Characteristics of the Ideal Material

1. Endless and readily available source of supply
2. Cheap to refine and produce
3. Energy efficient
4. Strong, stiff, and dimensionally stable at all temperatures
5. Lightweight
6. Corrosion resistant
7. No harmful effects on the environment or people
8. Biodegradable
9. Numerous secondary uses

1-CP

materials@home: Build a better hockey puck!

Practice your slap shot - and explore how it all adds up when you make a material tougher!

You'll need:

- **water**
- **sawdust**
- **strips of newspaper (you'll need 15 at about 0.5" x 3", or 2 cm x 8 cm)**
- **three small, round plastic containers (about 3" or 8 cm in diameter)**
- **a spoon**
- **a hockey stick**
- **a wall outside**

Here's what you do:

Make your pucks

1. Pour about 1" (3 cm) of water in the first container.
2. Pour 1" of water in the second container and add the newspaper strips. Make sure the strips are soaked through and evenly spread.
3. Pour 1" of water in the third container and add saw dust until you have a thick, runny paste.
4. Put all three in the freezer and freeze them solid overnight.

Slap your pucks around

5. Take the first container with frozen, plain water out of the freezer. Briefly run hot water over the outside of the container until the puck pops out.
6. Go outside with the puck and your hockey stick.
7. Count how many times you can smack the puck against a brick wall until it shatters.
8. Do the same thing with the newspaper puck and the sawdust puck.

Which lasted longest? Can you guess why?

What's happening?

You probably found that newspaper and sawdust pucks last longer than plain ice. Ice is hard, but it's brittle and pretty easy to crack.

By adding newspaper strips or sawdust to ice, you created a *composite material*. A composite is made by blending two or more materials, combining their properties to make a new, better material. Concrete - a mix of water, sand and small pieces of stone set in cement - is one kind of composite. And like concrete, composites can be very strong. In the case of your ice pucks, strips of newspaper and bits of sawdust block cracks and keep them from spreading. In fact, mixing ice and sawdust produces a cool material called Pykrete that has a fascinating history.

Games, experiments, videos and more...
http://www.strangematterexhibit.com

Strange MATTER

2-CP

Making the Strongest Beam

Name:__________________________
Date: ____________________ Period:____

Objective: You will work with a partner to construct the strongest beam with the provided materials. Keep in mind that, as in the real world, resources are limited. Wasteful practices will reduce the amount of resources you have to work with. The management group is reluctant to supply additional materials without some type of consequence.

Materials: Check to see that you have the following materials in your bag.

1 foam beam (approximately .5" x 1" x 6")
1 3" x 5" note card
1 container with glue (available in the front of the room and should be returned at the end of the period)
Clamps and weight sets for measuring deflection of beam (in the front of the room)
Balance (at side table)
Meter Stick

Preparation: Review the information you read on Stressed-Skin Composites. You do not have to use this concept to construct your "strongest" beam, but based on many years of research, it might be helpful to incorporate some of the ideas into the design and construction of your beam. Once you've decided on the combination of materials and how you plan to build your beam, make a 3 dimensional drawing of your design below. Label all the parts and list the materials you use.

Procedures:

1. Build your beam according to your design above. If your beam needs time for glue to dry, allow the necessary time and then proceed to the next step.
2. Set up a testing device with a clamp and your beam like the one shown below. Make "L" in your setup equal to 3 inches. Measure all of the other dimensions of your beam and record them in the table below. Record all values in centimeters.

Beam length overall (cm): __________________

Beam width – "B" (cm): __________________

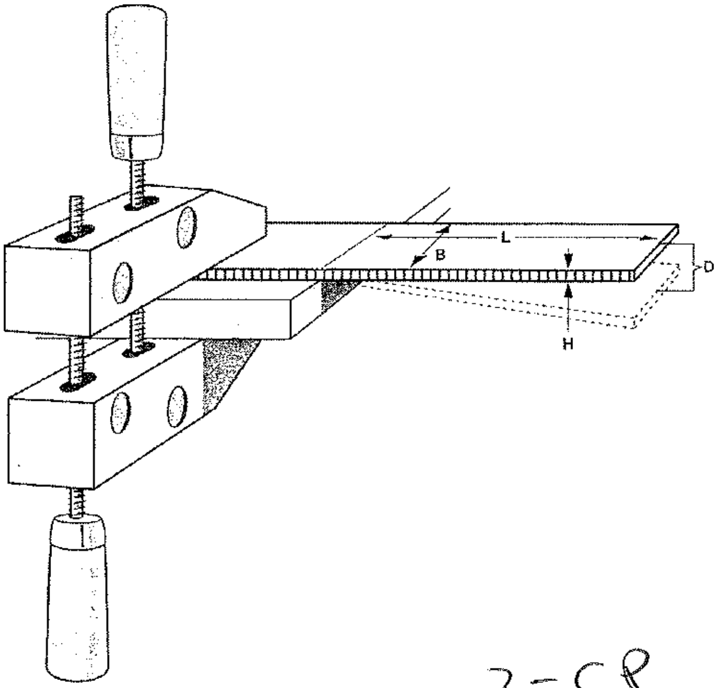
Mass of Beam (g): ____________________

Beam length beyond counter top – "L" (cm):

____

Beam thickness or height – "H" (cm):

____



3-CP

Procedures (continued)

3. Place your beam in the testing device as shown on the previous page. Measure the distance from the floor to the top edge of your beam, in centimeters. Record this in the table below as the Initial Beam Height – (I)
4. Attach a string with a loop to the top of the beam using masking tape. Have the loop hang over the end of the beam so that you can add weights to the beam by hanging them on the loop. Attach a 50 gram mass to the loop and measure the height of the beam from the floor. Subtract this height from the initial height of the beam to the floor and record this number as the "deflection" in the table below. Do this two more times, each time adding 50 grams and recording the deflection of the beam.
5. Using the data of deflection and mass added, as well as the dimensions of the beam, complete the table below by calculating Young's modulus for each mass and deflection entry. Use the formula for Young's Modulus given below. Find the average of the 3 Young's Modulus values. Record this as your final value for Young's Modulus. This represents the stiffness or strength of your beam.

Young's Modulus Formula
$$E = \frac{4 \times 98 \times m \times L^3}{D \times B \times H^3}$$

Mass Added - "m" (g)	Beam Height (I) (cm)	Beam Height (F) (cm)	Deflection of Beam "D" (cm) = (I – F)	Young's Modulus "E" (Pa)
		–	=	
		–	=	
		–	=	

Average Young's Modulus (Final Value) = ________________________________

6. Calculate the Strength to Weight ratio (Specific Stiffness) for your beam:

$$\text{Specific Stiffness} = \frac{\text{Young's Modulus}}{\text{Mass of Beam}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

7. Record the Specific Stiffness for each group's beam in the table below:

Group Number	**Specific Stiffness**	**Group Number**	**Specific Stiffness**
1		**9**	
2		**10**	
3		**11**	
4		**12**	
5		**13**	
6		**14**	
7		**15**	
8		**16**	

Which Beam has the highest Specific Stiffness? How was it constructed to give it the highest value?

4-CP

EXPERIMENT 2-1 **Stressed-Skin Composites**

Observations

Part A: Preparation of stressed-skin beams

Dimensions of the original beam:

______ cm × ______ cm × ______ cm

Diagram

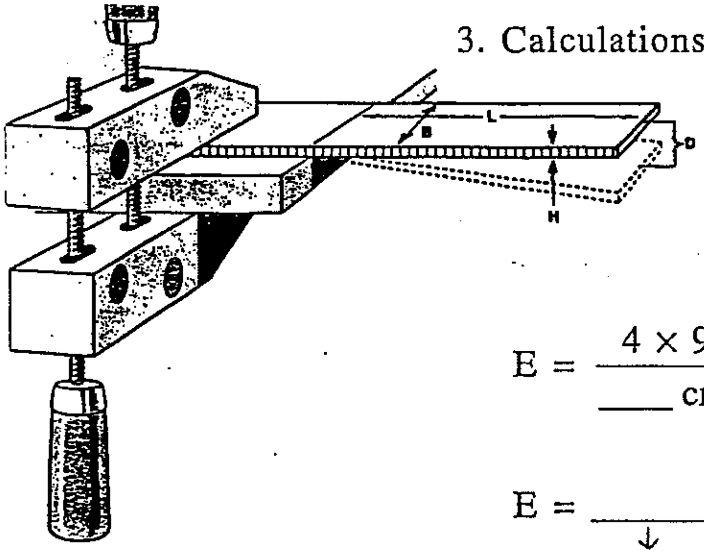
1. Apparent rank in stiffness: (1skin, 2skins, delamination, control)

______ < ______ < ______ < ______

2. Use the following Data Table to record beam measurements.

Data Table

Beam Description	Length (cm) L	Width (cm) B	Height (cm) H	Mass (g) m	Deflection (cm) D	Elasticity (Pa) E
Beam 1						



3. Calculations for Young's Modulus:

$$E = \frac{4 \times 98 \times m \times L^3}{D \times B \times H^3}$$

$$E = \frac{4 \times 98 \times \_\_\_\_\text{ g} \times \overbrace{\_\_\_\_\text{ cm} \times \_\_\_\_\text{ cm} \times \_\_\_\_\text{ cm}}^{L^3}}{\_\_\_\_\text{ cm} \times \_\_\_\_\text{ cm} \times \underbrace{\_\_\_\_\text{ cm} \times \_\_\_\_\text{ cm} \times \_\_\_\_\text{ cm}}_{H^3}}$$

E = ______ Pa

$\downarrow$

$$\frac{\_\_\_\_\_\_}{1{,}000{,}000}\text{ Pa} = \underset{\downarrow}{\_\_\_\_\_\_}\text{ mPa}$$

$$\frac{\_\_\_\_\_\_}{1{,}000}\text{ mPa} = \_\_\_\_\_\_\text{ GPa}$$

5-CP

CONCRETE LAB

PROCEDURE:

Note: You will make concrete using a mixture of three main ingredients: sand, gravel, and cement. You will also add water to this mixture. Your concrete will have a total of 6 cups of sand, gravel, and cement.

1. Obtain a cup, a mixing bucket, a mold, and a stick. Decide how much of each ingredient you will use to make your concrete. You must use at least 1 full cup of each main ingredient.
2. Place a total of 6 cups of materials into your mixing bucket. Be sure to use only full cups of each of the materials. Record how much of each material you use and thoroughly mix the ingredients together.
3. You need to add water to form the concrete. Try not to use too much water—just enough to thoroughly wet the mixture and still be able to stir it. You might try about a cup to start.
4. Use Vaseline as a mold release on your mold. Just a thin coating will work.
5. Pour the concrete mixture into the mold that acts as a concrete form. Use the stick to make sure all of the corners are full of concrete. Then use an up and down motion of the stick to puddle the concrete in order to get all of the gravel below the surface.
6. Identify your mold and set your concrete aside to cure. You will test it on Friday.

Part B: Testing the concrete

1. Accurately measure and record the length, width, and thickness of your bar of concrete.
2. Place the concrete on the two stands and measure the distance between the two stands that are supporting the concrete bar. This value is the "length between supports" in the formula below.
3. Gradually add masses to the center of the bar until it fails. Record the total mass needed to bring about catastrophic failure.
4. Calculate the flexural strength of your concrete bar and compare your results with those of your classmates.

$$\text{Flexural Strength} = \frac{3 \times \text{weight} \times \text{length between supports}}{2 \times \text{base width} \times \text{height}^2}$$

6-CP

BACKPACK SURVIVABILITY INDEX OF PORTABLE SNACKS

Created by Peg Jones, Saginaw Valley Chapter, ASM International for 5th Grade Girls
peggy.jones@gm.com

Objectives:

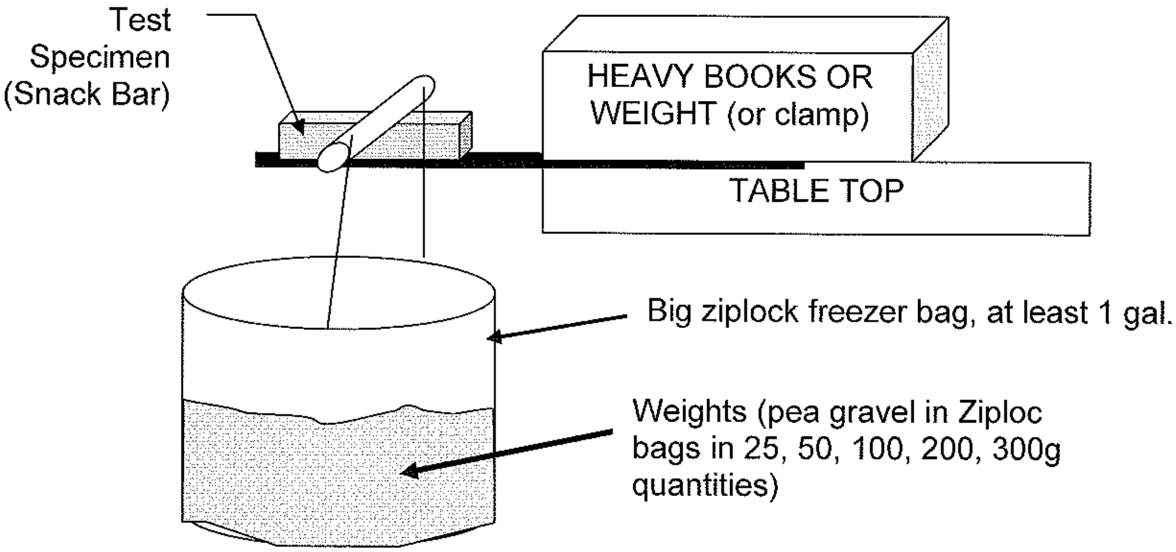
1. Define desired properties for portable snacks.
2. Measure the fracture load for several kinds of portable snacks.
3. Observe how the snacks break.
4. Recommend which snacks might be best to carry in your backpack.

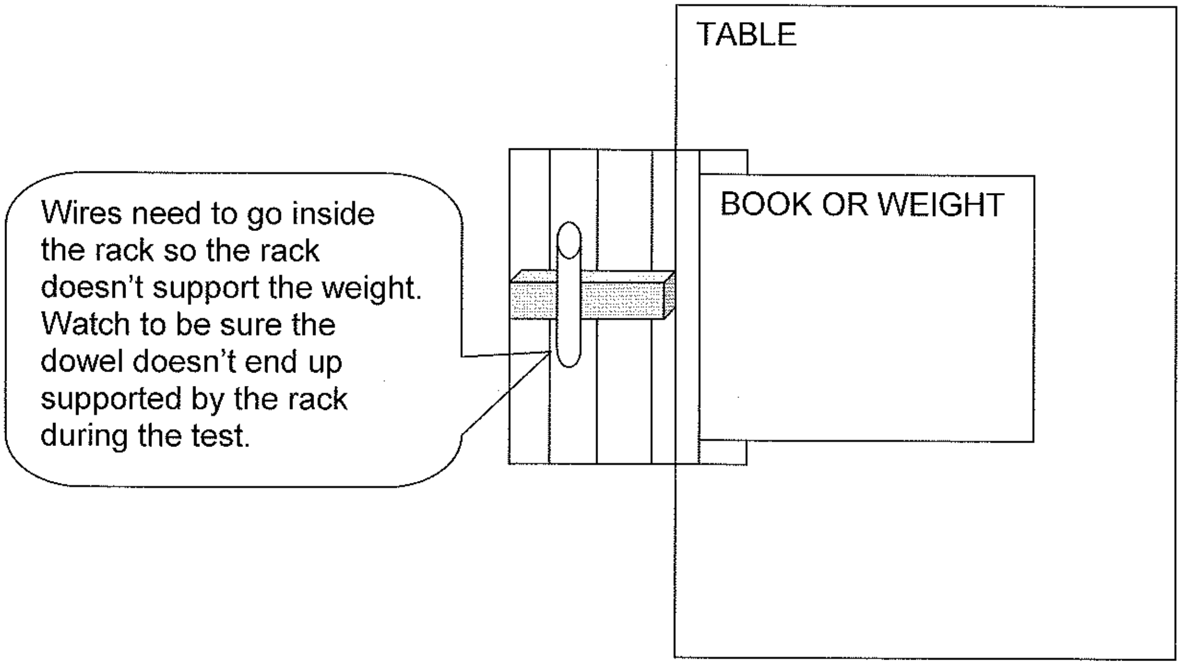
Supplies: (for each station)

1. 1 or 2 gallon ziplock freezer bag to hold weights with holes below the closure, about ¼ of the width from the edges. (Need a big enough opening in the middle to put weights in the bag.) Experimental supplies can be stored in the bags for next year.
2. String or pipe cleaners or wire to attach the freezer bag to the loading dowel. I used 2 pipe cleaners.
3. 15-20 cm. long pieces of ½" diameter wooden dowel rod with a string or pipe cleaner attached to both ends.
4. Weights (various weights of clean pea gravel in Ziploc bags) Steel shot would also work, but is harder to clean up if it spills. Do not use "copper shot" for making bullets or shot gun shells – this can be copper coated lead shot. Marbles wouldn't pack densely enough. You need at least 4 kg. total weight.
5. Bucket or box to "catch" the weights and keep kids' feet from ending up right under the bag of weights. *We didn't have this and it was the biggest safety problem with the activity.*
6. Cooling rack or oven shelf
7. Very heavy books to hold the cooling rack or shelf on a table, or C-clamps. Clamps would be better.
8. Snacks to break (rice crispy treats, granola bars, graham crackers, celery sticks....)
9. Data recording sheet
10. Paper plates to collect the broken snacks for "Fractographic Evaluation"
11. Pencils or pens to label the plates & take notes
12. Magnifying glass to examine fracture surfaces
13. Scale (can be shared), or a calculator to add up the weights required for fracture.

Set Up:

We will put the snack in 3 point bending by placing it on a cooling rack or oven shelf, perpendicular (crosswise) to the metal wires that make up the rack. Put the dowel rod on top of the snack and hook the wires on the ends of the dowel rod to the big ziploc freezer bag that will hold the weights. We need to be sure there's enough weight on the back end of the rack so it won't flip off the table during the test. (Clamps could also be used to hold the rack on the table.) See the sketches below.





Candidate Specimens:

Commercially produced rice crispy treats & granola bars
Celery sticks
Twinkies, Graham Crackers, Jerky, String Cheese, Apple Slices…..
Homemade "rice crispy treats" with different additions (coconut, peanuts, peanut butter)
Homemade "rice cripy treats" bound together with popcorn ball syrup instead of marshmallows to make them harder.
Replace rice crispy cereal with bran flakes or oatmeal and the two binders to see how that affects the strength and fracture appearance

Starting Point: Regular Gooey vs. Hard & Brittle Rice Crispy Treats

This combination demonstrates that by changing the "process" applied to essentially the same ingredients, we can change the "properties" of the material. The "Regular" rice crispy treats are sticky and soft. They gradually fracture between the grains of cereal and we can observe little tendrils of marshmallow glue stretching between the grains. The "hard and brittle" version fractures suddenly and makes crumbs. It tends to break across the cereal instead of between them. In our tests the regular ones fractured between 1.5 and 2 kg., and we couldn't break the hard ones with 4 kg. of weight. (We ran out of weights.) We ended up breaking the hard ones by hand to observe the fracture characteristics. The regular ones can also be "reassembled"—they'll stick back together but the hard ones can't be easily repaired.

Regular:

3 T. margarine
10 oz. Regular marshmallows or 4 C. mini marshmallows
½ t vanilla (optional)
6 C puffed rice

Line a 9x13 pan or cookie sheet with waxed paper, and grease the wax paper with cooking spray or margarine. Grease a spatula for stirring and handling the treats.

In a big heavy pan or big microwave safe bowl, melt the marshmallows & margarine. Stir in the vanilla and puffed rice. Dump onto the wax paper and press out to as uniform a thickness as possible. Cut into 1x3" bars with a greased knife or pizza cutter.

Hard Rice Crispy Treats:

1 C Light Corn Syrup
3/4 C White Sugar
1 T Margarine
1/2 t Vanilla (optional)
6 C Puffed Rice

Spray a spatula with cooking spray and line a 13x9 baking pan or cookie sheet with waxed paper. Heavily grease the waxed paper with cooking spray.

Heat the corn syrup, sugar, and margarine over med-med/low heat in a heavy pan. Stir until the sugar dissolves and the mixture is clear. Boil it for about 5 minutes until it just starts to caramelize and forms a brittle thread when dripped into ice water. (Cook it to the "hard crack stage". A cookbook will give the right temperature for this--I think it's about 385F, but you need a candy thermometer to measure it.)

Take it off the heat and stir in the vanilla, then the puffed rice.

Using your greased spatula, scrape the sticky glob onto the waxed paper and spritz the top of it with cooking spray. Working quickly and trying not to burn yourself---because the sugar is really hot!--- press it into as uniform a thickness as you can. Press it with the greased spatula and NOT your hands. (Next time I might grease the bottom of a cookie sheet and see if I can use that to quickly press the glob into a more uniform thickness.) The sugar hardens fast so you don't get a lot of time to pursue uniform thickness samples. It is very easy to get a bad burn when you are working with this....just like when you build gingerbread houses glued together with sugar syrup.

Let it cool and lift it out of the pan so you can cut it.

Using a long serrated knife for cutting bread, or perhaps even a clean hacksaw blade, try to saw it into approx. 1x3" pieces. Mine wanted to break. Try not to let the end of the knife batter the crispies, and try to saw all the way through. I ended up sawing a little from one side, then from the other so I wasn't impacting the treats with the end of the knife.

They are edible, but not nearly as good as the originals. (1/3 the fat...)

DESIRED PORTABLE SNACK PROPERTIES

The perfect portable snack would be:

1. Delicious chocolate with no calories, lots of fiber, and plenty of vitamins and minerals.
2. Hard to smash
3. Not messy if it breaks
4. Lasts for months without refrigeration
5. Light weight
6. Not really sticky
7. Doesn't melt on a hot day, floats, ...

So the "properties" we'd like our snack to have are:

1. Strong—takes a lot of force to break it
2. Tough—doesn't fracture into lots of pieces
3. No refrigeration needed
4. High strength to weight ratio
5. High melting or softening point ("glass transition temp")
6.
7.

OBSERVATIONS:

Specimen ID	As Received Condition	Fracture Load (grams)	Fracture Characteristics
Example: Rice Crispy Bar	Sticky Round Rice Crispies One piece Low odor Mostly white	900	Marshmallow glue stretched while it was breaking 3 pieces Took a long time to break Some rice crispies are broken, but most of them are whole where it broke
Rice Crispy "Group A" (Regular)			
Rice Crispy "Group B" (Hard)			

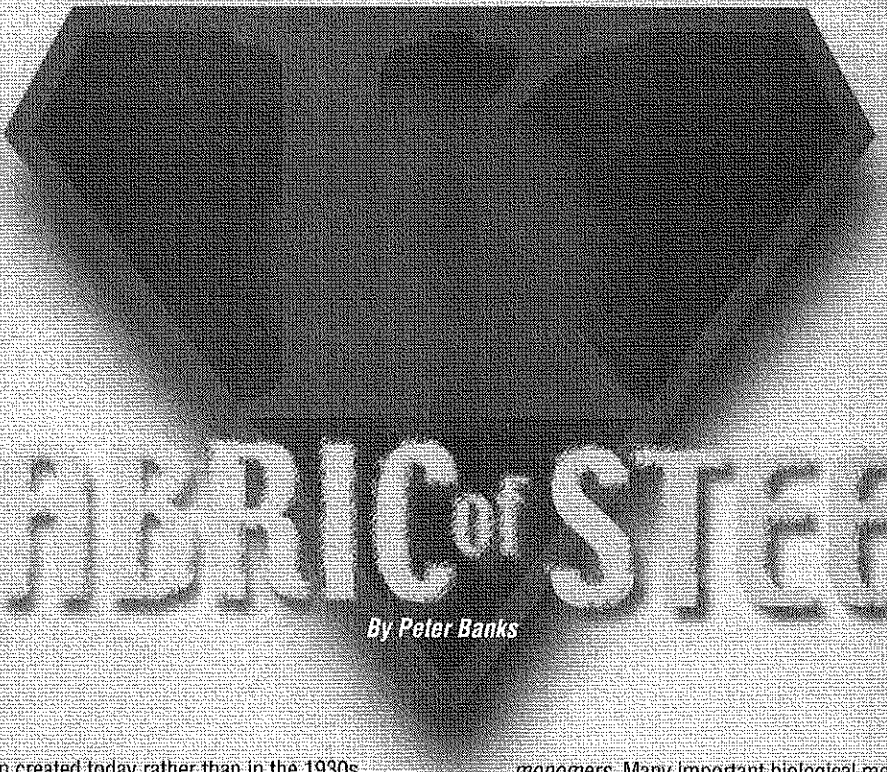
~20 minutes with pairs of 5th grade girls

Specimen ID	As Received Condition	Fracture Load (grams)	Fracture Characteristics
Rice Crispy "Group C"			
Celery	(Longitudinal or transverse? Concave up or down?)		
Other			

RECOMMENDATIONS: The snack with the best chance to survive 6 months in your backpack is ______________________ because ____

IDEAS FOR FURTHER INVESTIGATION:

13-CP



FABRIC of STEEL

By Peter Banks

If Superman had been created today rather than in the 1930s, he would probably not be the "Man of Steel", but instead the "Man of Kevlar®". Five times stronger than steel, this super material has some extraordinary powers.

Need to stop a speeding bullet? Kevlar can be woven into bullet-resistant vests and helmets for police and military forces. These Kevlar vests have saved lives from urban streets to the battlefields of Kosovo and Mogadishu.

Want to leap a tall building? Kevlar's combination of being lightweight and strong makes it a natural for the bodies of aircraft and spacecraft. This year, Kevlar served as a component of the pressurized capsule for the Orbiter 3 balloon that circled the globe in March.

And remember those pesky runaway trucks and locomotives Superman was always picking up? Because it withstands high heat and abrasion, Kevlar is widely used in transmissions, cooling systems, and brake linings.

And don't forget the fabric in Superman's cape! Kevlar made the leading edge of fashion this year, when designer Helmut Lang's futuristic spring collection featured Kevlar flight jackets. Call it "geek chic".

Superman may have come from the planet Krypton, but Kevlar's history, equally fascinating, comes from our own world of technology.

A recent FBI study showed the risk of sustaining a fatal gunshot injury is 14 times greater for officers who do not routinely wear body armor than for those who do. In this test, Kevlar fabric absorbs the impact of a bullet (left photo), leaving a shallow depression in the wall behind it (right photo).

PHOTOS COURTESY OF DUPONT

Kevlar's composition

Kevlar is a synthetic material known as a polymer. Like a long train of boxcars, a polymer is a chain of similar molecular groups, known as *monomers.* Many important biological molecules, like protein and DNA, are polymers, as are many common household plastics and fibers, among them nylon, Teflon, lycra, and polyester.

For Kevlar, the monomer unit—one "boxcar" of the train—is an aromatic amide, or aramid for short. In this case, aromatic doesn't mean "fragrant". Instead, it means that the molecule contains a group of six carbon atoms attached in a ring called a benzene ring. The amide group is an arrangement of carbon, nitrogen, oxygen, and hydrogen atoms (see Figure 1). This bit of chemical anatomy turns out to be key to understanding Kevlar's strength.

The secret of Kevlar's strength

To gain strength, a polymer chain has to have a certain structure. The chain cannot flop around loosely, like a linked bicycle tire chain. Instead, it should form long, straight chainlike rods. These rods should line up parallel to each other like matches in a box. The polymer gains strength, too, if the chains next to each other stick together in a tight bundle. Making strong polymers is a lot like making strong rope. If you bundle fibers into strands bunched in a regular array, you wind up with a rope tough enough for heavy lifting.

Here's where those aromatic and amide groups work their magic. The bulky aromatic rings stiffen the polymer into long straight rods. The Kevlar chain remains straight because the intrinsically rigid rings keep it from being folded.

The amide group is important for strength, too,

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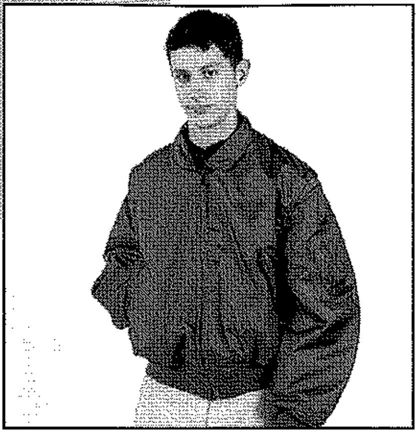

PHOTO BY MIKE CIESIELSKI

Kevlar flight jackets combine strength and fashion.

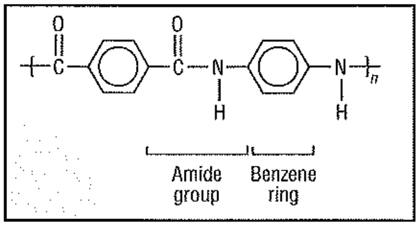

Figure 1. A monomer unit of Kevlar is an aromatic amide, or *aramid*.

but for a different reason. It provides a kind of molecular "glue" to hold adjacent polymer chains together. This glue is actually a type of chemical bond known as a hydrogen bond. Hydrogen bonds form when regions of adjacent molecules with opposite charges attract each other (see Figure 2). In an amide, the oxygen atom attracts some of carbon's electrons to itself, giving it a partial negative charge. By contrast, the hydrogen attached to the nitrogen atoms has a partial positive charge caused by the fact that electrons tend to be drawn toward the nitrogen, partly exposing the positively charged hydrogen nucleus.

One more factor adds to Kevlar's strength. The benzene rings can stack on top of one another, like pancakes on a plate. This stacking, combined with their straight conformation and the hydrogen bonding that cements them together, makes Kevlar polymer chains line up in a perfect array. In fact, although Kevlar is woven into fibers, it's much less like thread than it is like steel or ice—a hard crystal in which the molecules interlock in a neat, flawless package.

There's only one problem with something so tough—making it in the first place. Because Kevlar chains line up so precisely and cling together so tenaciously, almost no solvent will dissolve them. Heat doesn't work either, because Kevlar remains stable at high temperatures. In fact, its molecules disintegrate before they ever reach their melting point. It is a huge challenge, then, to process amide polymers into long Kevlar fibers for vests and other products. Imagine using a spinning wheel to make thread out of a chunk of steel, and you get the picture.

From crystals to fibers

Fortunately, an enterprising chemist at chemical manufacturer DuPont in Delaware found the chemical concoction needed to prepare Kevlar. Polymer chemist Stephanie Kwolek and her colleagues were looking for a material that could be used to replace steel in radial tires.

Kwolek's innovation was to make workable solutions of Kevlar in an unusual form—the liquid crystal. Widely used in digital watch and calculator displays, liquid crystals represent a strange state of matter halfway between a true liquid like water and a true solid like ice. (See "Smart Windows", opposite page.)

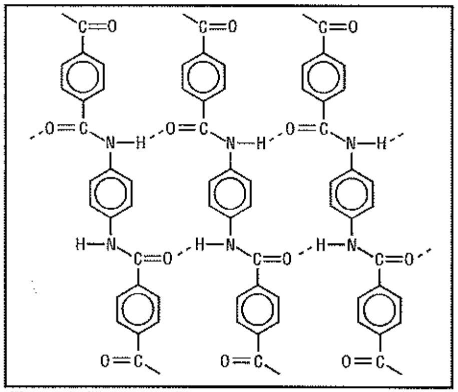

Figure 2. The attraction between hydrogen and oxygen on adjoining polymer chains binds the chains solidly together.

Stephanie Kwolek

Kwolek began working on a new way to dissolve Kevlar. She picked organic solvents and then added calcium, which prevents the amide group from forming hydrogen bonds. The positively charged calcium ions surround the negatively charged oxygen atoms and prevent them from grabbing on to hydrogen. What Kwolek made was in fact a liquid-crystal solution. In such a solution, polymer chains can still swim about somewhat, but they interact with one another to form organized clumps, like logs lashed together for a raft.

To make fibers from Kevlar, the chemists further dissolved the clumps in strong sulfuric acid (H_2SO_4) and then forced the solution through a fine pore filter, which serves as a molecular spinning wheel. As the solution flowed through the tiny holes in the filter, the liquid crystals were forced into parallel alignment with one another and long fibers were "spun".

At first, the technician running the spinning equipment at DuPont was reluctant to process Kwolek's solution. It was cloudy-looking, and he worried it would clog the fine pores. When he relented, however, the results were amazing—fibers with a strength never seen before! Kwolek hesitated to report her results for fear mistakes could have been made. But there was no mistake. It took a few years to perfect the manufacturing process, but when it was brought out in 1971, Kevlar quickly found hundreds of uses—vests, aircraft, sports equipment, protective gloves, fiber-optic cables, boats, and many other products.

Among Kwolek's many awards she receives, her most satisfying is to be recognized at meetings of the Kevlar Survivors Club. With a membership topping 2,300, the members are police officers whose lives were saved because they wore Kevlar armored vests.

We don't need to look to Krypton for the source of this super polymer. The making of Kevlar, a feat worthy of Superman himself, is a product of down-to-earth chemistry by chemical problem solver Stephanie Kwolek and her research team. ▲

Peter Banks is a freelance writer living in Fairfax, VA. His most recent *ChemMatters* article was "Weighting in the Wings", which appeared in the December 1997 issue.

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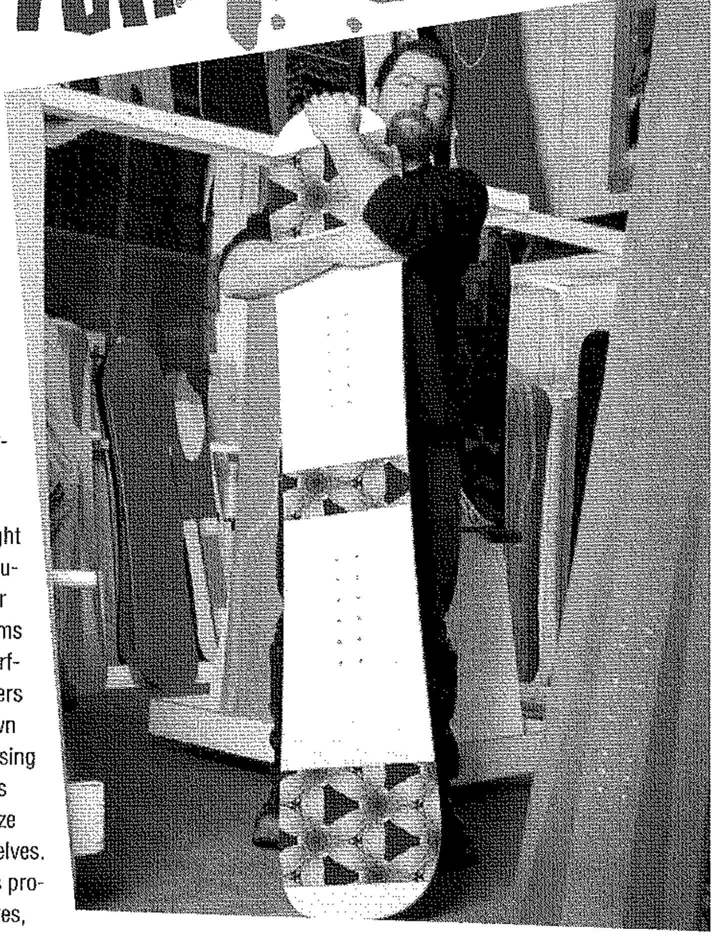
15-CP

ON BOARD WITH EPOXY



PHOTOGRAPHS FROM ACS STOCK FILE

By David Thielk

Whether it's cruising the slopes with the latest snowboard, or riding the big wave on a surfboard, both body and board get a workout. Ask any novice snowboarder or surfer about bumps and bruises, and they will tell you that the only thing that takes more abuse than their own bodies is the board they ride. With experience, the surfer or snowboarder learns to avoid the spills. The boards, however, must be built to withstand them.

Modern snow- and surfboard construction involves sandwiching lightweight core material between tough, impact-resistant surfaces. Epoxy–fiberglass combinations—also used in the construction of canoes and kayaks—are the materials of choice for these surfaces. The resulting products are light enough to be carried or paddled long distances. And they stand up to the pounding offered by surf, sand, snow, ice, and rocks.

Core construction

At the core of a snowboard are the *stringers.* Stringers are made from six-foot-long strips of hardwood that are arranged side-by-side and then glued together. Depending on the width of each stringer, there may be anywhere from 11 to 99 stringers in a single snowboard. The more stringers, the more strength and flexibility in the board.

Once the stringers are glued, the board is cut to the proper length and given some shape. Toes and heels are trimmed, and a waist is cut into the board. Only the top of a snowboard is epoxied. The bottom gets a coating of P-TEX, an abrasion-resistant polyethylene polymer that skiers and boarders appreciate for its wax-holding ability.

Before adding the translucent epoxy–fiberglass combination, the manufacturers add logos and graphics to the top of the core. After drilling holes for bindings and other inserts, they apply the top coat (see illustration on opposite page).

Surfboards—lighter and simpler in design than snowboards—are frequently built at home. A lightweight foam polymer, usually polystyrene or polyurethane, forms the core of the surfboard. Many surfers construct their own boards by purchasing rectangular blanks that they customize and shape themselves.

During mass production of the cores, the polystyrene or polyurethane is injected into molds. Most surfboard cores are cut in several places lengthwise, and between one and seven stringers—usually of basswood or redwood—are inserted to give the core more strength and flexibility. The stringers are glued in place and shaped to conform to the curves in the board.

Laminating with epoxy

Both snowboard and surfboard cores roughly resemble their finished products. But if tested on the slopes or in the water, they wouldn't last a single thrill. The strength and durability of the finished boards come from the addition of a final layer of fiberglass cloth and epoxy on top and bottom. Although the technique for applying the cloth and epoxy varies between snowboard and surfboard, the chemistry involved and the end result are the same.

To make the epoxy adhesive, you need to purchase two separate viscous liquids—a *resin* and a *hardener.* Epoxy resins can differ from each other in minor ways, but most consist of a compound in which the important reacting group or *functional group* is an *epoxide.* An epoxide consists of a triangular arrangement of two carbon atoms and one oxygen atom. The core of the resin molecule is named *ether of bisphenol-A.* This is the part of the molecule that contains two rings of carbon atoms (the bisphenol) and an oxygen atom that is contained right in the long chainlike part of the molecule (the ether). The structure of a typical resin molecule is shown in Figure 1.

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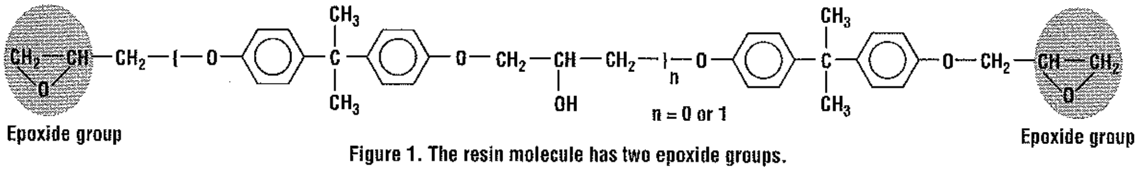


Figure 1. The resin molecule has two epoxide groups.

The choice of hardener molecule also varies. However, all epoxy hardeners are *polyamines*. Polyamines are organic molecules that contain two or more amine groups (NH_2) (see Figure 2). The amine and epoxide functional groups are the primary characters in the epoxy reaction.

When the resin and hardener are mixed, the amine groups on the hardener can link with the epoxide groups on the resin. Each amine group can form two links, since an amine group contains two hydrogen atoms. Thus, each hardener molecule can bind to up to four different resin molecules.

A three-dimensional polymer

The final result of all this bonding is a polymer with a three-dimensional, rather than a linear, structure. Because covalent bonds are formed in all three dimensions, the resulting polymer is tough yet flexible, since there are no weak spots along which fractures can propagate.

The rules of stoichiometry suggest that an important part of working with epoxy is mixing the proper ratio of resin to hardener. This ensures that all of the amine hydrogens and all the epoxide groups will have an opportunity to react. The epoxy manufacturer usually does all the calculations for the user and provides detailed directions. If the mixing directions are not followed correctly, not all of the functional groups will have an opportunity to react, and the result will be a board surface that is "gooey"—not a desirable feature of either a surfboard or a snowboard.

Toughness, strength, and impact resistance are greatly improved if the mixed epoxy is applied to the board along with one or more layers of fiberglass or Kevlar cloth (see "Fabric of Steel" in the October 1999 issue of *ChemMatters*). To apply, the builder saturates the cloth with epoxy and carefully places it over the entire surface of the board. Additional mixed epoxy, called the fill, is spread over the surface with a squeegee. The edges of the cloth are wrapped around the board and smoothed down to the surface. Now the builder simply waits for the epoxy to cure to a strong, translucent finish.

The epoxy cure

The reaction or *cure rate* is dependent on several factors. First of all, the reaction is heat-dependent. The warmer the temperature of the reactants, the faster the reaction will occur. Epoxy curing is also an exothermic reaction, which means that as the cross-linking occurs, heat is given off.

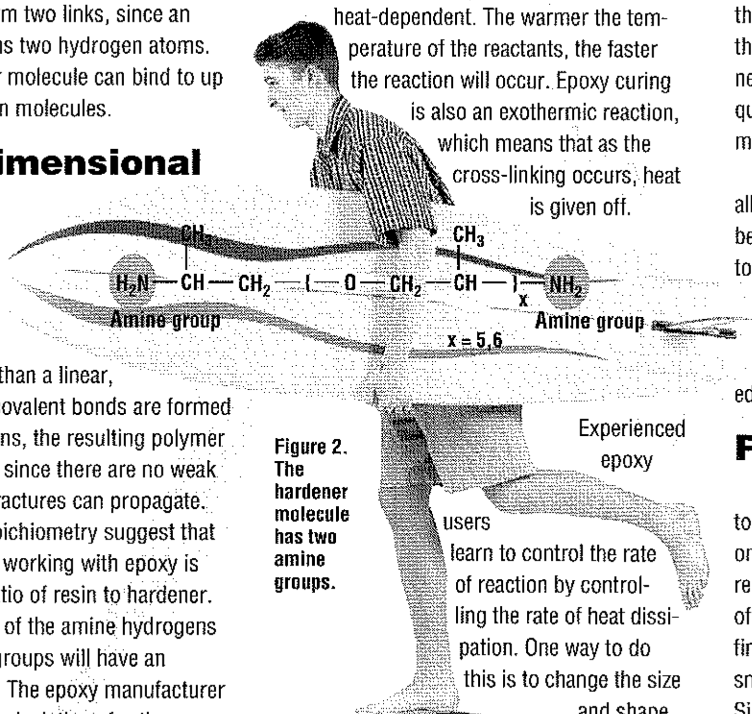
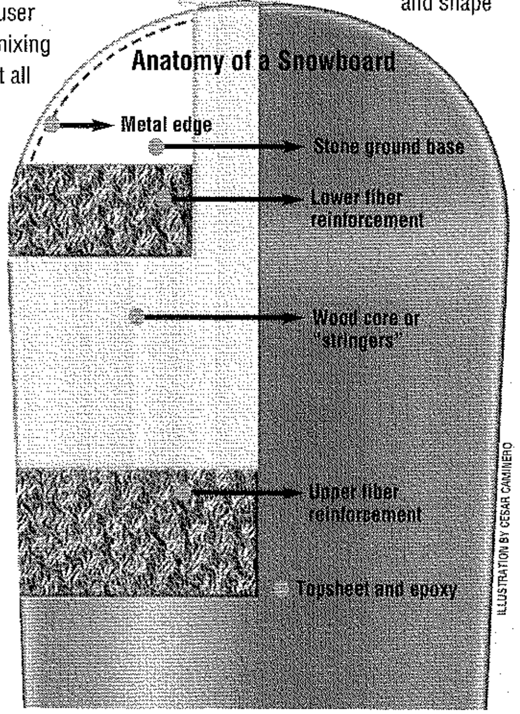


Figure 2. The hardener molecule has two amine groups.

Experienced epoxy users learn to control the rate of reaction by controlling the rate of heat dissipation. One way to do this is to change the size and shape of the mixing container. To make a fast cure, the hardener and resin are mixed in large batches in a deep container and allowed to sit before applying. As the reaction proceeds, heat is given off, and the temperature of the mixture goes up. In fact, just 12 ounces of freshly mixed epoxy can generate enough heat to burn your fingers!



To make a slower cure, the same 12 ounces might be spread into shallow tray, or the epoxy might be applied to the surface of the board right away. Spread out in this manner, the large surface area of exposed epoxy quickly dissipates heat, and the cure proceeds more slowly.

Unlike surfboards, snowboards are usually laminated using fiberglass cloth that has been preimpregnated with epoxy and allowed to cure. The cloth is sold to the snowboard manufacturer in stiff sheets to be applied with heat and pressure to the top of the board. After lamination, snowboard edges are finished with metal or plastic.

Finishing touches

At this point, there are a few finishing touches—bindings on the snowboard and fins on the surfboard. Sanding and polishing removes any blemishes in the surface. Very often, the builder will finish with a final coat of finishing epoxy. Finishing epoxy goes on very smoothly and doesn't require any sanding. Since the epoxy and fiberglass combination is clear, the art and wood grain—protected from scratches—show through the finish.

The result is that a snowboard or a surfboard can handle a lot of abuse while remaining flexible, lightweight, and attractive. Now, if we could just figure out how to do the same for the boarder! ▲

David Thielk is a science education writer from Port Townsend, WA. This is his first article to appear in *ChemMatters*.

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Scientific Principles Of Composites

Definition

Composite materials are made from two or more distinct materials. The properties of the composite are superior to those of either individual material. Advanced composites are literally "designer" materials in the sense that the engineer can control both the identity of the materials and their physical arrangement to make them with highly specific properties.

Structure and Composition

Matrices

There are three main types of matrices: polymer, metal, and ceramic. Matrices hold and protect the fibers (or other reinforcing material geometries—e.g., particles, platelets, short fibers, or whiskers, etc.) from environmental and physical damage. Keeping the fibers separated decreases cracking and redistributes the load equally among all fibers. Thus, the matrix contributes greatly to the properties of the composites. The ability of composities to withstand heat, or to conduct heat or electricity depends primarily on the matrix properties since this is the continuous phase. Therefore, the matrix selection depends on the desired properties of the composite being constructed.

Polymers

For applications of 250 ° or lower the matrices of choice are polymers. A polymer is a substance consisting of a large number of atoms bonded together in a long chain. Polymeric matrices are used because they are light weight and easy to fabricate. Artificial skin, used for severe burn victims, is an example of a composite that contains a polymer matrix. There are two general types of polymer matrices: thermoset and thermoplastic. Thermoset polymers (such as epoxy) cure into an irreversibly hardened material. This is accomplished by "cross-linking", the formation of bonds between polymer chains that fixes the polymer in a three-dimensional array, limiting the motion considerably. Thermoplastic (such as polymethylmethacrylate—"Plexiglas") polymers are capable of being repeatedly softened by the application of heat, and hardened by cooling the polymer.

Metals

Metal matrices have an intermediate working temperature range between 200 - 800 °C. The metals most commonly employed as matrices are light weight alloys of aluminum, magnesium, and titanium. Metal matrices provide electrical conductivity, ductility, high strength, and high stiffness. These alloys are commonly used when it is necessary to extend the temperature range for a given application. Metal matrices are used in car engines and turbine blades. However, due to their relatively higher density and processing complexity as compared to polymer matrices, they are less commonly used.

Ceramics

Ceramic matrices are used for high temperature applications. Ceramic matrices are not as commonly used as polymers, because they are brittle and difficult to process. Their main constituents are alumina (Al_2O_3), silica (SiO_2), and other inorganic non-metallic substances that are abundant in nature. Ceramic materials are a combination of a metal (e.g., aluminum) or intermediate-metal (silicon) with a non-metal (e.g., oxygen, nitrogen, or carbon). Their bonding is either ionic or covalent. Generally, ceramics are oxidation resistant, corrosion resistant, hard, strong, and able to withstand very high temperatures. The reinforcing material is usually selected to reduce brittleness. An example is the Al_2O_3/Al composites, where aluminum, a ductile material, serves as the reinforcing phase.

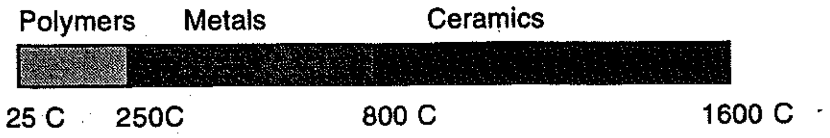

Figure 1: *For structural applications, the maximum use temperature is critical and will often dictate the choice of matrix. Approximate use temperature ranges for the different matrix materials are shown .*

Reinforcements

The strength, stiffness, and density of the composite material is very dependent on the reinforcing material. The ultimate tensile strength of a composite is a result of the synergy between the reinforcement and the matrix. The matrix forces load sharing among all the fibers, strengthening the material. The main types of reinforcements are continuous fibers, discontinuous (short fibers), whiskers, and particulates.

The elements selected as reinforcements are usually the lower atomic numbered elements of groups 2, 13, 14, 15, and 16 (Fig. 2) because of the desirable engineering traits of light weight, high strength, and stiffness. These elements, or compounds of these elements, can be made into various kinds of reinforcements. The stable covalent bonding contributes to the strength and stiffness of the compounds.

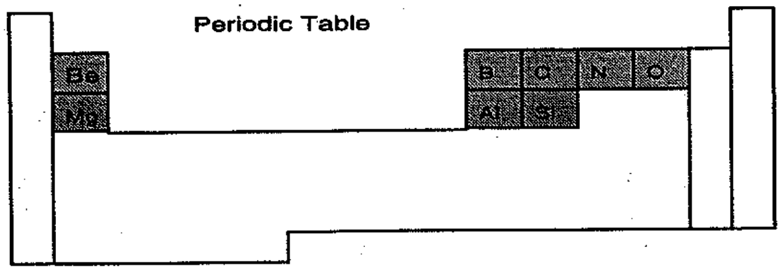

Figure 2: *Candidate elements for reinforcement materials in composites.*

Some of the common reinforcing fibers include:

- carbon or graphite (C)—high stiffness, strength, and cost—unidirectional
- glass (SiO_2)—amorphous, isotropic, low cost—often used with polymers
- organic fibers—high stiffness, strength, low cost
- silicon carbide fibers (SiC)—high temperature stability—used with metals and ceramics
- boron fibers (B)—used to reinforce metals
- metallic fibers (Mg, Ti)—used with metal matrices

The main types of reinforcements, continuous fibers, discontinuous (short fibers/whiskers), and particles, are shown in Figure 3.

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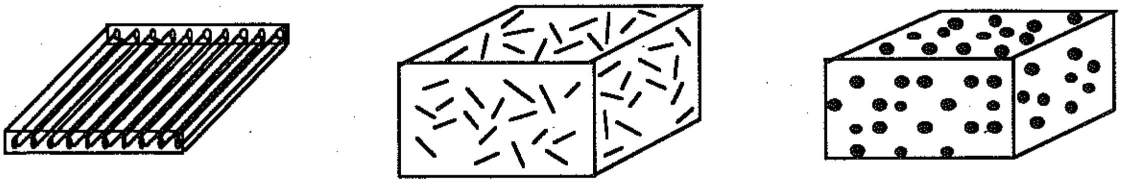

a) Continuous Fibers

b) Short Fibers / Whiskers Discontinuous

c) Particulates

Figure 3: *Types of reinforcements*

Continuous fibers are long strands of fibers having a small cross sectional area. The fibers are placed in bundles containing between 1,000 to 12,000 fibers each depending on the parameters of the load the composite must carry. The bundles are then placed in the matrix in geometrical patterns. If aligned in a single direction, the resulting composite will have anisotropic properties. **Anisotropic materials** have different properties in different directions. When a load is applied in the direction of the fibers, the fibers become the principle load carrying constituent of the composite. Anisotropic composites are extremely strong in the fiber direction but are generally weak in a direction perpendicular to the fiber. This is analogous to bone, a natural composite. Sometimes one directional properties are not what is called for in the design. A composite may need to bend when it is twisted, or be able to withstand loads in two directions. Laminates, see Figure 4, allow for such flexability in design. Laminates are made by combining one directional composites which have fibers oriented at different angles. The properties of the laminate as a whole depend on the orientation and thickness of each layer. This flexability of design has helped composites to become popular in high tech applications.

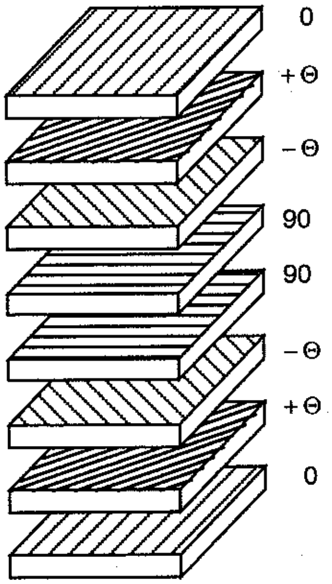

Figure 4: *Schematic of a laminated composite.*

Figure 4 shows a typical arrangement of unidirectional prepregs stacked at determined angles to produce a laminate. The number of layers and their orientation is directly related to the properties of these layered composites.

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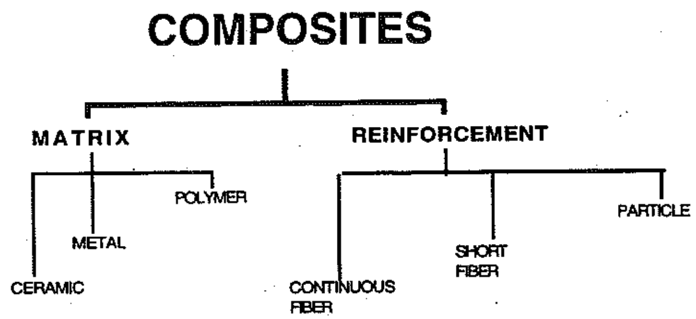

Figure 5: *To achieve the desired properties, a particular reinforcement is chosen for a particular matrix.*

A second type of reinforcement are discontinuous (short) fibers (0.3 cm or less), which are placed randomly into a matrix. The advantage of discontinuous fibers lies in the fact that the resulting composite tends to be more isotropic than continuous fibers and they are generally easier for industry to fabricate particularly for complex irregularly-shaped component geometries.

Whiskers can also be used as reinforcement. These are very short fibers (less than 1 mm in length), usually of silicon carbide (SiC). Whiskers are used to make brittle ceramic matrixes more crack resistant and to increase the specific stiffness and strength of a metal. Although whiskers don't have the same reinforcing capability as continuous fibers, composites with whiskers are easy to fabricate.

Another type of reinforcement is particles. Particle composites contain ceramic (or metal) powders with very small particle dimensions. Particles are not commonly used for fracture resistance. They are used when improved performance is desired at elevated temperatures. Particle composites reduce friction, increase wear resistance, increase abrasion resistance, improve machinability, increase surface hardness, and reduce shrinkage. Their main advantage is that they are extremely cost effective, since lay-up of fibers is not required.

Properties of Composite Materials

Three major factors determine the properties and performance of composites: 1) properties of the constituent materials, 2) the size, shape, quantity, and distribution of the reinforcement, and 3) the effectiveness of the bond between matrix and reinforcement in transferring stress across the interface (Fig. 5).

Properties of MATRIX + Properties and Distribution of REINFORCEMENT + Properties and Bonding at INTERFACE = COMPOSITE

A unidirectional continuous fiber composite is strong and stiff along the fiber axis, but considerably weaker perpendicular to the fiber direction. The properties of a short fiber composite can resemble those of a continuous fiber composite if the fibers are aligned, but are quite different if they are not. More randomly oriented fibers produce more isotropic composites (Fig. 6).

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Unidirectional Continuous Fiber

	Strength (MPa)	Stiffness(GPa)
Parallel to fibers	1400	220
Perpendicular to fibers	40	10

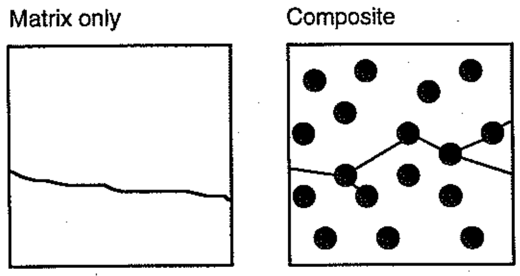
Young's Modulus(GPa):

Unidirectional continuous fibers, parallel to fibers	127.0
Unidirectional continuous fibers, perpendicular to fibers	7.4
Random short fibers, either direction	44.4

Figure 6: *Directional Properties of Composites*

Microstucture of Composite Materials

In order to fully appreciate the properties of a composite, it is necessary to view them from a microscopic perspective. Why does any material fail under a load? Failure occurs when sufficient energy is built up within the material and that energy is then dissipated in the form of cracks. As more and more energy is added to the material, the crack propagates through the material until failure occurs. One of the functions of a matrix in a composite is to bind the reinforcements together in a cohesive structural unit, while protecting the reinforcement from damage due to abrasion. The matrix has two other functions: it separates the fibers so cracks cannot run from fiber to fiber and it bonds to the fiber surface so that the load can be transferred to the fibers. Therefore, as a crack begins to propagate through a matrix, it hits a reinforcement which forces the crack to change direction in order to go around the reinforcement. The crack must traverse a larger distance which means more energy is being absorbed by the composite. **NOTE: Energy dissipated is proportional to distance traveled by the crack.(Fig. 7)**



Comparison of Crack Propagation

Figure 7: *In the matrix, the crack travels easily through the medium unhindered. In the composite, the crack has to travel around the reinforcements, using much more energy.*

The choice of reinforcement is directly dependent upon the job the composite is designed to do. The choice for the materials of reinforcement fibers depends on their chemical and physical properties which include strong covalent bonding, abundance, thermal stability, and low density. These fibers may be continuous or discontinuous, be aligned within the matrix or randomly oriented.

abrasion: The wearing away of a portion of the surface by either natural (rain, wind, etc.), mechanical (misfit, etc.) or man-made (oversanding, etc.) means.

advanced composites: Composite materials applicable to aerospace construction and made by imbedding high-strength, high modulus fibers within an essentially homogeneous matrix.

anisotropic material: A material which has different properties in different directions. For example, unidirectional fiber composite is much stronger and stiffer along the fibers (in the longitudinal direction) than across them (in the transverse direction).

antioxidant: A substance that, when added in small quantities to the resin during mixing, prevents its oxidative degradation and contributes to the maintenance of its properties.

aramid: A type of highly oriented polymer used as reinforcing fibers in composites, the best known is Kevlar by DuPont.

ceramic: A rigid, frequently brittle material made from clay and other inorganic, nonmetallic substances and fabricated into articles by sintering, that is, cold molding followed by fusion of the part at high temperature.

C- glass: A glass with a soda - lime - borosilicate composition which is used for its chemical stability in corrosive environments.

composite: A material created from a fiber (or reinforcement) and an appropriate matrix material in order to maximize specific performance properties. The constituents do not dissolve or merge completely but retain their identities as they act in concert. The matrix acts as a load transfer medium between fibers.

composite material: A combination of two or more materials (reinforcing elements, filler, and composite matrix binder), differing in form or composition on a macro scale. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

continuous filament: An individual small-diameter reinforcement which is flexible and indefinite in length.

crack: An actual separation of material, visible on opposite surfaces of the part, and extending through the thickness. A fracture.

creep: The irreversible dimensional change in a material under mechanical load over time.

cure: To change the physical properties of a thermoset resin irreversibly by chemical reaction via heat and catalysts, alone or in combination, with or without pressure.

E - glass: "Electrical glass"; the borosilicate glass most often used for the glass fibers in conventional reinforced plastics.

epoxy plastic: A polymerizable thermoset polymer containing one or more epoxide groups and curable by reaction with amines, alcohols, phenols, carboxylic acids, acid anhydrides, and mercaptans. An important matrix resin in composites and structural adhesive.

fabrication: The manufacture of products from molded parts, rods, tubes, sheeting, extrusions or other forms by appropriate operations such as punching, cutting, drilling and tapping. Fabrication includes fastening parts together or to other parts by mechanical devices, adhesives, heat sealing, welding, or other means.

fiber: A single homogeneous strand of material, essentially one-dimensional, used as a principal constituent in composites because of its high axial strength and modulus.

fiberglass: An individual filament made by drawing molten glass. A continuous filament is a glass fiber of a great or indefinite length. A staple fiber is a glass fiber of relatively short length, generally less than 430 mm (17 inches), the length related to the forming or spinning process used.

graphite fiber: A fiber made from a precursor by oxidation, carbonization, and graphitization process.

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hand lay-up: the process of placing (and working) successive plies of reinforcing material or resin-impregnated reinforcement in position on a mold by hand.

hardener: A substance or mixture added to a plastic composition to promote or control the curing action by taking part in it.

interface: The boundary or surface between two different, physically distinguishable media. On fibers, the contact area between fibers and sizing or finish. In a laminate, the contact area between the reinforcement and the laminating resin.

isotropic: Having uniform properties in all directions. Metals and unreinforced plastic are usually isotropic.

Kevlar: DuPont's trade name for aramid fibers. See also aramid.

lamina: A single ply or layer in a laminate made up of a series of layers. A flat or curved surface containing unidirectional fibers or woven fibers embedded in a matrix.

laminar: One layer of laminated product.

lay-up: The placement of a layer of reinforcement in a mold.

matrix: The essentially homogeneous resin or polymer material in which the fiber system of a composite is embedded. Both thermoplastic and thermoset resins may be used, as well as metals and ceramics.

modulus: A measure of the stiffness of a material defined as the ratio of stress to strain in the range of elastic deformation. A high modulus indicates a stiff material.

modulus of elasticity: The ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed. If a tensile strength of 13.8 MPa (2.0 ksi) results in an elongation of 1%, the modulus of elasticity is 13.8 MPa (2.0 ksi) divided by 0.01, or 1380 MPa (200 ksi). Also called **Young's modulus.**

mold: The cavity or matrix into or on which the plastic composition is placed and from which it takes form. To shape plastic parts of finished articles by heat and pressure. The assembly of all the parts that function collectively in the molding process.

nylon: The generic name for all synthetic polyamides.

orientation: The alignment of the crystalline structure in polymeric materials in order to produce a highly aligned structure. Orientation can be accomplished by cold drawing or stretching in fabrication.

oxidation: 1. In carbon/graphite fiber processing, the step of reacting the precursor polymer (rayon, PAN, or pitch) with oxygen, resulting in stabilization of the structure for the hot stretching operation. 2. In general usage, oxidation is any chemical reaction in which electrons are transferred.

plastic: A material that contains as an essential ingredient, an organic polymer of large molecular weight, hardeners, fillers, reinforcements, etc.; is solid in its finished state, and at some stage in its manufacture or its processing into finished articles, can be shaped by flow. Made of plastic. A plastic may be either thermoplastic or thermoset.

ply: 1. A single layer of a composite laminate. 2. A sheet of prepreg ready for inclusion in a laminate.

polyacrylonitrile (PAN): A polymer used as a base material in the manufacture of certain carbon fibers.

polyarylsulfone (PAS): A high temperature resistant thermoplastic (Tg=275°C, or 527°F). The term is also occasionally used to describe the family of resins which includes polysulfone and polyethersulfone.

polycarbonate resin: A transparent thermoplastic polymer with the highest impact resistance of any transparent plastic.

polyether etherketone (peek): A linear semi-crystalline thermoplastic. A composite with a peek matrix may have a continuous-use temperature as high as 250°C (480°F).

polymer: A substance in which each molecule contains a large number of atoms bonded to each other in a long chain or a three-dimensional network of short chains bonded to each other. The main chain may be branched, that is, may have short chains attached along its length.

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polymerization: A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization.

polysulfone: A high temperature resistant thermoplastic polymer with the sulfone linkage, with Tg of 190°C (375°F).

preform: A preshaped fibrous reinforcement formed by distribution of chopped fibers of cloth by air, water flotation, or vacuum over the surface of a perforated screen to the approximate contour and thickness desired in the finished part. Also a preshaped fibrous reinforcement of mat or cloth formed to the desired shape on a mandrel or mock-up before being placed in a mold press.

prepreg: A combination of mat, fabric, or non-woven material, or roving impregnated with resin or other matrix material.

reaction injection molding (RIM): A process for molding polyurethane, epoxy, and other liquid chemical systems. Mixing of two to four components in the proper chemical ratio is accomplished by a high-pressure impingement-type mixing head, from which the mixed material is delivered into the mold at low pressure, where it reacts (cures).

resin: A solid or pseudosolid organic material, usually of high molecular weight, that exhibits a tendency to flow when subjected to stress. It usually has a softening or melting range, and fractures conchoidally. Most resins are polymers. In reinforced plastics, the material used to bind together the reinforcement material; the matrix.

resin content: The amount of resin in a laminate expressed as either a percentage total weight or total volume.

resin-transfer molding (RTM): A molding process in which catalyzed thermoset is transferred under moderate pressure into an enclosed mold into which the fiber reinforcement has been placed; cure normally is accomplished without external heat. RTM combines relatively low tooling and equipment costs with the ability to mold large structural parts. In general, thermoplastics are too viscous to be used in RTM.

s-glass: Structural glass; used as fiber reinforcement, designed to provide very high tensile strength.

shear modulus: The ratio of shearing stress to shearing strain within the range of elastic behavior of a material.

shear strain: The tangent of the angular change, caused by a force between two lines originally perpendicular to each through a point in a body. Also called angular strain.

shear strength: The maximum shear stress that a material is capable of sustaining before failure. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original cross-sectional area of the specimen.

sheet molding compound (SMC): A composite of fibers, usually a polyester resin, and pigments, fillers, and other additives that have been compounded and processed into sheet form to facilitate handling in the molding operation.

spray up: Technique in which a spray gun is used as an application tool. In reinforced plastics, for example, fibrous glass and resin can be simultaneously deposited in a mold. In essence, roving is fed through a chopper and ejected into a resin stream that is directed at the mold by either of two spray systems. In foamed plastics, fast-reacting urethane foams or epoxy foams are fed in liquid streams to the gun and sprayed on the surface. On contact, the liquid starts to foam.

stiffness: A measure of modulus. The relationship of load and deformation. The ratio between the applied stress and resulting strain. A term often used when the relationship of stress to strain does not conform to the definition of Young's modulus.

strain: Elastic deformation due to stress. Measured as the change in length per unit of length in a given direction, and expressed in percentage or mm/mm (in./in.)

stress: The internal force that resists change in size or shape, expressed in force per unit area.

synergy: The sum of the combination of the materials is greater than the sum of each of the materials separately

tensile strength: Stress caused by the different expansion in different directions of plies in a laminate at different orientations.

tensile strength: The maximum stress sustained by a plastic specimen before it fails in a tension test.

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thermoplastic: A plastic material that is capable of being repeatedly softened by application of heat and repeatedly hardened by cooling. Softening and hardening are reversible for a thermoplastic.

thermoset: A plastic material that is capable of being cured by heat or catalyst into an infusible and insoluble material. Once cured, a thermoset cannot be returned to the uncured state. Thus, hardening is irreversible for a thermoset.

voids: Pockets of entrapped gas that have been cured into a laminate.

working life: The period of time during which a liquid resin or adhesive, after mixing with catalyst, solvent, or other compound ingredients, remains usable.

All definitions were provided by the Composites Glossary, GREAT LAKES COMPOSITE CONSORTIUM

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