use different mix designs (same materials, but added in different amounts) for different applications. For example, cement can be designed to minimize the influence of a specific chemical attack on the final composite by decreasing the amount of certain compounds that are used to make the cement powder. However, what works for one type of chemical attack may be very detrimental for a different type of chemical attack. This is why cement mix designs are often tweaked based on the intended use of the finished concrete (outside vs. inside; chemically aggressive environments vs. normal environments, etc.).

STUDENT LAB HANDOUT

Engineered Concrete: How Would You Design a Composite?

Introduction: Portland cement is a ceramic material that forms the main building block of concrete. When water is mixed with Portland cement, it forms a strong bond with the cement particles and starts to cure. Curing means that the water does not evaporate, but becomes part of the hardened cement – the water and cement particles become locked together in an intertwining matrix. This matrix will gradually harden over time to form a solid material which is typically called cement paste. Addition of other items such as sand, rock, or fibers, to the cement paste while it is being mixed creates a composite material. When sand is added to cement paste, it forms a composite material called mortar. When sand and rock are added to cement paste, it forms a composite material called concrete.

Composite materials, such as concrete, exhibit characteristics different from the characteristics of the individual materials used to create the composite.

In concrete, the addition of sand, rock, or fibers provides reinforcement, and the cement paste provides a way of bonding the materials together. The final material properties of the composite are dependent on how much of each individual material is used in the composite. Scientists and engineers must carefully plan how much of each material will go into a composite to make sure that the composite will have the final material properties needed for a given application.

When initially designing a composite, the appropriate amount of each material to add is often unknown. Scientists and engineers often create the first mix design (indicates the quantity of each component to add) based on how the individual components behave. As previously discussed, a composite has characteristics different from the characteristics of the individual materials used to create the composite, so this first mix design is really just a hypothesis, or educated guess, about what should go into the composite. The results of the first mix design are examined, and then the mix design is tweaked to create a second mix design (which hopefully performs better than the first). This second mix design is then tested, and the process is repeated until the desired material properties are achieved. When designing a new material, one rarely gets the mix design right the first time! It usually takes multiple iterations to achieve the desired properties for a specific application or material. This design process is an integral part of developing new composites to meet the challenges of our ever-changing world.

Lab Description: In this lab, you will design and make a reinforced cement paste. For the first part of this lab, you and your class members will discuss with your teacher what goes into your cement paste. You will then pour your reinforced paste into a mold and allow it to harden overnight. Your hardened cement 'puck' will then be tested by dropping the puck from a height of at least 15 feet. For the second part of the lab, you will use the results from the first part of the lab to make a second mix design. This time, you will decide how much water and reinforcement to add to your cement paste! You will again make a cement puck and test it to see if your mix design improved the performance of the puck.

Keywords: Portland cement, concrete, design, composite, reinforcement

Materials List (this list is for a group of 3)**:**
3 Plastic measuring spoons
1 Balance (shared among everyone in the class)
1200g Portland cement (200g per student for each part of the lab)
6 Plastic cups (3 for each part of the lab)
6 Styrofoam bowls or 3 PVC pipe molds (3 for each part of the lab)
6 Popsicle sticks (3 for each part of the lab)
Plastic wrap
Reinforcement items that you brought from home.

Safety Precautions: The Portland cement will be a very fine powder. Care should be taken when transferring the powder from the bag to the plastic cups to keep from generating a dust cloud. If a cloud occurs, allow the powder to settle and then wipe it up with a damp paper towel. Short-term skin exposure to Portland cement is not harmful, but you should avoid skin contact if possible. If you get some of the wet or dry cement mixture on your hands, wipe your hands off with a damp paper towel immediately, before the cement has time to dry. If needed, ask your teacher for gloves to help protect you from skin exposure to the cement.

Instructions:

1. Measure 200g of cement powder into a plastic cup. Each student in your group should do this.
2. Fill another plastic cup with water for your group to share.
3. Using the 3 water to cement (w/c) ratios provided by your teacher, calculate the number of spoonfuls of water that should be added to the cement powder to obtain a paste that has each w/c ratio. The volume of the white measuring spoon is $4.93cm^3$ and the density of water is $1g/cm^3$. Remember, you are starting with 200g of cement powder.
4. Show your teacher your calculations for all 3 w/c ratios.
5. Discuss with your teacher and the rest of the class, what amount of reinforcement should be added (for example, 2g of your reinforcement item, 1 spoonful of your item, etc.). The class should come to a consensus on the amount to add – all groups will use this number for their reinforcement item.
6. You are now ready to make your cement puck. Divide the w/c ratios among the members of your group so that each member is making a puck with a different w/c ratio. Each group should be making 3 pucks (1 per student). Each puck should have the same amount of cement and reinforcement item and different amounts of water.
7. Measure the amount of water that you need for your particular w/c ratio into an empty plastic cup (each student in your group should do this).
8. Using the cup of pre-measured cement powder, slowly add some of the cement powder to the water. Do not 'dump' a large amount of cement powder into the cup as this usually creates a small dust cloud.

9. Stir the mixture with a popsicle stick until well blended.
10. Continue adding cement powder and stirring until all of the powder has been added and the mixture is well blended.
11. Once each mix is well blended, think about how you want to add your reinforcement item to the paste (all at once, a little at a time, as you are putting it in the mold, etc.)
12. Record on your Data Sheet the method used for incorporating the reinforcement.
13. Once you are satisfied with your method choice, add your reinforcement and get your paste into a Styrofoam bowl/PVC pipe mold with as little sloshing as possible. If using the bowl, be sure to fill only to the marked line and then discard any leftover paste. If using the PVC pipe mold, fill to the top of the pipe mold and discard any leftover paste.
14. Record any differences among your group's reinforced cement pastes on your Data Sheet – was one paste runnier than the other, did the reinforcement stick out of the top, etc.
15. Cover the top of the bowl/ pipe mold with plastic wrap and allow it to cure overnight.
16. The following day, de-mold the cement paste pucks by gently pulling on the sides of the Styrofoam bowl to loosen the bond between the paste and bowl. Place your hand over the top of the bowl and turn it over. Most of the time, the puck will fall out of the bowl. If it does not, start tearing pieces of the bowl away in large chunks until the puck can be removed. If using the PVC pipe molds, remove the duct tape from the bottom of the mold and gently push the puck out of the mold. The Vaseline should prevent the puck from sticking.
17. Label your puck with your name and w/c ratio using a permanent marker.
18. After all of the pucks are de-molded, comment on any differences you notice about the color or texture of each group's pucks.
19. Drop the pucks from a height of at least 15 feet. Try to drop the puck in an 'upright' position (how they were poured in the bowl/pipe mold). Try to drop the pucks as evenly as possible – as if you were dropping a bowl full of oatmeal and want it to land in an upright position so that nothing spills.
20. After each puck is dropped, record on your Data Sheet what happened to the puck (did it crack into lots of pieces, a few pieces, stay in one piece, etc.). Describe what the fracture surfaces look like (is the reinforcement sticking out of the cross-section or sheared off, is the reinforcement spread throughout the cross-section or clumped up in one section, etc.).
21. If your puck was the one dropped, pick up the pieces so that the site is ready for the next puck to be dropped.
22. Once the pucks have all been tested, compare the performance of your group's 3 pucks. Discuss which one was best and why – was it the w/c ratio, the quantity of reinforcement added, the type of reinforcement added, etc.

23. Record your observations on the Student Question Handout and share your observations with the class.
24. Next, as a class, discuss the performance of the different groups. Consider the influence of different types of reinforcement items.
25. Record your observations about the other groups' pucks on the Student Question Handout.
26. For the second part of the lab, you will create your own mix design. Evaluate the results of the first part of the lab and decide how much water and reinforcement item you think should be added to your cement paste. Each member of your group can come up with a different mix design, but you must agree as a group on the 3 designs you want to try.
27. Repeat steps 7-21 and again discuss the results within the group and together as a class.
28. Record your observations on the Student Questions Handout.

Clean Up: Dispose of the plastic cups, popsicle sticks, Styrofoam bowls, and crushed cement paste pucks in the trash. The plastic measuring spoons should be washed with soap and warm water, dried, and returned to the kit for later use. The balance should also be wiped down with a damp paper towel and returned to the kit. If using the PVC pipe molds, wash the mold with soap and warm water to remove any Vaseline and cement residue. Dry it and return it to your teacher.

Data Sheet for Pucks

Mass of Portland cement:	w/c ratio of your puck:	Type and amount of reinforcement added:
Number of spoonfuls of water that need to be added to your puck:		
Method for adding reinforcement:		
Differences in your group's reinforced cement pastes:		
Performance of puck 1:		
Performance of puck 2:		
Performance of puck 3:		
Performance of puck 4:		
Performance of puck 5:		
Performance of puck 6:		
Performance of puck 7:		
Performance of puck 8:		
Performance of puck 9:		
Performance of puck 10: .		
. *(add as many additional pucks as needed for your class)* .		
Performance of puck 18:		
Performance of puck 19:		
Performance of puck 20:		

STUDENT QUESTION HANDOUT

Engineered Concrete: How Would You Design a Composite?

1. What type of reinforcement did you bring from home to strengthen your puck? Why?

2. For the first part of the lab, which of your group's 3 pucks performed the best? Why?

3. How well did your puck perform compared to the rest of the class? Why?

4. Which puck performed the best out of the entire class? Why?

5. What did you choose to change for the second round of testing? Why?

6. Did this improve your puck's performance?

7. Which puck performed the best during the second round of testing? Why?

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TEACHER INSTRUCTIONS

Thermal Processing of Bobby Pins

Objective: To show the difference that processing, especially thermal processing, can have on the properties of a material.

Background Information: A material can possess a variety of different mechanical properties such as strength, stiffness, plasticity, elasticity, and deflection. Deflection is the amount of displacement experienced by a material when placed under a load. This property is of great importance in building construction, and building codes often specify a maximum allowable deflection, generally as a fraction of the length of the beam. A material's mechanical properties are dependent on the material's microstructure, including the phases present, the number and arrangement of dislocations, and the grain size and shape.

Thermal processing is used to change the crystal structure, defect structure (dislocations), and/or grain structure of a material. Annealing is a process used to weaken metals, such as steel, to make them easier to form into desired shapes. To anneal metal, it must be heated above a critical temperature, maintained at that temperature, and then allowed to cool. For steel, that critical temperature is the transformation temperature to austenite or austenite/cementite. If a metal is annealed for too long it is considered to be "over-aged," and in this state, it has very few dislocations and is very ductile. Heating the metal to a red-hot temperature causes the atoms to move faster and more freely. By slowly cooling from this high temperature, the atoms are able to adopt more ordered arrangements and create a more perfect crystal. The more perfect the crystal of the metal, the easier atoms can "slide" past one another, and thus, the more easily the metal can bend. The material also tends to have large grains after annealing and slow cooling (Figure 1), and this leads to a more malleable material. In contrast, to make a metal hard and brittle through thermal processing, it must be rapidly quenched from high temperature to room temperature. This quick cooling of the metal from red-hot temperatures freezes the atoms into a disordered phase with many defects. Due to the large number of defects, the atoms cannot move easily, and the metal is considered hard to bend and brittle. Quenching a metal such as steel will also cause it to change phases (or atomic arrangements) and sometimes form a phase called martensite (Figure 2), which is very hard and brittle. See the Introductory presentation for examples of real-world applications where thermal processing is used to modify materials.

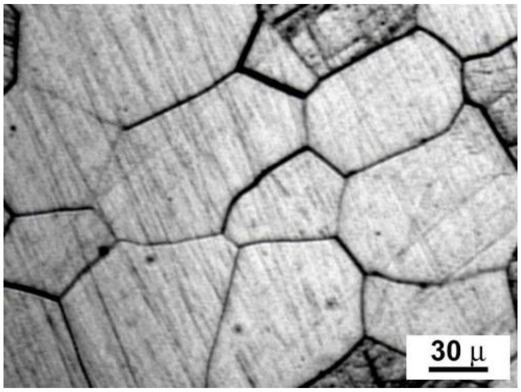

Figure 1. Grain structure of polycrystalline metal (http://en.wikipedia.org/wiki/File:CrystalGrain.jpg).

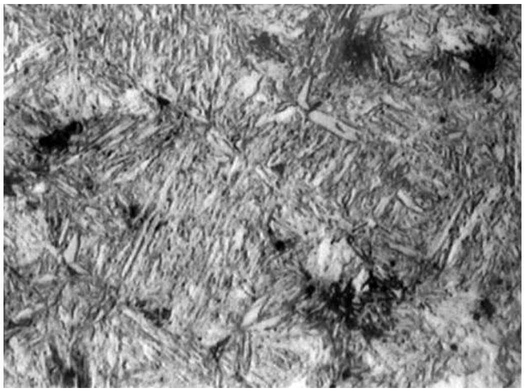

Figure 2. Martensitic grain structure of quenched steel (http://en.wikipedia.org/wiki/File:Steel_035_water_quenched.png).

Lab Description: In this lab, students will see how thermal treatment of a normal steel bobby pin can influence its mechanical properties, especially strength, ductility, and deflection. This will be done using a control sample, an annealed sample, and a quenched sample.

Keywords:
Thermal processing: using temperature changes to impact material properties
Annealing: heating a material and allowing it to cool slowly
Strength: ability of a material to withstand applied stress without failure
Stiffness: ability of a material to withstand deformation (bending)
Elasticity: ability of a material to deform non-permanently without breaking
Plasticity: ability of a material to deform permanently without breaking
Ductility: ability of a material to deform under tensile stress
Malleability: ability of a material to deform under compressive stress
Over-aging: having been annealed for too long, decreasing desired material properties
Deflection: amount of displacement experienced by a structural element (e.g. beam) under a load
Elastic modulus: the tendency of a material to be deformed elastically (i.e. not permanently)

Microstructure: structure of a material as observed through microscopic examination
Grain: an individual crystal in a polycrystal
Dislocation: a defect or irregularity in the ordered arrangement of atoms in a material

Materials List:

Items provided in the kit
1 Package of bobby pins
5 Plastic cups with twine
5 C-clamps

Items to be provided by the teacher/school
Bunsen burners (1 per group)
Corks/tongs/pliers (something for the students to hold the bobby pins with during heating)
Pennies (300 per group)
Cup filled with cold water (Styrofoam/paper/plastic disposable cups – cheapest you can find works)

Safety Precautions: Proper care and procedures should be used when handling the Bunsen burners, including wearing safety glasses. Remove the plastic tips from bobby pins if present. The bobby pins will get very hot during heating. Do not touch the bobby pins until they have cooled.

Instructions:

1. Set aside one pin to be used as the 'control.' The control sample will not receive any heat treatment and will be tested 'as received.'
2. Heat a second pin using the Bunsen burner. The entire pin should be heated until the bobby pin glows red-hot. (***Note:*** *When heating a pin, it is best to use pliers to grip the 'open end' of the pin so that it separates the two sides of the pin. This allows the pin to heat much faster*.) Keep the bobby pin in the flame for 20-25 seconds after it starts glowing red.
3. After the bobby pin has been removed from the flame and returns to a gray color, set the bobby pin on a paper towel and allow it to continue to cool. This bobby pin has been 'annealed.'
4. While the second bobby pin is cooling, heat another bobby pin on the Bunsen burner. For this pin, place the looped end in the flame, heating the loop and about 1/3 of the pin. The pin should again be kept in the flame until glowing hot for 20-25 seconds.
5. Remove the pin from the flame and immediately plunge it into the cup of cold water.

6. Set the bobby pin on a paper towel and allow it to dry completely. This bobby pin has been 'quenched.'
7. Measure and record the width (mm) and height (mm) of the 'smooth' side of the bobby pin.
8. Set up the control bobby pin as shown in Figure 3. Be sure that the cup and string are hanging from the end of the bobby pin.

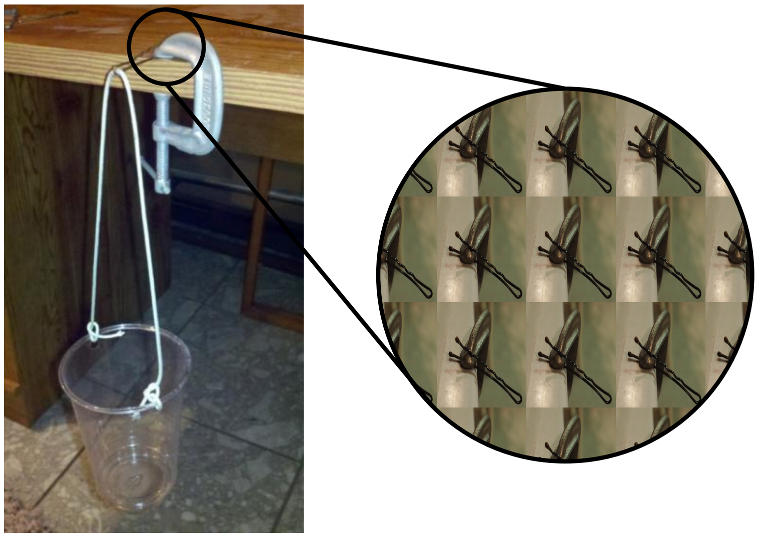

Figure 3. Test set-up

9. Record the length (mm), L, of the control bobby pin that is not supported by the table.
10. Measure and record any deflection that occurred due to the weight of the cup and twine (this will usually be very small, if it is measurable at all). The deflection is how far below the level of the table the far end of the bobby pin has been moved.
11. Create a paper funnel by rolling a piece of paper and either stapling or taping it.
12. Using the funnel, start placing pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of 2-3 pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
13. Add a total of 300 pennies to the cup.
14. Measure and record the deflection of the control bobby pin using a ruler. The typical deflection of a control bobby pin subjected to a load of 300 pennies is 20-30mm.
15. Unload the control bobby pin. Measure and record any permanent deflection. The control bobby pin typically has only a slight permanent deflection (usually less than 10mm).

16. Bend the control bobby pin back to its original position to remove the permanent deflection. The control bobby pin should return to its original position.

17. Unclamp the control bobby pin and pull the two sides apart until the control bobby pin forms a straight line. Bend the bobby pin back to its original position. Observe and record any changes that occur during the bending and straightening process. Repeat several more times.

18. Calculate the force applied to the control bobby pin during the penny loading. Find the mass of the cup, string, and the pennies in the cup using a mass balance. The force, P, applied to the bobby pin can then be calculated as follows:

    $$P = (\text{mass of cup/twine/pennies})*(\text{gravity} = 9.8 m/s^2)$$

    If you do not have access to a mass balance, use the following values to approximate the mass.

    a. Mass of one penny = 2.4 grams
    b. Mass of the cup and twine = 25 grams

    The force, P, applied to the bobby pin can then be calculated as follows:

    $$P = ((\text{mass of penny})*(\text{\# of pennies}) + \text{mass of cup/twine})*(\text{gravity} = 9.8 m/s^2)$$

19. Calculate the area moment of inertia for the bobby pin:

    $$I = \frac{1}{12}bh^3 = \frac{1}{12}*1mm*(0.5mm)^3 = 0.0104mm^4 \text{ (for provided pins)}$$

20. Calculate the deflection using the cantilevered beam deflection equation:

    $$deflection = \frac{PL^3}{3EI}$$

    where P = force applied at the end of the bobby pin, L = unsupported length of the bobby pin, E = modulus of elasticity, and I = area moment of inertia. The modulus of elasticity for a steel bobby pin without additional thermal processing is 200,000 N/mm^2.

21. Compare the measured deflection to the calculated deflection.

22. Set up the annealed bobby pin as shown in Figure 3.

23. Load the annealed bobby pin in the same fashion as the control bobby pin. Measure and record the deflection of the pin using a ruler. The typical deflection of an annealed bobby pin subjected to a load of 300 pennies is 25-30mm (usually slightly higher than the control bobby pin).

24. Unload the bobby pin. Measure and record any permanent deflection. The annealed bobby pin typically has a permanent deflection of 20-30mm (much higher than the control bobby pin).

25. Bend the annealed bobby pin back to its original position. The annealed bobby pin may break when you try to do this.

26. If the annealed bobby pin does not break by moving it back to the original position, unclamp the annealed bobby pin and pull the two sides apart until the bobby pin forms a straight line. Bend the bobby pin back to its original shape. Observe and record any changes in the annealed bobby pin during the bending and straightening process. Unlike the control bobby pin, this pin should break after being bent/straightened the first time.

27. Using the cantilevered beam deflection equation given in Step 20 and the deflection measured during testing, find the elastic modulus of an annealed bobby pin.

28. Compare the elastic modulus of the annealed bobby pin to the control bobby pin. The elastic moduli of these two pins should be very similar. Annealing does not have an influence on the elasticity of the pin, but on the microstructure.

29. Set up the quenched bobby pin as shown in Figure 3.

30. Load the quenched bobby pin in the same fashion as the control bobby pin.

31. If properly quenched, this bobby pin will break before reaching the maximum load of 300 pennies (usually at a loading of ~70 pennies). Carefully monitor the deflection during the loading process. Calculate the deflection using the cantilevered beam equation. The force, P, applied to the pin will be based on the number of pennies in the cup at the time of failure of the pin. Assume that the elastic modulus, E, of a quenched steel bobby pin is 3000 N/mm^2.

32. Compare the measured deflection at failure to the calculated deflection for a quenched bobby pin.

Demo Delivery Hints: If the calculations become too difficult for younger students, simply compare the deflections (both measured during testing and deflection recovery after testing) and the number of pennies in the cup at failure load. The control, annealed, and quenched pins will behave differently with respect to these properties. For math intensive courses, ask the students to turn in their deflection calculations along with the lab.

Troubleshooting: The pins must remain in the heat long enough to anneal (20-25 seconds should be sufficient.) The quenched pin will be very brittle and will likely break after only a light loading (aka small deflection). If the entire pin is heated and then quenched, it will be too brittle to clamp. Therefore, be sure to heat only the 1/3 of the pin towards the looped end (the end that will be loaded) for the quenched bobby pin.

Cleanup/Replacement parts: Allow the Bunsen burners to completely cool before storing. Dispose of the bent and broken bobby pins. Return the cups with twine, pennies, and c-clamps to the kit.

TEACHER DISCUSSION QUESTIONS

Thermal Processing of Bobby Pins

Discussion Questions to Ask Before the Demo

1. What are strength and stiffness?

   Discussion: Strength is the ability of a material to withstand applied stress (or strain) without failure. Stiffness is the ability to withstand deformation (bending).

2. What makes a material strong or stiff?

   Discussion: This actually depends on the microstructure of the material: how the grains are arranged, if there are precipitates or defects in the material, etc.

3. What is plasticity (ductility, malleability)?

   Discussion: Plasticity is a material's ability to plastically deform without breaking. Ductility is specifically in response to tensile stress and malleability to compressive stress.

4. Why are all of these properties important to engineers and architects?

   Discussion: For engineers and architects, all of these properties must be considered when choosing the right material for any structure. Sometimes, a material must be strong enough to withstand the load upon it, for example the weight of cars on a bridge. Other times, a material must be stiff enough not to bend under the applied load. For example, to an engineer designing a new tool or an artist interested in metal jewelry, ductility and malleability are very important (as opposed to just strength), as the material needs these properties to withstand forming processes such as hammering and rolling.

5. How does adding heat affect a material?

   Discussion: The atoms rearrange themselves inside of the material. The heat provides enough energy to allow the motion of the atoms into arrangements of lower energy, which is more energetically favorable.

6. Predict which bobby pin you expect to deflect the most.

   Discussion: Ask this question of students to get them thinking about the differences between the three pins that will be examined. Encourage discussion. There is no right or wrong answer to this question as the students have not yet performed the lab and most likely do not understand the influence of thermal processing on deflection.

Discussion Questions to Ask During the Demo

1. What do you think is happening when the bobby pin is held in the hot flame?

   Discussion: The crystal structure (arrangement of atoms) in the bobby pin is changing, as is the grain structure. The new structure leads to a soft, ductile nature.

2. Will the annealed bobby pin be stronger or weaker than the control bobby pin?

   Discussion: Ask students to make a prediction before testing and explain why they chose this prediction. Encourage them to consider what the processing has done to the bobby pin and how they think that will influence the bobby pin.

3. What is happening when the bobby pin is placed into the cold water after annealing, instead of cooling on the paper towel?

   Discussion: The atoms are being frozen into their hot temperature positions, which is a more disordered crystal.

4. Will the quenched bobby pin be stronger or weaker than the control bobby pin?

   Discussion: Ask students to make a prediction before testing and explain why they chose this prediction. Encourage them to consider what the processing has done to the bobby pin and how they think that will influence the bobby pin.

Discussion Questions to Ask After the Demo

1. Did your prediction of which bobby pin should deflect the most match your experimental results?

   Discussion: The annealed pin should deflect the most. The quenched pin should break under even small loadings. Encourage students to discuss their predictions and why they were either the same or different than the experimental results.

2. Why did the annealed bobby pin deflect with much less load then the control pin?

   Discussion: To anneal the pin, heat is used. This heat provides enough energy for the atoms of the material to rearrange themselves. This allows the grains to grow larger and for dislocations in the material to be destroyed. Less dislocations allow materials to bend more easily.

3. Why is the quenched bobby pin brittle?

   Discussion: The microstructure of the pin has been changed. It is now martensite, a very strained crystal structure with a large number of dislocations and many carbon precipitates. Martensite also has a very needle-like microstructure which results in brittle behavior.

STUDENT LAB HANDOUT

Thermal Processing of Bobby Pins

Introduction: A material can possess a variety of different mechanical properties such as strength, stiffness, plasticity, elasticity, and deflection. Deflection is the amount of displacement experienced by a material when placed under a load. This property is of great importance in building construction, and building codes often specify a maximum allowable deflection, generally as a fraction of the length of the beam. A material's mechanical properties are dependent on the material's microstructure, including the phases present, the number and arrangement of dislocations, and the grain size and shape.

Thermal processing uses heat to change the crystal structure, defect structure (dislocations), and/or grain structure of a material. Heating a metal to red-hot and then allowing it to cool slowly is called annealing. By heating the metal, the atoms are given enough energy to move faster and more freely. Slow cooling allows the atoms to arrange themselves in low energy positions, specifically to create highly ordered crystal structures. When a metal's crystal structure is highly ordered, the atoms can slide past one another more easily, making the metal easy to bend. If a metal is annealed for too long it is considered to be "over-aged," and in this state, it has very few dislocations and is very ductile. To make a metal hard and brittle through thermal processing, it must be rapidly quenched from high temperature to room temperature. This quick cooling of the metal from red-hot temperatures freezes the atoms into a disordered phase with many defects. Due to the large number of defects, the atoms cannot move easily, and the metal is considered hard to bend and brittle.

Lab Description: In this lab, you will see how thermal treatment of a normal steel bobby pin can influence its mechanical properties, especially strength and ductility. This will be done using a control sample, an annealed sample, and a quenched sample.

Keywords: Thermal processing, annealing, strength, stiffness, elasticity, plasticity, ductility, malleability, over-aging, deflection, elastic modulus, microstructure, grain, dislocation

Materials List:

Items provided:

3 Bobby pins

1 Cup with twine

1 C-clamp

1 Bunsen burner

1 Pair of Tongs/pliers/corks (something to hold the bobby pins during heating)

~300 Pennies
1 Cup filled with cold water

Safety Precautions: Proper care and procedures should be used when handling the Bunsen burners, including wearing safety glasses. The bobby pins will get very hot during heating. Do not touch the bobby pins until they have cooled!

Instructions:

1. Set aside one pin to be used as the 'control.' The control sample will not receive any heat treatment, and will be tested 'as received.'
2. Heat a second pin using the Bunsen burner. The entire pin should be heated until the bobby pin glows red-hot. (When heating a pin, it is best to use pliers to grip the 'open end' of the pin so that it separates the two sides of the pin. This allows the pin to heat much faster.) Keep the bobby pin in the flame for 20-25 seconds after it starts glowing red.
3. After the bobby pin has been removed from the flame and returns to a gray color, set the bobby pin on a paper towel and allow it to continue to cool for several minutes. This bobby pin has been 'annealed.'
4. While the second bobby pin is cooling, heat another bobby pin using the Bunsen burner. For this pin, place the looped end in the flame, heating the loop and about 1/3 of the pin. The pin should again be kept in the flame until glowing hot for 20-25 seconds.
5. Remove the pin from the flame and immediately plunge it into the cup of cold water.
6. Set the bobby pin on a paper towel and allow it to dry completely. This bobby pin has been 'quenched.'
7. Measure and record the width (mm) and height (mm) of the 'smooth' side of the bobby pin.
8. Set up the control bobby pin as shown in Figure 1. Be sure that the cup and string are hanging from the end of the bobby pin.

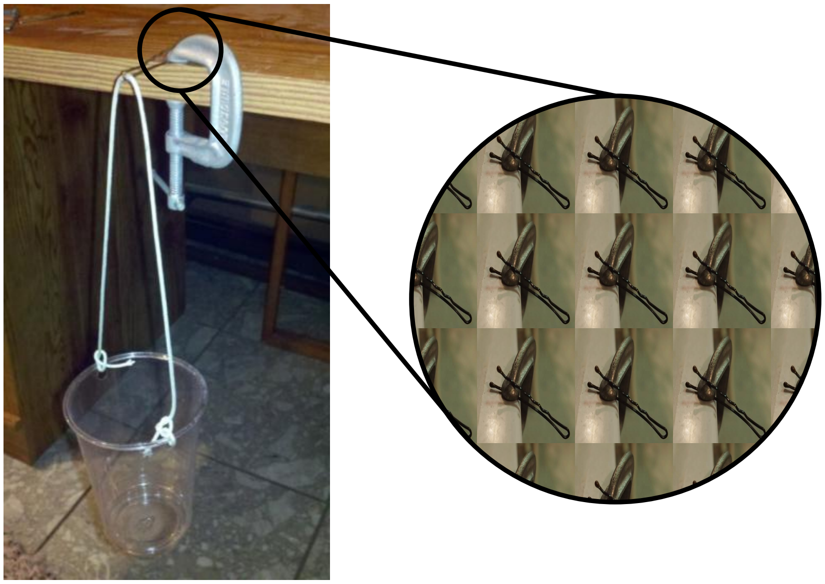

Figure 1. Test set-up

9. Record the length (mm), L, of the control bobby pin that is not supported by the table.
10. Measure and record any deflection that occurred due to the weight of the cup and twine (this will usually be very small, if it is measurable at all). The deflection is how far below the level of the table the far end of the bobby pin has been moved.
11. Create a paper funnel by rolling a piece of paper and either stapling or taping it closed.
12. Using the funnel, start placing pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of 2-3 pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
13. Add a total of 300 pennies to the cup
14. Measure and record the deflection of the control bobby pin using a ruler.
15. Unload the control bobby pin. Measure and record any permanent deflection.
16. Bend the control bobby pin back to its original position to remove the permanent deflection.
17. Unclamp the control bobby pin and pull the two sides apart until the bobby pin forms a straight line. Bend the control bobby pin back to its original position. Observe and record any changes that occur during the bending and straightening process. Repeat several more times.

18. Calculate the force applied to the control bobby pin during the penny loading. Find the mass of the cup, string, and the pennies in the cup using a mass balance. The force, P, applied to the bobby pin can then be calculated as follows:

$$P = (\text{mass of cup/twine/pennies})*(\text{gravity} = 9.8\text{m/s}^2)$$

If you do not have access to a mass balance, use the following weights to approximate the mass.

a. Mass of one penny = 2.4 grams
b. Mass of the cup and twine = 25 grams

The force, P, applied to the bobby pin can then be calculated as follows:

$$P = ((\text{mass of penny})*(\#\text{ of pennies}) + \text{weight of cup/twine})*(\text{gravity} = 9.8\text{m/s}^2)$$

19. Calculate the area moment of inertia, I, for the bobby pin:

$$I = \frac{1}{12}bh^3$$

where b is the width of the bobby pin, and h is the height.

20. Calculate the deflection using the cantilevered beam deflection equation:

$$deflection = \frac{PL^3}{3EI}$$

where P = force applied at the end of the bobby pin, L = unsupported length of the bobby pin, E = modulus of elasticity, and I = area moment of inertia. The modulus of elasticity for a steel bobby pin is 200,000 N/mm^2.

21. Compare the measured deflection to the calculated deflection.

22. Set up the annealed bobby pin as shown in Figure 1.

23. Load the annealed bobby pin in the same fashion as the control bobby pin. Measure and record the deflection of the annealed bobby pin using a ruler.

24. Unload the annealed bobby pin. Measure and record any permanent deflection

25. Bend the annealed bobby pin back to its original position. The bobby pin may break when you try to do this.

26. If the annealed bobby pin does not break by moving it back to the original position, unclamp the bobby pin and pull the two sides apart until the annealed bobby pin forms a straight line. Bend the annealed bobby pin back to its original shape. Observe and record any changes in the bobby pin during the bending and straightening process.

27. Using the cantilevered beam deflection equation given in step 20 and the deflection measured during testing, find the elastic modulus of an annealed bobby pin.
28. Compare the elastic modulus of the annealed bobby pin to the control bobby pin.
29. Set up the quenched bobby pin as shown in Figure 1.
30. Load the quenched bobby pin in the same fashion as the control bobby pin.
31. Carefully monitor the deflection during the loading process. Calculate the deflection using the cantilevered beam equation. The force, P, applied to the pin will be based on the number of pennies in the cup at the time of failure of the pin. Assume that the elastic modulus, E, of a quenched steel bobby pin is 3000 N/mm^2.
32. Compare the measured deflection at failure to the calculated deflection for a quenched bobby pin.

Cleanup/Replacement parts: Allow the Bunsen burners to completely cool before storing. Dispose of the bent and broken bobby pins. Return the cups with twine, pennies, and c-clamps to your teacher.

STUDENT QUESTION HANDOUT

Thermal Processing of Bobby Pins

Processing History	Total Pennies Added	Maximum Load Applied	Maximum Deflection Measured	Maximum Deflection Calculated
As Received				
Annealed				
Quenched				

1. What makes a material strong or stiff?

2. How is the microstructure of the bobby pin changing when it is heated up?

3. Why would one want to be able to soften a metal?

4. What is happening differently in the quenched bobby pin than the annealed bobby pin? Why does this change the material behavior?

5. Are your measured deflections and calculated deflections similar? If not, what could explain the difference?

6. Compare the deflection and elastic modulus of the control, annealed, and quenched bobby pins.

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TEACHER INSTRUCTIONS

Happy Ball / Sad Ball

Objective: To demonstrate the dependence of material properties on temperature and material structure by examining two polymers which visually look identical but have different material structures.

Background Information: An introduction to material properties is crucial to understanding the world of materials science. Materials are selected and engineered based on the desired properties for an application. Developing an understanding of material properties is the first step in understanding why different materials are used for different applications. Many material properties cannot be determined just by visually examining a material. This lab will demonstrate that two polymers balls that look identical may exhibit different material properties under various temperature conditions due to differences in the material structure. The two polymer balls are made of Neoprene© and Norsorex©.

Neoprene® (Happy ball) is the trade name for polychloroprene. It will have a softer texture and will bounce well. It has high hysteresis, meaning that when it is deformed (such as when it collides with something) it wants to return to its 'normal' condition (the ball immediately bounces back up to try to return to its original shape). This material is often used in swimsuits and wetsuits because it is very flexible while still maintaining its shape, and it retains heat well.

Norsorex® (Sad ball) is the trade name for polynorbornene. It is also known under the names Noene®, Sorbothene®, and Astrasorb®. It has low hysteresis, meaning that when it is deformed it has no desire to return to a 'normal' condition. This ball tends to absorb or dampen the kinetic energy of the bounce. It produces a characteristic "thud" sound upon impact. It too is used as clothing in the form of artificial leather as well as for sound insulation, damping, and seals and gaskets. Norsorex® is also commonly used for making body armor as it is a dense, closed cell foam that has the ability to spread impact forces over a wide area.

Polymers, such as these, have a rather unique property referred to as the glass transition temperature. This property is the temperature at which the material changes from a hard, glassy crystalline material to a soft, rubbery, amorphous material. The two balls have different glass transition temperatures, and that partially accounts for the reason they bounce at different levels. The Happy ball's glass transition temperature is -42°C. Therefore, it is highly elastic at temperatures above its glass transition temperature and has a high level of rebound vs. bounce rate. Upon cooling the Happy ball below its glass transition temperature with liquid nitrogen (LN_2), the ball becomes less elastic, and the bounce rate is also less. Heating the Happy ball in boiling water has no appreciable effect, and it will basically bounce the same as it did at room temperature. The Sad ball has a glass transition temperature of 35°C. It is, therefore, very non-elastic and does not bounce very high. The Sad ball is often characterized as falling "like a rock". Upon cooling it with either ice cubes in a Styrofoam chest, dry ice, or LN_2, the ball bounces even less than at room temperature. Heating the Sad ball in boiling water makes the ball considerably more elastic, and it will bounce to perhaps one-third that of the room temperature Happy ball bounce. See the Introductory Presentation for examples of real-world applications of these polymers.

Lab Description: In this lab, students will test the material properties of two seemingly identical polymer balls. Students will evaluate and compare the mass, radius, density, and rebound of the two balls at different temperature conditions. Three stations will be set-up with each station containing one pair of balls. The stations will correspond to room temperature, chilled, and heated temperature conditions. Students will rotate through the stations performing the same set of experiments at each station to evaluate the influence of temperature on the material properties of the two balls.

Keywords:
Material property: characteristic attribute of a material which can be measured in a meaningful way
Polymer: chemical compound with a structure of many repeating sub-units
Impact: a force applied over a short period of time when 2 or more bodies collide
Absorb: to receive an impact or vibration without rebound
Elasticity: ability of a material to deform when loaded and then return to its original shape upon unloading
Rebound: to bounce back after colliding with another body
Deform: to alter the original shape of a material, usually by pressure or stress
Friction: force that resists the motion of 2 materials sliding against each other

Materials List:
Items provided in the kit:
3 Happy (Neoprene®) balls
3 Sad (Norsorex®) balls
Mass balance

Items to be provided by the teacher/school:
Freezer
Hotplate
6 Meter sticks (6 yard sticks or 6 tape measures will also work)

Salt (Kosher salt works best for this lab as it creates a clear solution. Table salt produces a cloudy solution)
2 Pans or beakers (one needs to be appropriate for heating, the other just needs to be large enough to have a water depth of ~ 3 inches)
1 Insulated container full of ice
Tongs
Water
Dry ice/liquid nitrogen – OPTIONAL

Safety Precautions: This lab does not require any safety apparel, although standard lab rules and procedures (e.g. using the items as described in the handout, not for any other purposes) should be followed. If you are using hot water, be aware of the temperature of the water. If you are using liquid nitrogen or dry ice, be aware of the extreme cold temperatures these materials have and take necessary precautions. Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Keep liquid nitrogen away from students.
- Wear safety goggles at all times.
- Use tweezers to handle small objects that have been/will be submerged in liquid nitrogen. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

1. The day before the demonstration, take one pair of Happy/Sad balls and place them in the freezer. Leave the balls in the freezer until just before the lab. Place the balls in the insulated container filled with ice (such as a large Styrofoam cup or an insulated coffee mug) when removing them from the freezer. Since the balls look identical, it is often helpful to label the balls with an 'H' for Happy and an 'S' for sad using a silver or white-

colored paint pen. This will help keep students from mixing up the two balls since they will not know how each ball is expected to behave prior to performing the lab.

2. A few minutes prior to the start of the lab, fill one of the pans with water and begin heating it on the hotplate (it will take several minutes for the water to heat to an appropriate temperature, so begin this process early).
3. Set-up 3 stations in the classroom. The stations will correspond to room temperature balls, chilled balls, and heated balls. The following is a list of the items that should be at each station:
    a. Room temperature station
        i. Room temperature pair of Happy/Sad balls
        ii. Pan full of room temperature water
        iii. Salt
        iv. 2 Meter sticks
    b. Chilled temperature station
        i. Chilled pair of Happy/Sad balls in a cup filled with ice
        ii. 2 Meter sticks
    c. Heated temperature station
        i. Heated pair of Happy/Sad balls in a pan of heated water on a hotplate.
        ii. Tongs
        iii. 2 Meter sticks

    Place the mass balance at a convenient location for all 3 stations as this must be shared among the stations.
4. Split the students into 3 groups. Assign each group a station. The following steps outline the calculations performed at each station.
5. Room temperature station
    a. Make a prediction about the density of the Happy/Sad balls – which one do you think will be more dense? Make a prediction about which ball will perform better in terms of % rebound (i.e. which one will bounce better). Make a prediction about which ball will roll down the inclined plane the fastest.
    b. Measure the radius (cm) of the Happy ball and the Sad ball and record it on the Student Question Handout.
    c. Weigh each ball and record the mass (g) on the Student Question Handout.
    d. Calculate the volume and density of each ball using the following equations:

$$Volume = \frac{4}{3}\pi\ r^3$$

$$Density = \frac{Mass}{Volume}$$

where r = radius of the ball. Density should be in units of g/cm^3.

e. Hold the meter stick in a vertical position and bounce each of the balls one at a time from a height of 1 meter. Record the height to which each ball bounces, or rebounds. Repeat this 3 times for each ball and calculate the average rebound for each ball using the following equation:

$$\%\ rebound = \frac{rebound\ \ height}{initial\ \ height} * 100$$

The Sad Ball should have a rebound of 0 meters, and the Happy Ball about 0.6 meters.

f. Hold the meter sticks side by side (leave a few inches in between) in an inclined position. Roll the balls simultaneously down the meter sticks, one on each stick. Repeat 3 times for consistency. Record which ball reached the floor first. The Sad ball should reach the floor first since it has a lower coefficient of friction, allowing it to roll faster.

g. Place both balls in the pan full of room temperature water. Record what happens to the balls. Both balls should sink, indicating that the balls are more dense than water (density of water = 1 g/cm^3).

h. Slowly add salt to the water and stir the salt/water solution. Continue adding salt until something happens to one of the balls. As the density of the water increases, one of the balls will float up first. This ball is the Sad Ball. This indicates that the Sad ball is less dense than the Happy ball.

i. Remove both balls from the salt water and dry them. Dispose of the salt water and refill the pan with fresh water so it is ready for the next group.

6. Chilled temperature station

   a. Repeat Steps a-f in Step 5 with the chilled Happy and Sad ball.

   b. Place the chilled balls back in the ice after testing so that they are ready for the next group.

7. Heated temperature station

   a. Using the tongs, carefully remove the Happy and Sad ball from the boiling water.

   b. Repeat Steps a-f in Step 5 with the heated Happy and Sad ball.

c. Place the balls back into the boiling water after testing so that they are ready for the next group

8. Compare the results from all 3 stations to determine the influence of temperature conditions on the Happy ball and the Sad ball material properties.

Demo Delivery Hints:

1. Making the connection between the temperature effect on a property and the behavior of the material is key. Taking the time to analyze the bounce back of each ball at each temperature treatment is crucial to highlighting the ability to engineer desired properties.
2. If using liquid nitrogen/dry ice to cool the balls, be sure to allow the balls to warm to almost room temperature before dropping. If the balls are dropped immediately after removing from the liquid nitrogen/dry ice, they will shatter! It is recommended that you assist students with the chilled temperature station if you are going to use liquid nitrogen or dry ice to cool the balls.
3. Depending on your class size, it may be beneficial for you to have more Happy/Sad ball pairs so that students can be split into smaller groups at each station. Happy/Sad ball pairs can be purchased from a number of different websites, but be aware that the materials used in the balls might vary. It is recommended that you purchase the same balls that were included in this kit in order to ensure that similar behavior is demonstrated among the different pairs. The balls included in this kit came from Arbor Scientific (http://www.arborsci.com/happy-unhappy-balls-happy-sad-balls).

Troubleshooting: It is advised that the chilled balls be kept in the freezer as long as possible, and the heated balls should be kept as close to the boiling temperature of water as possible. The wider the temperature range, the wider the spectrum of material behavior.

Cleanup/Replacement parts: Allow each set of balls to return to room temperature. Dry each pair and return them to the kit. Turn off the hotplate and allow it and the glass cup to return to room temperature before storing. Dispose of any leftover water or ice.

TEACHER DISCUSSION QUESTIONS

Happy Ball / Sad Ball

Discussion Questions to Ask Before the Demo

1. What is a material property?

   Discussion: A material property is a characteristic attribute of a material that can be measured in a meaningful way.

2. What are some examples of properties?

   Discussion: Corrosion resistance – ability to not react with surroundings (e.g. stainless steel)
   Reactivity – reactive towards other chemicals and materials (e.g. explosives)
   Electrical conductivity – Ability of electrical current to flow through a material (e.g. wires)
   Magnetism – generates and interacts with magnetic fields (e.g. magnets)
   Density– mass per volume (e.g. g/cm^3)
   Elasticity – ability of a material to deform under force, then return to its original shape (e.g. rubber bands)
   Hardness – ability to withstand surface deformation under applied force (e.g. diamond)
   Tensile Strength – ability to withstand tensional force (e.g. steel cable)
   Color – color material appears to be (e.g. crayons)
   Reflectivity – ability to reflect (e.g. mirror)
   Melting Point – temperature that the material becomes liquid (e.g. ice to water)

3. What is elasticity?

   Discussion: Elasticity is the ability of a material to deform when loaded and then return to its original shape upon unloading. All the energy of the stretch is returned as it un-stretches.

4. What are some examples of materials that are elastic?

   Discussion: Rubber bands, exercise tubing, rubber balls, springs

Discussion Questions to Ask During the Demo

1. Upon seeing how the two rubber balls react differently, what will happen when the balls are either heated or cooled before testing?

   Discussion: The point of asking this question is to get the class to discuss the possible outcomes of the different temperature treatments. It is recommended that you encourage the students to discuss not only why they make these predictions, but how they can test their hypothesis.

Discussion Questions to Ask After the Demo

1. Upon completion of the various temperature treatments, how did your predictions match the outcome of the temperature treatments?

   Discussion: Have the students compare their results with their predictions. Encourage students to discuss why they match/differ. Try to explain what is happening inside the material by using the provided Background Information in the Teacher Instructions.

2. What are the benefits of having a material act in either of these two distinctly different ways?

   Discussion: Having a material either elastically deform quickly or slowly can be useful in the development of rubber parts such as coatings, pads, and toys.

STUDENT LAB HANDOUT

Happy Ball / Sad Ball

Introduction: An introduction to material properties is crucial to understanding the world of materials science. Materials are selected and engineered based on the desired properties for an application. Developing an understanding of material properties is the first step in understanding why different materials are used for different applications. Many material properties cannot be determined just by visually examining a material. This lab will examine two polymers balls that look identical but have different material structures. The two polymer balls are made of Neoprene© and Norsorex©.

Lab Description: In this lab, you will test the material properties of two seemingly identical polymer balls. You will evaluate and compare the mass, radius, density, and rebound of the two balls at different temperature conditions. Three stations will be set-up with each station containing one pair of Happy/Sad balls. The stations will correspond to room temperature, chilled, and heated temperature conditions. You will rotate through the stations performing the same set of experiments at each station to evaluate the influence of temperature on the material properties of the Happy/Sad balls.

Keywords: Material property, polymer, impact, absorb, elasticity, rebound, deform, friction

Materials List:

Room temperature station
- Room temperature pair of Happy/Sad balls
- Pan full of room temperature water
- Salt
- 2 Meter sticks

Chilled temperature station
- Chilled pair of Happy/Sad balls in a cup filled with ice
- 2 Meter sticks

Heated temperature station
- Heated pair of Happy/Sad balls in a pan of heated water on a hotplate.
- Tongs
- 2 Meter sticks

Safety Precautions: Be aware of the temperature when handling the hot and cold polymer balls. If liquid nitrogen is being used, extra precautions should be taken to assure safe handling. Liquid nitrogen is a hazardous substance. If misused, it may cause frostbite, eye damage, torn flesh, or asphyxiation. **ALWAYS FOLLOW THESE SAFETY RULES:**

- Wear safety goggles at all times.
- Use tweezers to handle small objects that have been/will be submerged in liquid nitrogen. Plastic tweezers are desired but should be tested for embrittlement (see last caution) before use in the classroom.
- Wear insulating gloves when handling liquid nitrogen containers or large, cold objects.
- Use liquid nitrogen only in well ventilated places.
- Do not allow liquid nitrogen to touch any part of your body.
- Items in contact with liquid nitrogen become **EXTREMELY COLD**. Do not touch any item that has been immersed in liquid nitrogen until it has warmed to room temperature.
- Do not store liquid nitrogen in any container with a tight-fitting lid. A tightly sealed container will build up pressure as the liquid boils and may **EXPLODE** after a short time.
- Many substances become brittle and may shatter when cold, sending pieces of the material flying. Avoid common glass and large, solid plastics.

Instructions:

1. There will be 3 different stations set-up around the classroom. A mass balance will be located in the center of the room. You must share the mass balance with the other stations.

2. Read through all of the following steps to be sure you understand the procedures and calculations to be performed at each station. Go to the station assigned by your teacher and perform the appropriate procedures and calculations for each station.

3. Room temperature station

    a. Make a prediction about the density of the Happy/Sad balls – which one do you think will be more dense? Make a prediction about which ball will perform better in terms of % rebound (i.e. which one will bounce better). Make a prediction about which ball will roll down the inclined plane the fastest. Record your predictions on the Student Question Handout.

    b. Measure the radius (cm) of the Happy ball and the Sad ball and record it on the Student Question Handout.

    c. Weigh each ball and record the mass (g) on the Student Question Handout.

    d. Calculate the volume and density of each ball using the following equations:

$$Volume = \frac{4}{3}\pi\ r^3$$

$$Density = \frac{Mass}{Volume}$$

where r = radius of the ball. Density should be in units of g/cm^3.

e. Hold the meter stick in a vertical position and bounce each of the balls one at time from a height of 1 meter. Record the height to which each ball bounces, or rebounds. Repeat this 3 times for each ball and calculate the average rebound for each ball using the following equation:

$$\%\ rebound = \frac{rebound\ \ height}{initial\ \ height} * 100$$

f. Hold the meter sticks side by side (leave a few inches in between) in an inclined position. Roll the balls simultaneously down the meter sticks, one on each stick. Repeat 3 times for consistency. Record which ball reached the floor first.

g. Place both balls in the pan full of room temperature water. Record what happens to the balls.

h. Slowly add salt to the water and stir the salt/water solution. Continue adding salt until something happens to one of the balls.

i. Remove both balls from the salt water and dry them. Dispose of the salt water and refill the pan with fresh water so it is ready for the next group.

4. Chilled temperature station

   a. Remove the chilled Happy and Sad ball from the insulated container of ice.

   b. Repeat Steps a-f in Step 3 with the chilled Happy and Sad ball.

   c. Place the chilled Happy/Sad balls back in the ice after testing so that they are ready for the next group.

5. Heated temperature station

   a. Using the tongs, carefully remove the Happy and Sad ball from the boiling water.

   b. Repeat Steps a-f in Step 3 with the heated Happy and Sad ball.

   c. Place the Happy/Sad balls back into the boiling water after testing so that they are ready for the next group

6. Compare the results from all 3 stations to determine the influence of temperature conditions on the Happy ball and the Sad ball material properties.

Cleanup: Allow each set of balls to return to room temperature. Dry each pair and return them to the kit. Turn off the hotplate and allow it and the glass cup to return to room temperature before storing. Dispose of any leftover water or ice and dry any damp items with a paper towel.

STUDENT QUESTION HANDOUT

Happy Ball / Sad Ball

1. Make a prediction about which ball has the higher density at room, chilled, and heated temperatures.

2. Given the mass (g) and radius (cm) of each ball, calculate the density for of each ball using the following equations:

$$Volume = \frac{4}{3}\pi\ r^3 \qquad Density = \frac{Mass}{Volume}$$

	Room Temp. Happy Ball	**Room Temp. Sad Ball**	**Chilled Happy Ball**	**Chilled Sad Ball**	**Heated Happy Ball**	**Heated Sad Ball**
Mass						
Radius						
Volume						
Density						

3. Which ball had the higher density at room, chilled, and heated temperatures?

4. What can the material's density tell you about the material's stiffness?

5. Make a prediction about which ball has the higher rebound at room, chilled, and heated temperatures.

6. Measure and record the bounce height of the Happy and Sad ball at room, chilled, and heated temperatures.

Temperature Condition	Happy Ball Bounce Heights (3 measurements)	Happy Ball Bounce Height Average	Sad Ball Bounce Heights (3 measurements)	Sad Ball Bounce Height Average
Room Temp				
Chilled				
Hot				

7. Calculate the % rebound for each ball at each temperature condition. Which ball had the higher % rebound at room, chilled, and heated temperatures?

8. Did the behavior of either ball change as the temperature changed?

9. How does the material's stiffness correlate to bounciness?

10. Make a prediction about which ball will be the fastest to roll down the inclined plane at room, chilled, and heated temperatures.

11. Evaluate which ball rolls down the inclined plane the fastest at room, chilled, and heated temperatures.

Temperature Condition	Fastest Ball
Room Temp	
Chilled	
Hot	

12. Which ball rolled the fastest at room, chilled, and heated temperatures? Why?

13. What would be a useful application of either of these materials?

14. Name 2 material properties that would be useful to engineers. What applications would these properties be useful for?

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TEACHER INSTRUCTIONS

Chocolate Strength – How Strong is Your Chocolate?

Objective: To demonstrate how material properties, such as microstructure, can influence the strength of a material.

Background Information: Materials such as *metals* (aluminum, iron, copper, etc.), *ceramics* (porcelain, silicon carbide, etc.) and *polymers* (milk jugs made of polyethylene) are tested by scientists and engineers to reveal the material's mechanical properties. There are a range of mechanical tests that can be performed depending on the needed application of a material. One type of mechanical testing is strength testing. Strength is a measurement of the maximum stress that a material can withstand. Stress is the force applied per the unit area (usually the cross-sectional area perpendicular to the force being applied). Using this metric, an engineer can determine the strength of any object, from a tiny bobby pin to a gigantic beam for a skyscraper.
Many of the materials that we see everyday are subjected to a variety of stresses and must be designed to provide a certain measure of strength. For example, a concrete bridge must have enough strength to withstand vehicles driving on it day after day.

It is necessary to understand how materials respond to stresses so that the correct material can be chosen for a specific application. A material's atomic structure, the type and way that atoms are bonded to one another into different arrangements, is a major factor that influences the strength of a material. However, two materials that share all of the same atomic traits can still have different strengths if their microstructure is altered due to processing. The chocolate bars in this lab are an excellent example of how microstructure can be altered due to processing. The chocolate in all of the bars has the same atomic traits (milk chocolate), however the microstructures differ (e.g. almonds in the bar, crisped rice in the bar, etc.). See the Introductory Presentation for examples of how material properties can influence the strength of a material in real-world applications.

Lab Description: In this lab, different types of chocolate bars will be tested to demonstrate the influence of different microstructures on the flexural strength (i.e. stress) of the chocolate bar. The flexural strength of the chocolate bars will be measured using a conventional 3-point bending test set-up as shown in Figure 1.

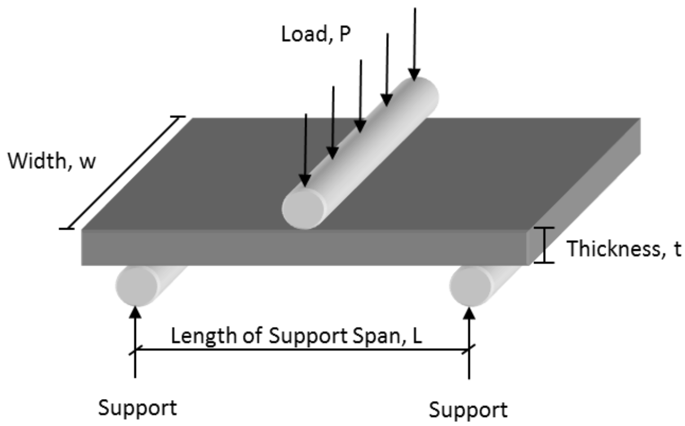

Figure 1. Test set-up for a 3-point bending test

For this test set-up, chocolate bars are placed on two supports (making 2 points of contact), and a force is applied to the center of the bar (making the 3rd point of contact in the 3-point bending test). The flexural strength of the bar is essentially the highest stress that the material experiences during its moment of rupture (failure) and can be calculated from the following equation:

$$\sigma = \frac{1.5PL}{wt^2}$$

where σ is the flexural strength (MPa), P is the applied force (N), L is the span length (mm), w is the width of the bar (mm), and t is the thickness of the bar (mm).

Keywords:

Mechanical properties: description of how a material behaves in response to applied forces
Stress: force applied per unit area
3-point bending test: standard test to measure the flexural strength of a material
Microstructure: structure of a material as observed through microscopic examination

Materials List:

Items provided in the kit
5 Plastic cups with twine
1 Mass balance

Items to be purchased/provided by the teacher
Pennies – each group will need approx. 350 pennies. Alternative mass objects, such as rice or beans can also be used to load the chocolate bars.
5 Protective mats to catch the chocolate when it falls (aluminum foil, saran wrap, etc.) – one for each group
5 Rulers – one for each group
5 Milk chocolate bars – one for each group
5 Milk chocolate bars with almonds – one for each group

5 Milk chocolate bars with crisped rice (such as Crunch® bars or cheaper equivalent) – one for each group

****Note:** try to purchase chocolate bars of approximately the same thickness**

Safety Precautions: This lab does not require any safety apparel, although standard lab rules and procedures (e.g. using the items as described in the handout, not for any other purposes) should be followed.

Instructions:

1. Measure and record the following information about the chocolate bar:
    a. Type (milk chocolate, almond, crisped rice, etc.)
    b. Width of the bar (mm), w
    c. Thickness of the bar (mm), t
2. For each type of chocolate bar, make a prediction of how many pennies you think the chocolate bar can hold.
3. Position two desks so that the chocolate bar can span across the space between the desks. Approximately ½ inch of the chocolate bar should be touching each desk.
4. Measure and record the length of the chocolate bar that is not supported by the desks. This is called the length of the support span, L.
5. Place the twine with the cup attached across the middle of the chocolate bar so that the cup hangs freely below the chocolate bar as shown in Figure 2.

    Note: If the chocolate bar is 'scored' (indents in the chocolate which make it easier to break into pieces), and the string is centered in the score as shown in Figure 2, the bar will be less strong than a bar of equal size that does not have score lines (ex. a Crunch® bar). While it would be best to be consistent (either have all the bars with score lines or no score lines at all), this can be difficult to find at times in a local grocery store. It is ok to run this lab with a combination of chocolate bars with/without scores, but the point should be made to the students that this may cause some differences in the bar's strength that has nothing to do with changes in the microstructure, but rather a difference in geometry. This is part of the reason why this lab utilizes the calculation of flexural strength rather than just comparing the chocolate bars based on the number of pennies in the cup at failure. The flexural strength calculation attempts to account for the geometry of the bar during the loading process. If the bar contains score lines, you can have students measure the thickness of the bar at a score line and away from the score line. Use each set of dimensions to calculate the flexural strength of the bar and compare the two values. The actual flexural strength of the bar is most likely an average of these values.

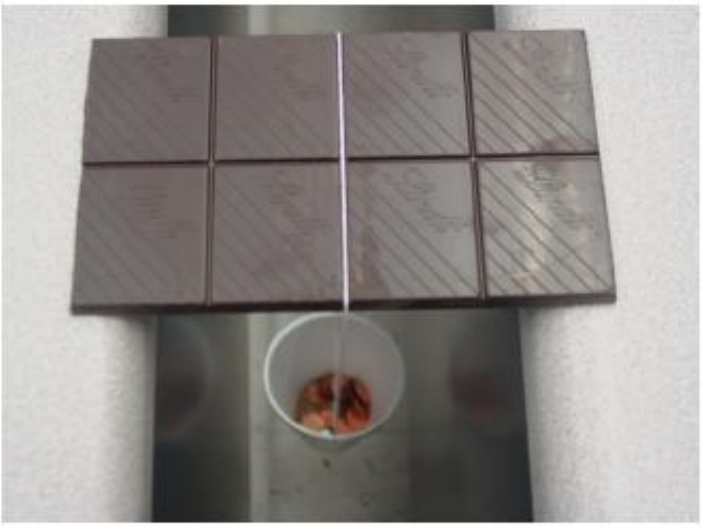

Figure 2. Chocolate bar subjected to a 3-point bending test

6. Place a mat on the floor to protect the chocolate when it falls. Plastic wrap, aluminum foil, or a Tupperware container work well for containing the chocolate and any pennies that might spill out of the cup when the chocolate bar falls.
7. Create a paper funnel by rolling a piece of paper and either stapling or taping it.
8. Using the funnel, start placing the pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of 2-3 pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
9. Continue placing pennies into the cup at a steady rate until the chocolate bar fractures. Be sure to note any deflections or bending of the chocolate bar during the loading process. Note: If it is difficult to see the bar start to deflect, place the ruler across the desk just to the side of the chocolate bar to help indicate when the bar starts to deflect from a horizontal line.
10. Record the number of pennies in the cup at the time of fracture.
11. Look at the fracture surface and record any observations.
12. Find the mass (in grams) of the cup, twine, and the pennies in the cup at fracture using the mass balance. The force, P, applied to the chocolate bar can then be calculated as follows:

    P = (weight of cup, twine, and pennies)*(acceleration due to gravity = 9.81m/s^2)

    If you do not have access to a mass balance, use the following weights to approximate the mass.

    a. Weight of one penny – 2.35 grams
    b. Weight of the cup and twine – 25 grams

    The force, P, applied to the chocolate bar can then be calculated as follows:

P = ((weight of penny)*(# of pennies) + weight of cup and twine)*(gravity = 9.81m/s^2)

13. Use the force, P, found in step 12 to calculate the flexural strength of the chocolate bar. The formula for calculating flexural strength is found in the Description section of these instructions.
14. Repeat steps 1-13 for each chocolate bar to be tested.
15. Have students discuss any differences in the strength of the chocolate bars. Example questions can be found in the Student Questions Handout

OPTIONAL ADDITIONS TO THE LAB

****Note:** these steps would need to be added to the Student Lab Handout and will require additional chocolate bars for testing**

16. Ask students to modify something about the test set-up (e.g. loading towards one end of the chocolate bar vs. in the middle, applying the pennies at a much faster rate, etc.)
17. Repeat steps 1-13 with a milk chocolate bar and using their new set-up
18. Have the students discuss what they chose to change and how it influenced the strength of the bar and why.
19. Take a milk chocolate bar and allow it to melt slightly (heat with a hairdryer until the chocolate bar feels mushy, or set outside for a few minutes on a hot summer day). Then place the chocolate bars at room temperature until the bars have re-hardened. This should typically be done the day before the lab so that the bars have plenty of time to cool and re-harden.
20. Repeat steps 1-13 with the 'heat-treated' chocolate bar.
21. Have students discuss any differences in the strength between the treated bar and the regular chocolate bar.

Lab Delivery Hints:

1. This lab is best done in groups of 3-4 students. One student should be responsible for taking the dimensions of the bar. Another student should be responsible for funneling the pennies into the cup, and 1-2 students should monitor any changes in the chocolate bar during the loading process. These responsibilities should be rotated as different chocolate bars are tested.
2. Chocolate can get expensive for this lab. Be creative with how you purchase and use the chocolate! For example, the 6 pack of regular size Hershey's® bars is often sold for almost half of what 6 bars would cost individually. In addition, the regular size bars can often be broken in half so that you get 2 tests out of each bar. That is the main reason that this lesson uses flexural strength (which takes geometry of the bar being tested into account) – it allows you the flexibility to use different size bars! Feel free to experiment with snack size or mini-size bars as well. These can often be purchased in a multi-pack which tend to include crisped rice bars, almond (or peanut) bars, and milk chocolate bars. You may even have enough left over from a multi-pack of small bars to use them as rewards later in the semester.

Troubleshooting: This lab is easy to set-up and run. It may take students a few tries to figure out how to funnel the pennies into the cup at a consistent rate. You can have the students practice funneling using a ruler in place of the chocolate bar. This will allow them plenty of time to get comfortable with their technique since the ruler would require a much heavier load to break.

Cleanup/Replacement parts: Eat the chocolate! Clean any chocolate residue from the cup and twine with a wet paper towel and return it to the kit for later use. The chocolate bars will need to be replaced before the lab can be performed again. It is best to use fresh chocolate that has not been subjected to extreme hot or cold temperatures. Exposing the chocolate to extreme temperatures may change the strength of the bar and can cause a lot of variability in the measurements from group to group.

TEACHER DISCUSSION QUESTIONS

Chocolate Strength – How Strong is Your Chocolate?

Discussion Questions to Ask Before the Lab

1. Ask students what type of materials they think that scientists and engineers test for mechanical properties.

   Discussion: Emphasize that scientists and engineers look at many different types of materials such as metals, ceramics, and polymers.

2. Ask students what type of testing they think that scientists and engineers perform to determine material mechanical properties.

   Discussion: Emphasize that there are a range of mechanical tests that can be performed depending on the needed application of a material. One type of mechanical testing is strength testing. Strength is a measurement of the maximum stress that a material can withstand before breaking. Common mechanical testing for strength includes compression, tension, and flexural (bending) testing. See the Introductory Presentation for examples of various mechanical testing methods. Many of the materials that we see everyday are subjected to a variety of stresses and must be designed to provide a certain measure of strength. It is necessary to understand how these materials respond to mechanical stresses so that the correct material can be chosen for a specific application. The atomic structure of a material is a major factor that influences the strength of a material and involves the elements in the material – the way they are bonded to each other and the way the atoms are arranged to make different structures. However, two materials that share all of the same atomic traits can still have different strengths if their microstructure is altered due to processing. The chocolate bars in this lab are an excellent example of how microstructure can be altered due to processing. The chocolate in all of the bars has the same elemental make-up and atomic traits (all of the bars are milk chocolate), however the microstructures differ (e.g. almonds in the bar, crisped rice in the bar, etc.). It is important to understand how these changes in the microstructure can affect the strength of the chocolate bar.

3. Ask students why it is important for scientists and engineers to understand the mechanical properties of different materials.

   Discussion: Show the video of the I-35W Mississippi River Bridge collapse in 2007. This video is available on the Wikipedia website as well as a number of other websites (http://en.wikipedia.org/wiki/File:35wBridgecollapse.gif). The I-35W bridge collapsed during rush hour in August 2007, killing 13 people and injuring 145 (***Note:*** *The bridge collapse video was captured by a security camera that was located just to the side and below the bridge, therefore the video does not show any people. It is difficult to even see the vehicles on the bridge during collapse. However, this collapse did result in fatalities* *and multiple injuries. It is at the teacher's discretion whether to show the video and discuss that fatalities did occur. For younger students, this information can be 'glossed' over and the point can still be made that the bridge collapsed due to loading issues*). The reason for the collapse was attributed to a design flaw coupled with additional weight, or load, on the bridge at the time of collapse. The design flaw led to the bridge being under-designed (should have used larger steel members) for the loads it would normally be carrying. In the weeks prior to collapse, construction was being done on half of the bridge. At the time of collapse, **575,000 pounds** of construction equipment and supplies were on the bridge in addition to the typical vehicle traffic expected during rush hour. This, coupled with the design flaw, led to a catastrophic failure of the bridge. It is important for scientists and engineers to understand the mechanical properties of different materials so that they can make sure that the materials are being used in an appropriate way.

4. Give students a brief description of what will be done during the lab. Ask each student to make a prediction about the number of pennies they think that each type chocolate bar can withstand.

   Discussion: Encourage each student to choose a different number for each type of chocolate bar and explain why they chose that number. There is no right or wrong answer to this question – the point is to get the students thinking about how the bars are different and to make a prediction about the behavior of each bar.

Discussion Questions to Ask During the Lab

1. As each chocolate bar is tested, ask students what they noticed about the bar during the loading process. Did it sag before breaking? Did it stretch at all? Have them record their observations on the data sheet included in the Student Lab Handout.

   Discussion: Students should be able to see the chocolate start to sag, or deflect, before it breaks. Have them place the ruler across the desks just to the side of the chocolate bar to help them check whether the chocolate bar has deflected.

2. After each bar is tested, ask students what they think about the performance of that particular bar. Were there any differences between the bar they just tested and the previous bars they have tested? If yes, what do they think is the cause of this difference?

   Discussion: Have students test the milk chocolate bar first. This is the 'control' bar as nothing has been done to change the microstructure, and should be what the students use as a comparison to other chocolate bars. For the chocolate bar with almonds, the inclusion of almonds will tend to act like large defects. The almond is very strong compared to the chocolate bar, but it is also very dense and non-porous. This makes it difficult for the chocolate to achieve a strong bond with the almond. In addition, almonds are fairly large in diameter compared to the thickness of a typical chocolate bar. If the bond is already weak between the almond and chocolate bar, and this bond runs the entire thickness of the chocolate bar (meaning you can see the almond sticking out on both sides of the chocolate bar), it will influence the strength in a negative way. Depending on how close an almond is to the point of loading and the points of support, this chocolate bar should fail at a lower load (number of pennies) than the milk chocolate bar due to the failure of the bond between the almond and the chocolate. There will probably be a high variability in the max load that each group finds for the almond bar due to the fact that the almonds are spread randomly throughout the bar. In contrast, the inclusion of crisped rice in the chocolate bar is much more uniform. Crisped rice is also a very low density, high porosity material, meaning that the chocolate will tend to fill the pores of the crisped rice. This allows for a much better bond to be formed between the rice and chocolate. In addition, crisped rice is fairly small in comparison to the thickness of a chocolate bar which means that the chocolate will be spread more uniformly around the crisped rice and should allow for good load transfer across the bar. This bar typically performs the same as or better than the milk chocolate bar, and the max load that each group finds for the bar with crisped rice will probably be more consistent than for the bar with almonds.

A material's microstructure can be processed by using an additive (the crisped rice or almonds in our example), or by simply causing changes in the original microstructure (such as adding air voids or using heat treatment to produce different chemical compounds within a microstructure). Depending on the type of processing performed, the new microstructure may have properties that are different from the original microstructure. In some cases, these properties will be better, but in some cases the properties will be the same or worse than the original material. For example, in the case of adding an additive such as crisped rice to milk chocolate, perhaps this material is cheaper and substituting a percentage of the milk chocolate with crisped rice provides cost savings to the manufacturer. This allows the manufacturer to not only provide a chocolate bar that tastes different from the original and provides similar or better mechanical properties (meaning it won't easily break into pieces during shipping and transportation), but might also provide more profit for the company as most chocolate bars are sold at similar prices. In many real-world applications, such as adding fiber reinforcement to concrete (see the Engineered Concrete lesson for a discussion of this topic), processing of the microstructure can yield a much stronger material. In the case of processing the original microstructure, perhaps it is difficult for the manufacturer to maintain a 'pure' microstructure, so knowing that a certain percentage of change is still ok in terms of the desired material properties would allow the manufacturer to produce the material more easily. Table 1 provides a summary of the behavior of various types of milk chocolate bars. Teachers are encouraged to supplement the instructions with other types of bars to help students understand that additives/processing can cause the bar to behave differently and that it is important to understand this influence on a material's behavior so that the material can be properly designed for a given application.

Table 1. Chocolate Bar Testing Table

Type of Bar	Type of Processing	Bar Pictorial Description	Testing Dimensions* (mm) L** x W x T	Failure load in pennies (flexural strength in parentheses)
Hershey's® Milk Chocolate	None	Wrapper  Front  Cross-section  Back 	95 x 50 x 9	297 (25.4 MPa)
Hershey's® with Almonds	Almonds added	Wrapper  Front  Cross-section  Back 	95 x 50 x 10	186 (13.2 MPa)

Crunch® Bar	Crisped rice added	Wrapper  Front  Cross-section  Back 	95 x 42 x 8	296 (38.2 MPa)
Hershey's® Air Delight	Air bubbles added	Wrapper  Front  Cross-section  Back 	95 x 39 x 10	256 (22.9 MPa)

Mr. Goodbar®	Peanuts added	Wrapper  Cross-section 	Front  Back 	95 x 43 x 8	103 (13.8 MPa)
Butterfinger® Bar	Butterfinger pieces added	Wrapper  Cross-section 	Front  Back 	72 x 42 x 7	51 (7.6 MPa)

*Dimensions refer to the dimensions of the bar tested. In some cases, an extra-large bar was the cheapest bar to purchase. This large bar was split into smaller pieces and tested in the 3-point bending test.
**L refers to the unsupported length during the test as defined in the Lab Description section of the Teacher Instructions

Discussion Questions to Ask After the Lab

1. At the end of the lab, ask students to compare all of the chocolate bars that they tested. Have them state reasons for any differences in the flexural strength of the bars tested and why they think those differences occurred. Encourage discussion among the groups. Did everyone see the same thing? Did bars of the same type perform differently for different groups?

   Discussion: Should be the same as what was discussed in Questions 5 and 6, but have the students actually write down their reasoning in the Student Questions Handout and discuss what the other groups found as well.

2. Have students determine the average number of pennies that each type of bar withstood and compare it to their guess.

   Discussion: For example, if the number of pennies recorded by 3 groups for the milk chocolate bar was 234, 358, and 279, have students calculate the class average using the following formula:

$$average = \frac{\text{sum of all measurements}}{\text{\# of measurements}} = \frac{234+358+279}{3} = 290.33 = 290 \text{ pennies}$$

   For each type of bar, determine which student guessed closest to the class average. Offer a prize, such as an additional chocolate bar, to the student that had the best guess for each type of chocolate bar.

3. For older students, also have them calculate the standard deviation of the class averages found in Question 8 and compare the bars in terms of standard deviations.

   Discussion: For the same measurements of 234, 358, and 279, the standard deviation can be calculated as follows:

$$\text{standard deviation} = \sqrt{\frac{\sum_{i=1}^{N} (\mathrm{x_i} - average)^2}{\mathrm{N}}}$$

   where N is the number of measurements and x_i are the individual measurement values. The calculated standard deviation for this example is:

$$\text{st.dev.} = \sqrt{\frac{(234-290.33)^2 + (358-290.33)^2 + (279-290.33)^2}{3}} = 50.80$$

   The higher the standard deviation, the greater the spread (or variability) in the data. Have students compare the standard deviations of the chocolate bars that were tested. Alternatively, if computers are available, have the students plot the class data for each bar in an application such as Excel and add trend lines to examine the variability of the data. This provides a visual representation of the information provided by the standard deviation.

Bars that are heterogeneous, like the bar with almonds, will tend to have higher standard deviations. Since the almonds are scattered randomly throughout the bar, the number of pennies that the bar can hold will vary. Due to bonding issues between the almond and the chocolate, an almond near the location of the twine holding the cup or one of the supports will create a weak point quicker than if the almond is far away from the load contact points. Since the location of the almonds in each bar is different, the test result will be different as well.

STUDENT LAB HANDOUT

Chocolate Strength – How Strong is Your Chocolate?

Introduction: Materials such as *metals* (aluminum, iron, copper, etc.), *ceramics* (porcelain, silicon carbide, etc.) and *polymers* (milk jugs made of polyethylene) are tested by scientists and engineers to reveal the material's mechanical properties. One type of mechanical testing is strength testing. Strength is a measurement of the maximum stress that a material can withstand. Many of the materials that we see everyday are subjected to a variety of stresses and must be designed to provide a certain measure of strength.

The atomic structure of a material is a major factor that influences the strength of a material and involves the elements in the material – the way they are bonded to each other and the way the atoms are arranged to make different structures. However, two materials that share all of the same atomic traits can still have different strengths if their microstructure is altered due to processing. The chocolate bars in this lab are an excellent example of how microstructure can be altered due to processing. The chocolate in all of the bars has the same elemental make-up and atomic traits. However, the microstructures differ due to things that have been added to the chocolate, such as almonds or crisped rice.

Lab Description: In this lab, different types of chocolate bars will be tested to examine the influence of different microstructures on the strength of the chocolate bar. The flexural strength of the chocolate bars will be measured using a conventional 3-point bending test set-up (see Figure 1). For this test set-up, chocolate bars are placed on two supports (making 2 points of contact), and a force is applied to the center of the bar (making the 3rd point of contact in a 3-point bending test).

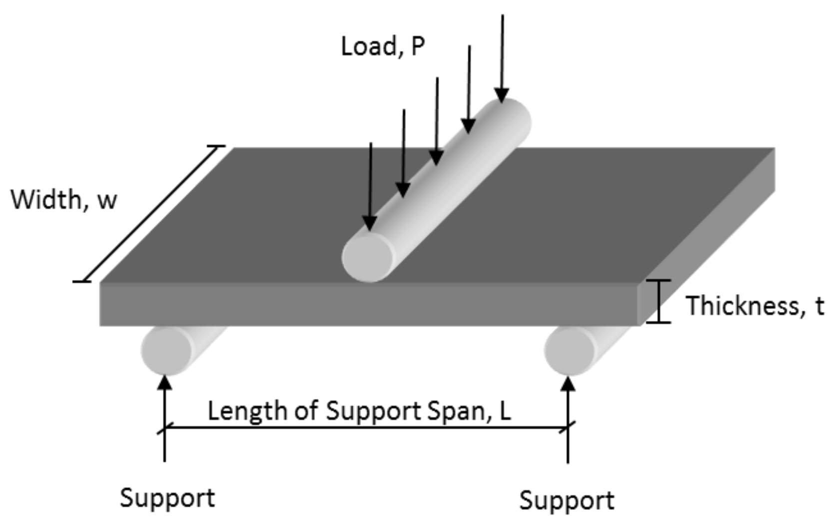

Figure 1. Test set-up for a 3-point bending test

Keywords: Mechanical properties, stress, 3-point bending test, microstructure

Materials List:
Protective mat (aluminum foil, saran wrap, etc.)
Tape or stapler
Plastic cup with twine attached
Mass balance
Pennies
Milk chocolate bar
Milk chocolate bar with almonds
Milk chocolate bar with crisped rice

Safety Precautions: This lab does not require any safety apparel. However, standard lab rules and procedures (only using the equipment as indicated in the instructions) should be followed.

Instructions:

1. Measure and record on your data sheet the following information about the bar:
    a. Type (milk chocolate, almond, crisped rice, etc.)
    b. Width of the bar (mm), w
    c. Thickness of the bar (mm), t
2. For each type of chocolate bar, make a prediction of how many pennies you think the chocolate bar can hold.
3. Position two desks so that the chocolate bar can span across the space between the desks. Approximately ½ inch of the chocolate bar should be touching each desk.
4. Measure and record (in mm) on your data sheet the length of the chocolate bar that is not supported by the desks. This is called the length of the support span, L.
5. Place the twine with the cup attached across the middle of the chocolate bar so that the cup hangs freely below the chocolate bar as shown in Figure 2.

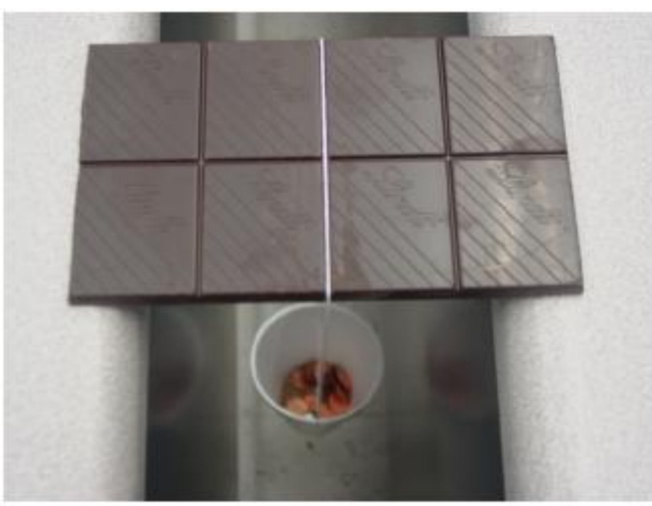

Figure 2. Chocolate bar subjected to a 3-point bending test

6. Place the protective mat on the floor to catch the chocolate when it falls.
7. Create a paper funnel by rolling a piece of paper and either stapling or taping it.
8. Using the funnel, start placing the pennies into the cup, one at a time. The pennies should be funneled in at a steady pace, ensuring that each penny lands in the cup before the next penny enters the cup (a pace of 2-3 pennies per second is good). Try funneling the pennies in a way that they do not fall a large distance when they enter the cup.
9. Continue placing pennies into the cup at a steady rate until the chocolate bar fractures. Be sure to note any deflections or bending of the chocolate bar during the loading process. *Note*: If it is difficult to see the bar start to deflect, place the ruler across the desk just to the side of the chocolate bar to help indicate when the bar starts to deflect from a horizontal line.
10. Record the number of pennies in the cup at the time of fracture.
11. Look at the fracture surface and record any observations.
12. Find the mass (in grams) of the cup, string, and the pennies in the cup at fracture using a mass balance. The force, P, applied to the chocolate bar can then be calculated as follows:

    P= (weight of cup, twine, and pennies)*(acceleration due to gravity = 9.81m/s^2)

    If you do not have access to a mass balance, use the following weights to approximate the mass:
    a. Weight of one penny – 2.35 grams
    b. Weight of the cup and twine – 25 grams

    The force, P, applied to the chocolate bar can then be calculated as follows:

    P= ((weight of penny)*(# of pennies) + weight of cup and twine)*(gravity = 9.81m/s^2)
13. Use the force, P, found in step 12 to calculate the flexural strength of the chocolate bar. The formula for calculating flexural strength is:

$$\sigma = \frac{1.5PL}{wt^2}$$

    where σ is the flexural strength (MPa), P is the applied force (N), L is the length of the support span (mm), w is the width of the bar (mm), and t is the thickness of the bar (mm).
14. Repeat steps 1-12 for each chocolate bar to be tested.
15. Complete the questions on the Student Question Handout.

Clean Up: Eat the chocolate! Clean any chocolate residue from the cup and twine with a wet paper towel and return the cup and twine to your teacher.

Data Sheet for a Chocolate Bar

Type of Bar	Penny Prediction	Width, w	Thickness, t	Length of Support Span, L
Changes in the bar during the loading process:				
Number of pennies in the cup when the bar failed:				
Observations of the fracture surface:				
Weight of the cup/twine/pennies:				
Calculation of load, P:				
Calculation of the bar's flexural strength, σ:				

STUDENT QUESTION HANDOUT

Chocolate Strength – How Strong is Your Chocolate?

1. Did you notice any changes in the chocolate bars during the loading process? Were these changes the same for all of the chocolate bars or different?

2. Which type of chocolate had the highest flexural strength? The lowest flexural strength?

3. Why do you think the bars had different strength values?

4. Which bar had the highest standard deviation for the number of pennies that it held? Which one had the lowest?

5. Why do you think that the standard deviations were different?

Questions for the OPTIONAL ADDITION TO THE LAB (remove these questions if not using the additions to the lab)

6. What did your group choose to modify about the test set-up?

7. Did this change influence the flexural strength of the bar? Why?

8. Was there a difference in the treated bar vs. the untreated bar in terms of flexural strength? Why do you think this happened?

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