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How Study of Chocolate as a Material Can Be Used to Enhance Engineering Education

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How Study of Chocolate as a Material Can Be Used to Enhance Engineering Education

Chocolate is a material that is typically not associated within a engineering curriculum. Yet when viewed as a material that has composition, structure, and properties, the topic can add interest and an alternative perspective to a traditional materials engineering or chemistry course.
The cocoa butter in chocolate is critical to the final product in terms of quality and price and will be the central focus of this paper. Cocoa butter is derived from an agricultural product, is polymorphic and has chemical and physical characteristics that are somewhat unique. The molecular structure and chemical characteristics can be used to enhance a chemistry class. The processing of chocolate to ensure the proper form of the cocoa butter as well as the detrimental changes to the product that can occur with an incorrect thermal cycle (in processing or in storage) can be used as examples of phase transformations and diffusion in a materials engineering course. The economics, standards, sustainability, and political aspects of cocoa butter can be used to reinforce topics related to ABET criterion 3h.

The authors of this paper—who represent the disciplines of chemistry, mechanical engineering, and the humanities/social sciences—were intrigued to discover multiple connections and areas of crossover potential related to using chocolate as a material in their courses. The following paper describes these connections in greater detail and includes possible student activities and assignments.

Description of Chocolate

The basis for chocolate is the tree "Theobroma cacao," which originated in South and Central America. The tree produces flowers, which become the pods that are harvested with each pod containing 30-45 beans and pulp. The beans are separated from the pulp, and fermentation and drying are done locally at, or near the farm. After drying, the cocoa beans are packed and shipped to chocolate producers around the world. Note: Cocoa is commonly used in the chocolate industry to describe the products produced once the pod is opened and the beans are fermented, while cacao refers to the tree and the raw products. However, the term cacao is also frequently used to indicate the products that originated with the cacao pod when classifying cacao products.[1,2]

The cocoa beans are roasted to develop flavor and then cracked open with the nibs being removed from the shells. The nibs, which contain both cocoa solid and cocoa butter, are ground into a paste, which is called "chocolate liquor." The chocolate liquor can be pressed to separate the cocoa butter and the cocoa powder, or processed with additional ingredients to become dark or milk chocolate. Besides the cacao products, sugar and flavoring (usually vanilla) are the main ingredients in dark chocolate, with milk solids added for milk chocolate.

The forms of chocolate indicate the relative amount of each major ingredient. Dark chocolate contains a minimum of 35 wt% cacao, milk chocolate contains between 10-30% cacao and a minimum of 12 wt% milk solids, and white chocolate contains a minimum of 20 wt% cocoa butter (no cocoa solids) and a maximum of 55 wt% sugar.[2,3,4,5].

The flavor of chocolate mainly comes from the cocoa solids, the sugar and vanilla, while the characteristic texture, snap and mouth feel of chocolate comes from the cocoa butter. The structure of the cocoa butter is very critical in obtaining the desirable characteristics of good chocolate and is an engaging classroom topic in chemistry and materials courses, especially for non-materials engineering majors.

The Chemistry of Chocolate

Chocolate is a colloid – solid cacao bean particles are dispersed throughout the solid cocoa butter. It is categorized as a solid dispersion because the cocoa bean particles are the solid dispersed phase suspended in the cacao butter, the solid dispersing medium. Melted chocolate is homogeneous, but not a solution, because the cocoa bean particles are insoluble and not divided at the molecular level. The particles are on the order of 20-50 microns in size.

A useful comparison to make in class is to compare a solution and a colloid. These comparisons are rarely made in general chemistry or materials courses, but important because students often misuse the term solution. Students could be given the column and row headings and complete the elements of the table either individually, in small groups or as a large group classroom discussion.

Table 1: Comparison of Colloids and Solutions

	Colloid	**Solution**
Phases Involved (solid, liquid, gas)	solid in solid; solid in liquid, liquid in liquid, gas in liquid	solid in liquid, liquid in liquid, gas in liquid, solid in solid, gas in gas,
Appearance (macroscopic)	homogeneous mixture (scatters light)	homogeneous mixture (light passes through)
Two components	dispersing medium/dispersed phase	solute/solvent
Stability	inherently unstable	stable
Polarity of molecules	different polarities	same or similar polarities
Appearance (molecular level)	colloidal particles – 1 to 1000 nm (too small to see)	size of molecule (about 1 nm or smaller) (too small to see)
Common Examples	chocolate, mayonnaise, paints	gasoline, sports drinks

Cocoa butter is the naturally occurring fat in cocoa beans, making up about 55 wt% of the roasted beans. The cocoa butter suspends and lubricates the other solids, and the unique properties of the fat molecules are what give chocolate its pleasant characteristics.

Unlike many foods, the natural fatty acids comprising cocoa butter are remarkably few; the fatty acids in cocoa butter are primarily palmitic acid, stearic acid and oleic acid. This is shown in Figure 1.[3] A fat molecule is comprised of three fatty acids bonded to a glycerol molecule so the types of fatty acids affect the properties of the fat. In cocoa butter, the structure of the three fatty acids dictates the physical properties of the fat molecules.

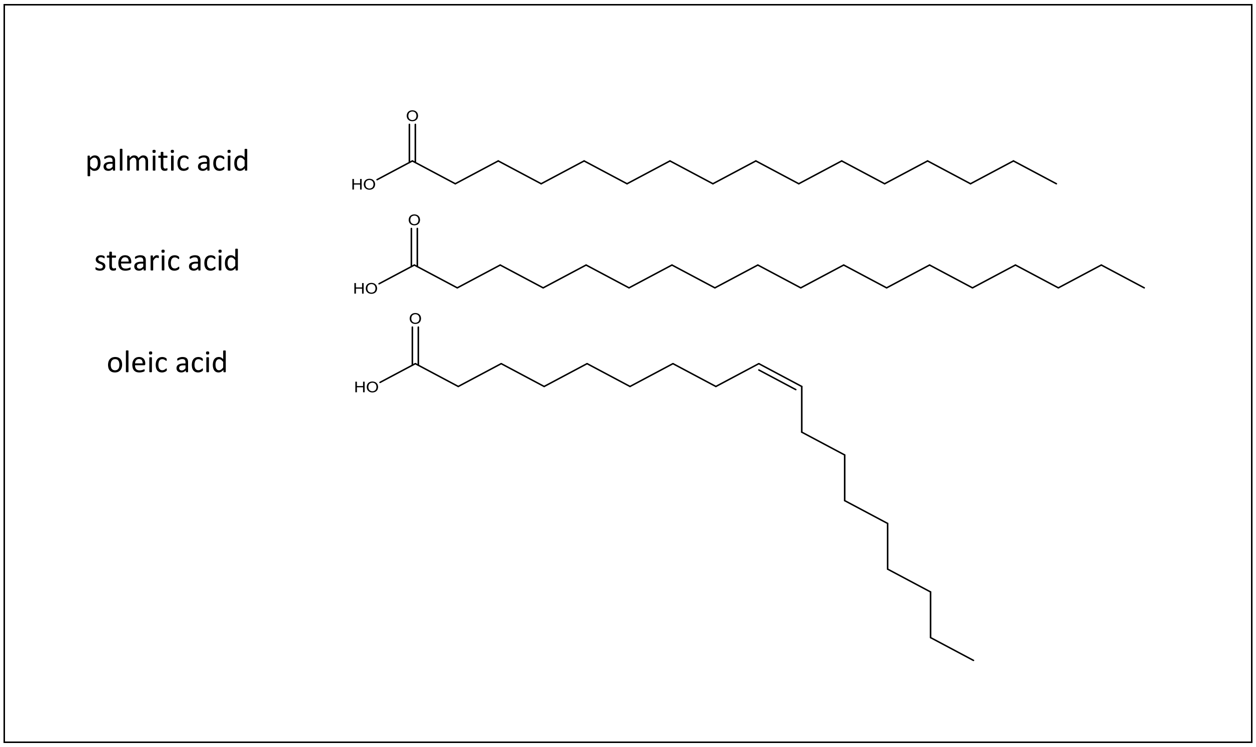

Figure 1 – The three fats in chocolate

The difference in the molecular structure of oleic acid is striking in that it is an omega-9 fatty acid, meaning that there is a double bond 9 carbons from the end of the hydrocarbon chain. This double bond affects the molecular shape and thus the melting point of cocoa butter. The double bond prevents rotation whereas the single bonds allow rotation. A useful student activity is for students to build a 6-carbon chain (omitting hydrogen atoms for simplicity) and compare that to a 6-carbon chain containing a double bond in the middle of the molecule. The overlapping p orbitals that form the pi bonding of the double bond prevent rotation whereas the overlap forming the sigma or single bonds allows rotation. A good model kit will show that there is no longer rotation around a double bond whereas there is rotation around all of the single bonds.

In general saturated fats have higher melting points than unsaturated fats. This difference occurs because of the presence of the double bonds. The double bonds cause a kink that prevents the molecules from settling into a crystalline arrangement in the solid phase at a particular temperature. Less kinetic energy at lower temperatures is required for the molecules to crystallize.

This example of molecular structure affecting physical properties is a common theme in both chemistry and materials engineering courses. Cocoa butter provides an interesting example of how the double bond electron density overlap prevents rotation. The real-world example transforms electron density overlap to an engaging topic for students. In a materials engineering course for mechanical engineers, the molecular bonding is less of a focus, but included to explain the differences.

In cocoa butter, over 95% of the fatty acids present are oleic acid, stearic acid and palmitic acid. Cocoa butter melts over a small temperature range because of its high uniformity. That temperature range of melting lies between room temperature and mouth temperature to pleasantly melt on the tongue when consumed.

Table 2: Percentages of each fat in cocoa butter [Beckett, 2008]

	Percentage in cocoa butter
oleic acid	35%
stearic acid	34%
palmitic acid	26%
Total	**95%**

Fat molecules are comprised of three fatty acids attached to a glycerol molecule, and so different arrangements of fatty acids lined up along the glycerol molecules create different molecules or different isomers. The variation of physical properties from different isomers is demonstrated with cocoa butter. Isomers are groups of molecules with the same chemical formula (same components), but with different structures. Because the isomers have different structures, the properties of the molecules vary as well. The important difference between the fat isomers in cocoa butter is the melting and freezing points. About 80% of the fat molecules in cocoa butter have oleic acid in the middle, an unsaturated fatty acid, and saturated fats on the outsides. The order of saturated fat, oleic acid, saturated fat is referred to as an SOS fat. About 1-2% of cocoa butter fat molecules contain only saturated fatty acids and are SSS fats. Without double bonds in the fatty acid chains, the SSS fats have a higher melting point than SOS fats. SOO fats contain two oleic acid molecules. SOO fats have a lower melting temperature and will be mostly liquid at room temperature. About 5-20% of fat molecules are SOO fats. The relative ratio of the types of fats in the chocolate will vary the melting point of the chocolate as shown in Figure 2. Milk chocolate adds milk fat to the ratio and results in chocolate that is softer to the bite.[3]

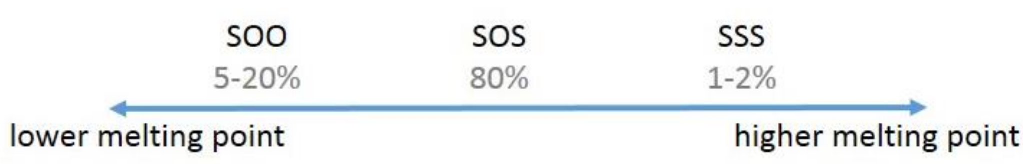

Figure 2 – Melting point of chocolate at varying ratios of fat types

Phases of Cocoa Butter

Cocoa butter is polymorphic and liquid cocoa butter can solidify into one of the six different polymorphs, which are generally referred to as forms and identified by Roman Numerals I-VI. Each polymorph is a slightly different arrangement of the fat molecules within the cocoa butter and has different properties, with only forms V and VI considered stable. Form 1 has the lowest packing and lowest melting temperature (61-65^oF) and form VI has the highest packing and highest melting temperature (94-97^oF). The desirable form of the cocoa butter is form V, which has a melting temperature between 90-94^oF and the associated properties of good chocolate.[3,5,6,7]

A useful activity to do is to have students work with form V cocoa butter and form IV cocoa butter to test the "snap" and the hardness (using Shore Durometer) of the different forms. The form V cocoa butter is in purchased dark chocolate, which is readily available. The form IV cocoa butter can be easily made by melting dark chocolate (temperature over 122 F), pouring into either a candy mold, or foil baking cups and allowing to cool. The hardness of the form V is much higher and makes a crisp snap when broken compared to the form IV. Students can experience the differences between the 2 forms/polymorphs and make the connection with the arrangement/structure of the different forms.

Tempering of Chocolate

The use of nucleation and growth theory that is typically taught in materials classes for engineering can be used to explain the process of "tempering" chocolate, which is intended to have the cocoa butter solidify into form V from the liquid state.

The tempering process in chocolate making is intended to produce numerous, small regions of form V cocoa butter in the chocolate in a timely manner so that during shaping and subsequent cooling, the remaining cocoa butter will solidify into form V and produce chocolate with the desired properties. The basic variables in the process are temperature, agitation and time.
A simple way to produce the desired form of cocoa butter would be to completely melt the chocolate (between 45^oC and 50^oC for dark chocolate) and then cool to just below 34^oC and slowly stir the chocolate while the chocolate remains at a constant temperature. This is in the temperature region of 32^oC to 34^oC in which form V forms and as the molecules are moved together, nucleation of small form V crystals would slowly occur. The goal is creating a sufficient number of small form V crystals (nucleation sites) in the remaining liquid chocolate so that upon subsequent cooling (which may be sudden), the remaining cocoa butter transforms to form V. This process can take several days, which is impractical. The two basic methods for tempering chocolate are illustrated in Figure 3 for dark chocolate.

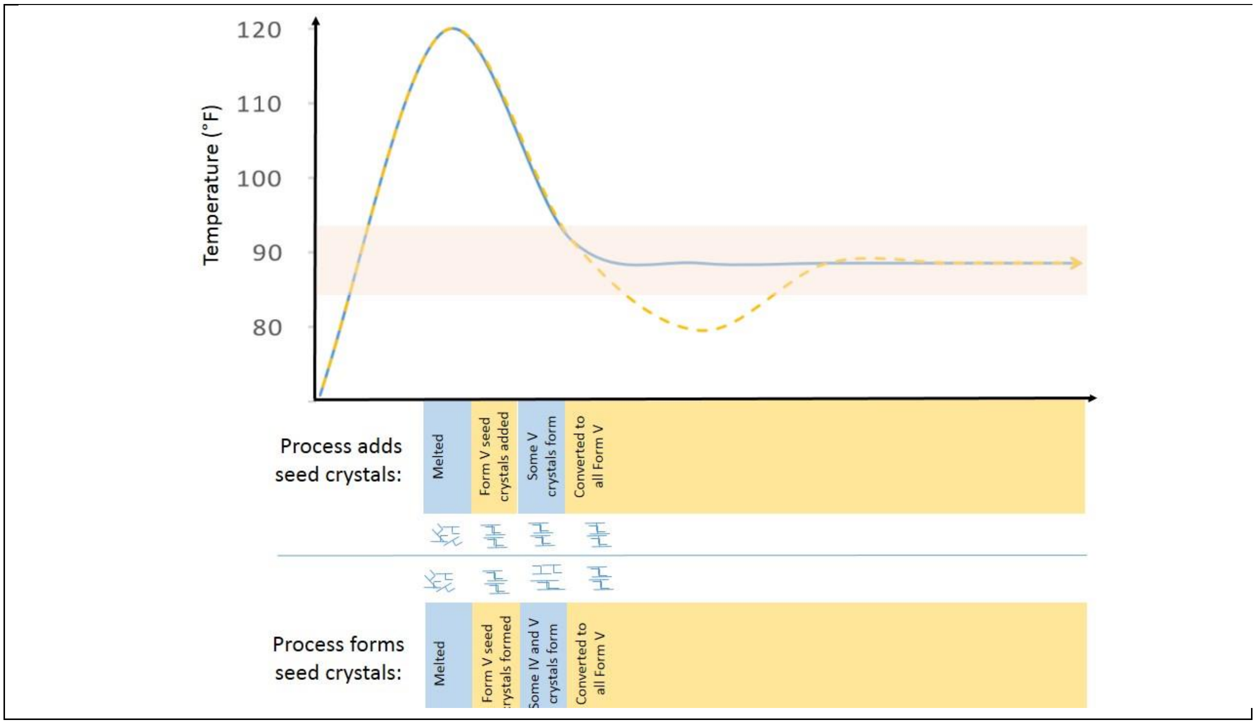

Figure 3 – Tempering Curve for Dark Chocolate

The tempering methods outlined in Figure 3 create the needed nucleation sites, which are the seed crystals of the desired form V of the cocoa butter.[8] One can view the above process as similar to homogeneous nucleation and the tempering process as heterogeneous nucleation. The process for the tempering of chocolate is not exactly the same as solidification of a metal, or other phase transformations in metals, but the concepts of nucleation, diffusion, heat transfer and thermodynamics can be discussed and examined in the process of cooling and forming chocolate. It is interesting to note that cocoa butter has a low thermal conductivity, a low specific heat and a high latent heat of fusion. Agitation is very important in both cooling the liquid chocolate and allowing movement of the cocoa butter molecules within the liquid.

The time to create the proper amount of small, numerous form V cocoa butter crystals in the liquid chocolate can be reduced by introducing solid, properly tempered chocolate to act as form V seed crystals in the melted chocolate. This is the solid curve in Figure 3. The process consists of melting the chocolate (between 112^{o}F and 122^{o}F for dark chocolate) and then cooling to just about the temperature range (95^{o}F to 100^{o}F) where the stable form V crystals will form and adding/stirring the solid chocolate while keeping the temperature in the tempering range of 88^{o}F to 90^{o}F. The solid chocolate added both cools the existing melted chocolate and acts as seed crystals as well. It is important to allow enough time in the tempering range for the solid chocolate to melt and become part of the existing liquid chocolate. The chocolate is held between 88^{o}F to 90^{o}F until needed.

The seed crystals can also be formed by essentially undercooling the liquid to promote the more rapid creation of solid cocoa butter in the liquid and controlling temperature to ensure only the form V cocoa butter crystals remain. This process is the dashed line in Figure 3. The first step is to heat the chocolate to 122^{o}F to completely melt the cocoa butter. The chocolate is allowed to cool, with agitation/stirring starting around 105^{o}F, and form V crystals start to form at 94^{o}F and continue to form as the chocolate cools to 85^{o}F. The liquid chocolate continues to cool, and both form V and form IV crystals are created as the chocolate mixture cools. The lower temperature enables the crystals to form at a more rapid rate (the liquid cocoa butter is more undercooled). After cooling to about 81^{o}F, the temperature is slowly increased to the tempering range of 88^{o}F to 90^{o}F and held until the unstable form IV crystals melt and the liquid chocolate contains the needed 1-2% seed crystals. The chocolate is held at this temperature until needed.

The tempering process for milk and white chocolate is similar to the process described for dark chocolate with the three basic steps of 1) melting all the cocoa butter 2) cooling to form starter crystals and 3) reheating to "tempering range" to melt out any unstable crystals. The temperature for all the steps in the process are lower for milk chocolate compared to dark chocolate and even lower for white chocolate. The ideal temperature range for milk and white chocolate will depend on the formulation of the particular chocolate.[2,5]

The role of both nucleation and growth in phase transformations and the associated variables in each process is important for engineering students to understand as background when studying solidification and heat treatment of metals. The concept that nucleation has to occur in order for a phase transformation to take place, and is controlled by thermodynamics, along with the concept of a driving force and barrier to nucleation, is not always immediately grasped. These concepts and the role of undercooling on the phase transformation, especially in regard to critical size of the nuclei (new phase) and how this is used in heat treating to create a desired microstructure can be reinforced by examining the tempering process for chocolate.

The two different methods for ensuring liquid chocolate cools with mainly form V cocoa butter in a timely manner can be used to have students explore the importance of both the thermodynamic considerations of a phase transformation and the variables associated with the kinetics, or overall rate of the transformation. The students can be given a copy of the time/temperature profile for each method and asked to 1) describe the structure of the cocoa butter for each step in the process, 2) explain from a nucleation and growth perspective what is happening when the liquid chocolate is seeded, and 3) explain why the undercooling step in the tempering recipe can produce a properly seeded chocolate mixture in less time than without the undercooling step. This works well as an in-class exercise in which the students work in small groups initially with a wrap-up general discussion with the entire class.

Fat Bloom in Chocolate

The importance of the tempering process in making chocolate products is to ensure the final form of the cocoa butter is mainly form V and not form IV. In addition to the reduced hardness and lack of the characteristic snap when broken, which occurs when the chocolate has not been tempered and solidified with mainly form IV, form IV is not stable. Form IV will transform to form V over time (usually days) and this can create what is known as "fat bloom." When a chocolate has fat bloom, the surface appears to be covered with a white layer, or there is a gray cast, streaks or spots as illustrated in Figure 4. Fat bloom is actually cocoa butter that has crystallized on the surface of the chocolate and can occur when the chocolate has not been processed, or stored correctly.

Figure 4 – Fat Bloom in Dark and Milk Chocolate

Fat bloom can occur when form IV cocoa butter transforms to the more stable form V cocoa butter over time. The packing of the molecules in form V is more efficient than in form IV with a resulting density increase when the cocoa butter transforms from form IV to form V. The increase in density from the transformation causes a contraction of the chocolate, and the liquid cocoa butter (there is a portion of the cocoa butter that is SOO and is liquid, even at room temperature) is squeezed between the particles and onto the surface where it will form large crystals that give the white appearance.

This process can also occur at a much slower rate (months to years) by the transformation of form V to the slightly more dense and stable form VI. It should be noted that form VI cannot be formed directly from the liquid cocoa butter and only forms by a solid-solid phase transformation from form V. This process is accelerated when the chocolate is exposed to higher temperatures. Fat bloom can also occur in chocolates with a nut center, by a process known as “fat migration.” In a box of chocolates, it is usually the chocolates with the nut centers that turn white (bloom) first. Most nuts have fats that are liquid at a lower temperature than cocoa butter, with some such as hazelnut that are almost all liquid at room temperature. The liquid fat can easily move into the chocolate covering until an equilibrium is reached. At the same time, the cocoa butter in the chocolate moves into the nut center. The result is the nut center becomes harder and the chocolate shell becomes softer (due to what is known as the “eutectic effect”), which minimizes the difference between the soft center and harder shell (loss of snap), making the candy less appealing. In addition, the liquid oil eventually reaches the surface, usually bringing some of the liquid cocoa butter with it, which crystallizes and produces the fat bloom. The potential solution to problems with fat migration (in addition to ensuring the chocolate is consumed quickly before it is damaged) is to provide a barrier around the nut center (a vegetable gum or a solid fat) to minimize the movement of the liquid fat into the chocolate. Note: milk chocolate is not affected as much as dark chocolate by fat bloom and since it is already softer, the loss of hardness is not as noticeable.[2,5,9]

In either a manufacturing processing course (to illustrate the importance of storage conditions) or in a materials course (to reinforce the relationship between processing, structure and properties), chocolate can be “bloomed” and examined. Small wrapped pieces of chocolate (plain dark or milk chocolate) can be “bloomed” by placing on a flat sheet in the sun or under a heat lamp until soft (but not deformed or melted) and then cooled to room temperature, remaining on the sheet. The package on the outside does not show any problems, but a clearly bloomed chocolate will be visible when the package is opened. The instructor can perform the process in advance and as an in-class exercise randomly pass out to the students both wrapped good chocolate and wrapped bloomed chocolates. The students, working in groups can un-wrap the chocolates and describe what they find along with testing the snap and hardness, as well as surface feel of both types of chocolates. The concept of the relationship between processing, structure and properties can be reinforced by having the students outline what is happening in each step to the structure and therefore properties of the cocoa butter.

The hands-on experience of opening what seems like a good product and finding a compromised product with fat bloom (damaged product that looks OK) can provide an opportunity for a class discussion on inspection techniques, importance of product quality on reputation and the role of proper handling and environmental control for some products.

Eutectic Effect in Chocolate

The movement of the liquid fat from the nuts into the chocolate changes the characteristics of the chocolate and what is known in the chocolate industry as the “eutectic effect” causes the chocolate to become softer. There concept of eutectic with regard to cocoa butter and other fats is similar to what occurs with the melting temperature of a mixture of copper and silver (one of the more common eutectic systems). When cocoa butter and the buttermilk in milk chocolate, or cocoa butter and the nut oil present in gianduja, or cocoa butter with coconut fat are combined, the melting temperature (or % solid fat at room temperature is often used) is lower than would be predicted by the average of the two fats, and there is a combination that has the lowest value. For example, the mixture of 75% coconut oil and 25% cocoa butter has a 30% solid fat content at room temperature, which is much lower than the 60% expected from a simple linear relationship. A similar, but less dramatic relationship exists for butter fat and cocoa butter and is the reason milk chocolate is so much softer than dark chocolate.[2,5,10]

Artisan (small batch) vs Mass-produced Chocolate

Cocoa butter is clearly critical to the properties of chocolate, but it is quite expensive as the only source is from the cocoa bean. Lecithin is a common chocolate additive that simplifies the chocolate processing and decreases the price by replacing some of the cacao butter. Lecithin is amphiphilic, meaning it contains both a polar region and a nonpolar region. Amphiphilic molecules are typically oblong in shape so that there is special separation between the two different regions. The amphiphilic nature of lecithin and other chocolate additives is critical to their function in stabilizing the chocolate dispersion. In chocolate the polar choline end of the lecithin molecule interacts with the cocoa bean solid particle and the nonpolar hydrocarbon chains of the lecithin molecule stick out into the cocoa butter. This coating-action reduces the amount of cocoa butter needed to coat the solid particles to keep the colloid stable. It also stabilizes the dispersion by reducing the surface energy between the two phases. Emulsifiers are also added to chocolate to simplify the processing. The dual polarity of these molecules again represents the significance of the structure of the molecule to its function. Other emulsifiers in commercial chocolate include polyglycerol polyricinoleate (PGPR) and ammonium phosphatide (AMP).

A simple demonstration could include layering oil on water in a capped container to demonstrate the differences in polarity. The container could then be mixed to create a very temporary, unstable colloid. Addition of an emulsifier such as lecithin followed by mixing shows the action of the lecithin as a stabilizer to the colloid. Lecithin is a commercially available through specialty grocery stores and olive oil works well because of its color contrast with water for demonstration purposes. Rather than an instructor-led demonstration, students can experience this in a short laboratory experiment.

Chocolate and ABET Criterion 3(h)

In addition to the technical topics of chocolate's unique molecular structures and behavior, closely examining chocolate in an engineering course can provide a logical segue to class discussion of ethical and sustainability issues associated with materials—if only to increase awareness that certain materials may become too costly, too scarce, or too abhorred by consumers to remain feasible in a product's manufacture.

If a material becomes too expensive or too difficult to obtain, manufacturing decisions have to be made. The price of silver may be too high, so different alloys are used. If a cobalt shortage results from violence in the war-torn Democratic Republic of the Congo, from which comes 50% of the world's supply, again different alloys would be used. Such materials substitutions may require changes in manufacturing processes in order to maintain product integrity. Identifying the many interrelated causal mechanisms associated with a material's supply chain makes obvious the importance of ABET's Criterion 3(h)—that engineering students have "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context".[11]

Studying chocolate alongside metals and plastics provides a particularly rich opportunity to use a material familiar to all students in highlighting the complex web of relationships between relatively controlled manufacturing environments and unpredictable outside influences.

The main ingredient in chocolate originates as an agricultural product from a small number of countries in tropical regions where trade, labor and sustainability practices are widely variable. At the same time that consumer demand for chocolate soars worldwide, particularly in China and India, cocoa production in the handful of nations supplying the crucial source material has dropped. Primary causes include below-average rainfall in Ivory Coast and Ghana (the two largest cocoa-growing countries), combined with inefficient traditional farming practices and misguided government policies (like Ghana's since-reversed change to its cocoa-subsidy program that gave farmers cash instead of fertilizer and seedlings).[12]

As with other raw materials, cocoa prices fluctuate continually—and have risen nearly 40% since early 2012. Not only is the price of cocoa butter already very high; it is still rising. By comparison, the price of cocoa powder is far less, and falling even lower.

Around 2006 chocolate manufacturers took the logical step (from a business perspective) of altering their products' ingredients to retain the less costly cocoa powder while substituting cheaper materials for some of the cocoa butter. If the cost of one material is too high, an engineering solution would be to substitute a less-expensive alternative. In this case the only absolute barrier to completely eliminating cocoa butter in favor of PGPR is political. A product cannot be legally sold as "chocolate" unless it contains a significant amount of cocoa butter.

In 2007 the Chocolate Manufacturers Association petitioned the US Food and Drug Administration (FDA) to change its official definition of "chocolate" to allow vegetable fats other than cocoa butter. However, cocoa butter is what gives chocolate its defining characteristics. The FDA's response was that "Cacao fat, as one of the "signature characteristics of the product, will remain a principal component of standardized chocolate," as it has been since the public "Standards of Identity" were established for the product in 1955.[13] So a product cannot be called "chocolate" unless it contains the key material of cocoa butter, and chocolate manufacturers hoping to cut costs were prevented from making extensive substitutions for their most expensive ingredient because that would result in having to relabel their product.

Not only did chocolate manufacturers have to contend with the regulatory authority of the FDA in their quest to minimize costs. Following the industry's widespread adoption cheaper ingredients, not only was there consumer backlash associated with the products' altered flavor, but also with time there came increased awareness of the products' altered nutritional content. The health benefits associated with chocolate arise from the cocoa butter, not the cocoa powder.

By November of 2015, bowing to consumer demand, Hershey had reversed its ingredients changes. In addition to removing genetically modified and artificial ingredients, Hershey also ended the use of PGPR (polyglycerol polyricinoleate), an emulsifier that had been used as a cheap replacement for cocoa butter since 2006.

Ethical concerns regarding the use of child labor and other unfair labor practices may also affect manufacturers. A Tulane University study funded by the US Department of Labor found 2.12 million children performing hazardous work on cocoa farms, a number that rose 18% between 2008 and 2014.[14] Concern over the use of forced labor in the labor-intensive cocoa-farming industry is not new. It has been associated with the industry since cocoa trading began in the fifteenth century. International Cocoa Agreements have tried to deal with labor conditions but with limited impact. Although Ivory Coast and Ghana have banned child labor, for example, local authorities cannot adequately monitor all the isolated rural farms.

Because maintaining a reliable supply of predictably priced cacao as a raw material is as crucial as it is precarious, the world's major chocolate manufacturers have recognized the need to step up and address issues of sustainability themselves: "The problems worry the industry so much that 10 of the largest chocolate producers and cocoa processors agreed in 2014 to begin sharing with each other a wide swath of private data on farming practices and crop yields. . . . The industry-wide total of approximately $1 billion includes spending on cocoa-sustainability programs . . . ." [12]

The past decade has seen rapid growth in the importance of private standards in chocolate value chains.[15] With changes in technology increasing demand for other materials with serious ethical and sustainability issues (especially cobalt, with 20% of the supply from Congo extracted by small-scale mining operations that have no oversight and rely on child labor and worker exploitation),[16] students may find that their future engineering careers depend not just on their knowledge of materials and manufacturing processes but possibly even more on their ability to place that knowledge within an awareness of larger supply chain issues resulting from myriad causes.

Conclusion

The authors have enjoyed exploring the topic of chocolate from a pure knowledge perspective, along with sharing the topic with current and future students. Our interdisciplinary approach gave us perspectives from each other's disciplines we could not have gained by studying the subject individually. Additionally, we are modelling this interdisciplinary behavior for our students.

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