Int. J. Engng Ed. Vol. 22, No. 5, pp. 925–936, 2006
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Strength By Chocolate*

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We have developed an open-ended 10-week design project called Strength by Chocolate. The intent of this project is to expose first-year undergraduate engineering students to the central paradigm of Materials Science and Engineering (MSE). The project allows students unfamiliar with materials concepts to wholly design, fabricate, predict and test the mechanical properties of a reinforced chocolate composite. This paper describes the students' efforts to strengthen chocolate, illustrates some of the classic materials processing–structure–property behaviours observed in the composites, and discusses the benefits of using the MSE paradigm to teach materials.

'Strength is the capacity to break a chocolate bar into four pieces with your bare hands—and then eat just one of the pieces.'—Judith Viorst

Keywords: chocolate; food-based composites; materials design; materials science engineering paradigm, mechanical testing; phase transformations, rule of mixtures.

INTRODUCTION

IN CANADA, STUDENTS currently entering first-year engineering studies directly from high school have cultivated their scientific interests in three possible ways: self-experience (uncontrolled), school programs (controlled), and popular culture (contrived). Of the three sources, self-experience, or more specifically hands-on experience developed by tinkering with chemistry sets, cooking, connecting electric motors, building a canoe, computer programming, etc., is the most varied, but can forge the strongest impressions. All fields of engineering have varying degrees of exposure at the self level, but student-starved engineering programs cannot rely upon this mechanism for attracting students to their specific discipline. Furthermore, the level of epiphany-rewarded, self-discovery through play with nature has decreased as more students arrive in class from urban settings. The study of Materials Science and Engineering (MSE) is particularly sensitive to identifying the cause–effect relationships between structure–properties–processing–performance, described aptly as the MSE paradigm [1, 2] (Fig. 1). Flemings and Suresh [3] have recently identified the MSE paradigm as the template for materials education. Of the paradigm relationships indicated in Fig. 1, the structure and properties linkage remains the most intensely studied and taught, especially as new materials systems are created, while the processing and performance relationships remain less so. It therefore remains a challenge for educators to introduce engineering students of varying backgrounds to the whole materials paradigm in an attractive and empowering manner [4].

In this context, a project entitled Strength by Chocolate has been developed at Queen's University to introduce first-year engineering students unfamiliar with MSE to phase transformations, microstructure and strengthening mechanisms in composite materials. At Queen's University, first-year engineering studies are general, such that discipline choices are not made until second year. Strength by Chocolate is one of many projects used in the course APSC 100—Active Design and Lab Course in first-year engineering [5] and is a specific example of an open-ended project-based approach for introducing first-year engineering students to MSE. Students take the module in either the first or second term of their first year.

In Strength by Chocolate, student teams are asked to design and fabricate a chocolate-based composite material with optimum strength and/or toughness. Chocolate is chosen because it has a relatively low melting point compared to typical engineering materials, and it can be safely processed with amorphous/crystalline structures similar to polymers. Mechanical properties (stiffness, yield strength, resilience, etc.) of chocolate cast into standard test geometries are first measured to set a baseline for the composite's matrix properties. Student teams then propose and test different biodegradable reinforcements as potential reinforcing phases for the chocolate. The combined properties of the composite are then estimated using a simple rule of mixtures [6], and each team proposes a final composite design. The student teams further develop 'proprietary' techniques to process the proposed chocolate-based composite. The final composite specimens are tested in uniaxial compression and flexure, and the results are compared to models of the upper and lower bound properties for composite materials [6]. Whenever possible, post analysis of the deformed composites is done by optical microscopy. This project takes about 10 two-hour

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* Accepted 15 May 2006.

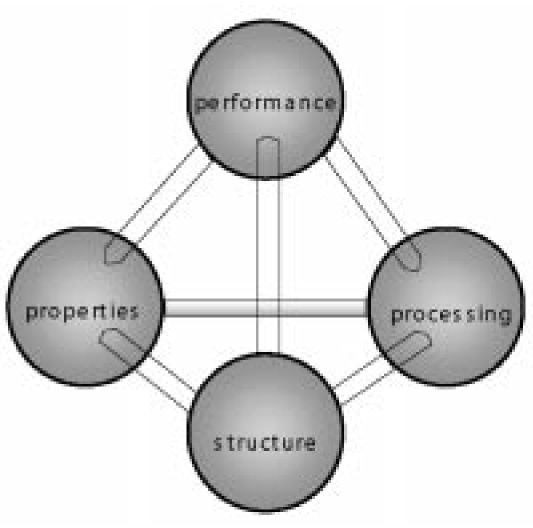

Fig. 1. Representation of the materials science paradigm, which consists of four elements of concentration and suggested linkages.

sessions, which includes interim and final oral and written presentations (see Appendix A). Upon project completion, the students demonstrate competent knowledge of stress, strain, elasticity, inelasticity, toughness, casting defects, microstructure concepts, composite failure modes, and, most importantly, students have developed a lasting impression of MSE!

This paper is presented in five parts to emphasize the teaching philosophy woven through the project: (1) the presentation of formal theory; (2) the first fabrication and testing of chocolate alone; (3) the design, fabrication and testing of the composite; (4) post-deformation analysis of the composite; and (5) final discussion of the lessons learned. Specific descriptions of the students' efforts (design, fabrication, and testing) in strengthening chocolate are presented along with some notable examples of classic materials processing–structure–property behaviours for those interested. Results from the 'in-class activities' such as oral and written reports, combined with a post-course survey (Appendix B) of the students' remnant memories of the project, are used to discuss the power of the MSE paradigm in teaching, and the general value of using open-ended projects to facilitate higher learning. The paper concludes with some thoughts on possible project variations for future exploration.

PROLOGUE:
PRESENTATION OF FORMAL THEORY

Background to mechanics of materials and composites

The initial meeting between the instructor and the students occurs in a formal lecture setting. Students arrive in teams of four, which are pre-organized by the course coordinator. A 50-minute introductory lecture is given at the outset to bring the students to a common starting-point in their knowledge of materials and then clearly set the engineering goal. Working from the students' understanding of Hooke's Law, concepts of stress, strain, and plastic behaviour of solids, stress and strain states, and their determination by mechanical testing techniques such as tension, compression, shear, torsion and flexure, are presented. The stress–strain curve is presented as an all-encompassing measure of stiffness, strength, ductility and toughness. The lecture also introduces composite materials by illustrating how natural systems have been used as templates for artificial engineering composites designed for specific applications, choice of matrix and reinforcement morphology, and pros and cons of use such as recyclability. The concept of structure (though at the macro-level) and its potential effect on mechanical properties is also described. To enable some form of predictive design for the students, the rule of mixtures used to describe the mass density of a composite, ρ, is defined as

$$\rho = \mathrm{f_r}\rho_\mathrm{r} + (1 - \mathrm{f_r})\rho_\mathrm{m} \qquad (1)$$

where $\mathrm{f_r}$ is the volume fraction of the reinforcement, ρ_r and ρ_m are the mass densities of the reinforcement and the matrix, respectively. This rule is then extrapolated without further explanation to predict the upper bound strengthening behaviour of a composite material as

$$\sigma = \mathrm{f_r}\sigma_\mathrm{r} + (1 - \mathrm{f_r})\sigma_\mathrm{m} \qquad (2)$$

where σ_r and $_\mathrm{m}$ are the yield stresses of the reinforcement and the matrix, respectively. The students are then referred to Ashby's overview on composites where he also develops lower bound predictions for the properties [6]. Reading and understanding the Ashby paper by the end of the project term is left optional to the students, but represents an excellent reference, which can be used as an external measure of the level of student learning over the duration of the project.

The chocolate matrix

The structure of chocolate is very sensitive to melting and cooling practice, which many students were not aware of unless they spend time in the kitchen. Fryer and Pinschower [7] offer a nice review of the various polymorphic forms of chocolate and emphasize its correlation to processing. Generally, it is agreed that there exists six crystalline forms of cocoa butter (I to VI) identified by the following possible stability sequence, and corresponding melting points (mp):

$$\begin{aligned} \mathrm{I}(\gamma)_{\mathrm{mp}=17.3^\circ\mathrm{C}} &\rightarrow \mathrm{II}(\alpha)_{\mathrm{mp}=23.3^\circ\mathrm{C}} \rightarrow \mathrm{III}_{\mathrm{mp}=25.5^\circ\mathrm{C}} \\ &\rightarrow \mathrm{IV}(\beta')_{\mathrm{mp}=27.3^\circ\mathrm{C}} \rightarrow \mathrm{V}(\beta)_{\mathrm{mp}=33.8^\circ\mathrm{C}} \\ &\rightarrow \mathrm{VI}_{\mathrm{mp}=36.3^\circ\mathrm{C}} \qquad (3) \end{aligned}$$

In the studies reviewed, they focused on the important food-science aspects of appearance and melting temperature, but not mechanical properties. Other researchers, such as Herrera and Hartel [8], have studied the effect of milk fat and processing conditions on chocolate manufacturing using low-frequency compression to identify visco-elastic components, a behaviour that makes chocolate a useful material to study if one is also interested in introducing mechanical behaviour of polymers to students. In Strength by Chocolate, the students are given the Fryer and Pinschower reference at the end of the first lecture to read on their own before the first laboratory session. Finally, to reinforce the concepts of strength and toughness, students are asked before a demonstration to predict how chocolate at room or liquid nitrogen temperatures will behave if dropped on the floor. Chocolate bars are then served over post-lecture discussion.

ACT ONE: CHOCOLATE'S SOLILOQUY

Casting practice (processing)

The first task of the project was to establish the base-line properties of solid chocolate, which forms the matrix of the composite. After reading Fryer and Pinschower [7], students were asked to cast chocolate into four standardized aluminum split test moulds with interior dimensions of 100 mm × 32.5 mm × 28.5 mm (l × h × w). Baker's® unsweetened chocolate was used for all investigations to set a property base-line. Melting was performed in a double beaker: the outer beaker contained water which was heated on a temperature-controlled hot-plate, and the inner beaker contained the chocolate. The temperatures of the water and chocolate were monitored during heating. The melting temperature in all cases was observed to be approximately 34°C. With continuous stirring the students superheated the chocolate to a reasonable temperature, which they kept constant before pouring into the mould. The moulds sat on an aluminum chill block. To investigate the effect of cooling rate on final mechanical properties the filled moulds were placed immediately in different environments—ranging from –30°C to ambient—and kept overnight. Within 12 hours of casting, the specimen bars were extracted from the moulds and stored in a refrigerator.

The quality of the casting surface was the first indication to the students about the control of their casting process. Rapid solidification from the melt usually resulted in a highly-aesthetic, dark, glossy, brown surface that easily came out of the moulds (Form I → II). In contrast, cooling to ambient temperature and storing overnight yielded a less-pleasing, dull, light-brown surface, but with no visible voids (Form IV).

Mechanical characterization by uniaxial compression and three- or four-point bending tests was carried out within one week of the casting. To meet the geometrical requirement of a compression test and increase the number of compression specimens, the bars were sectioned in half using a hot-knife.

Mechanical testing (properties)

The mechanical properties of the chocolate and chocolate-based composites were expected to be very rate dependent, and so every effort was made

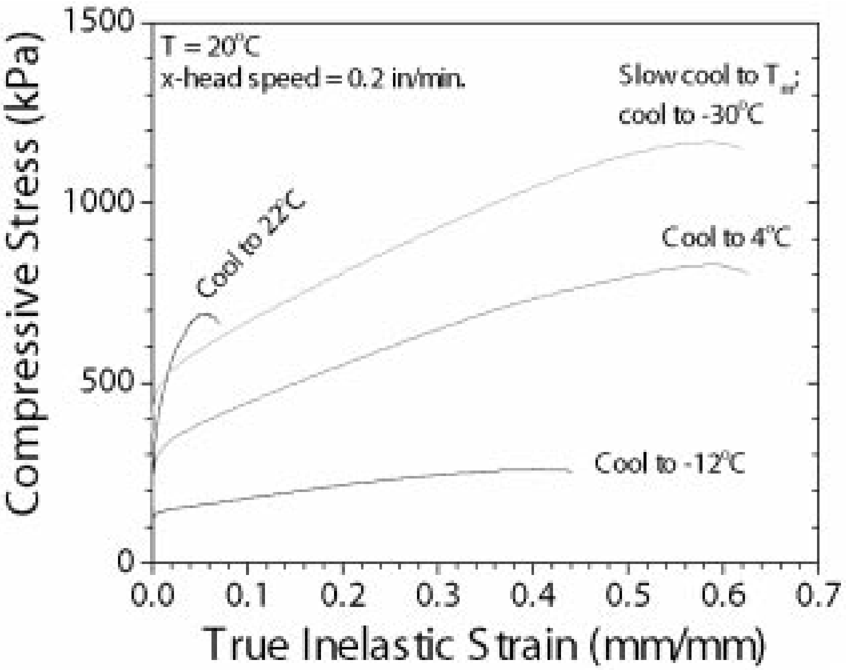

Fig. 2. True compressive stress versus true inelastic strain for bittersweet chocolate cooled from the melt to different storage temperatures. Improved pouring control resulted in fewer internal defects and larger deformations to failure. Rapid cooling to –30°C after initial solidification at the melting point, Tm, resulted in the highest yield and flow stress behaviour. Tests were performed at 20°C and a constant cross-head speed of 0.2 in./min.

to perform the tests at the same temperature and deformation rates. A very detailed and careful procedure was followed to expose students to the importance of sound experimental technique, and to give them confidence in interpreting their data. Testing was usually done one week after casting, and the specimens were removed from the refrigerator to allow time to reach the testing temperature. Compression and three- or four-point bending tests were performed using a screw-driven Instron testing frame with computerized data acquisition and display monitor. A complete description of the procedure and results are described elsewhere [9], but the general observations of interest are presented here. For most students, this project was their first exposure to mechanical testing, and created one of their most powerful memories of the module: watching the deformation of the specimen they fabricated, and seeing the force–distance response on the computer screen. Figure 2 shows the calculated stress–strain responses for the differently processed chocolate. In ductile specimens compressed to larger strains, students could easily see surface slip marks at 45° to the loading direction along the plane of maximum shear stress, which meet to form a tensile crack on the surface parallel to the loading direction (Fig. 3). The linkage is profound and harkens back to times past, when Alan Cottrell might have pricked the stress–strain curve of a deforming metal onto the recording drum of a Houndsfield mechanical test frame while turning a hand-crank to apply the deformation, all the time wondering about the origins of work hardening. Another realization and confirmation for the students was that chocolate's mechanical properties were very sensitive to the casting and storage process. For this reason, new chocolate specimens were prepared for reference when the composites were made, and data from those specimens were used for the rule of mixtures calculations.

Chocolate as a composite (structure)

At the macroscopic level, which is visible to the naked eye, casting defects were easily observed by the students. Sometimes, compression tests of similar samples revealed a completely enclosed shrinkage pipe at the centre of the casting (Fig. 4), which is classically attributed to control, or lack of control, of vertical and horizontal heat transfer during solidification [10]. Insulating the mould walls during low temperature cooling would reduce this effect but was not considered by the students.

Closer examination of as-cast and/or fracture surfaces revealed to the students, sometimes unexpectedly, that chocolate is not a single phase but a multi-phase material, or composite. For example,

Fig. 3. Formation of slip lines along directions of maximum shear stress during uniaxial compression, which leads to crack opening at larger strains.

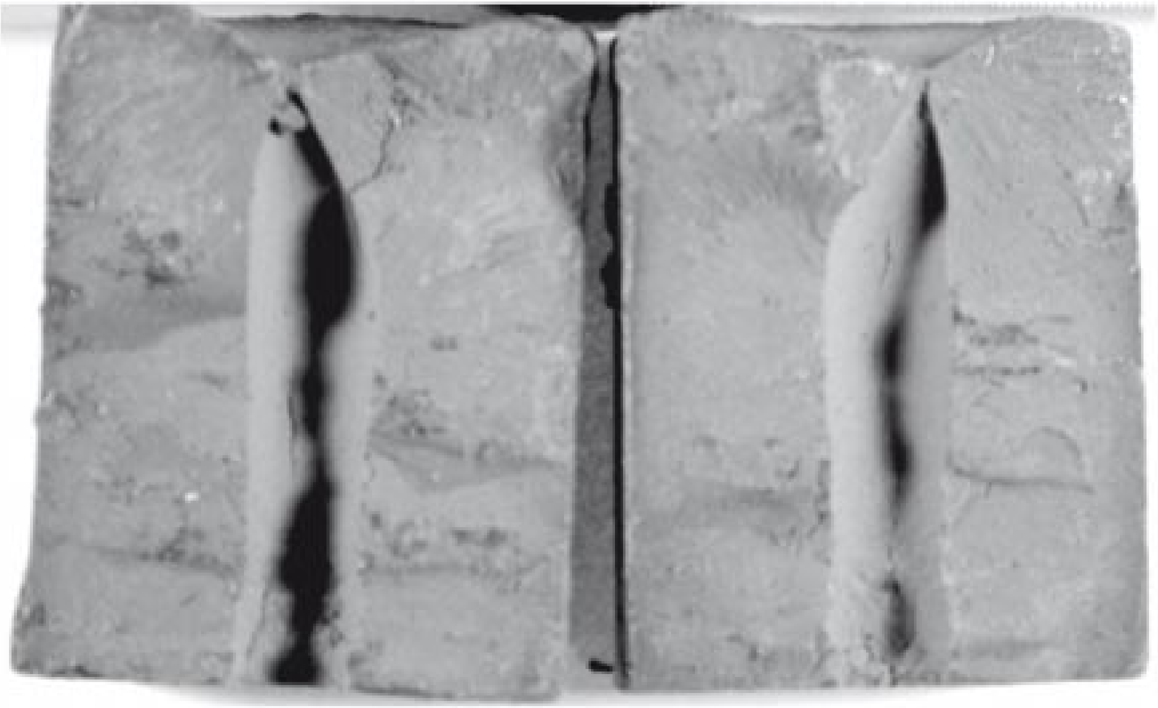

Fig. 4. Enclosed pipe defect observed in 4°C cooled bittersweet chocolate after uniaxial compression. The occurrence of both lateral and vertical heat conduction during cooling in the mould contributes to the formation of this defect.

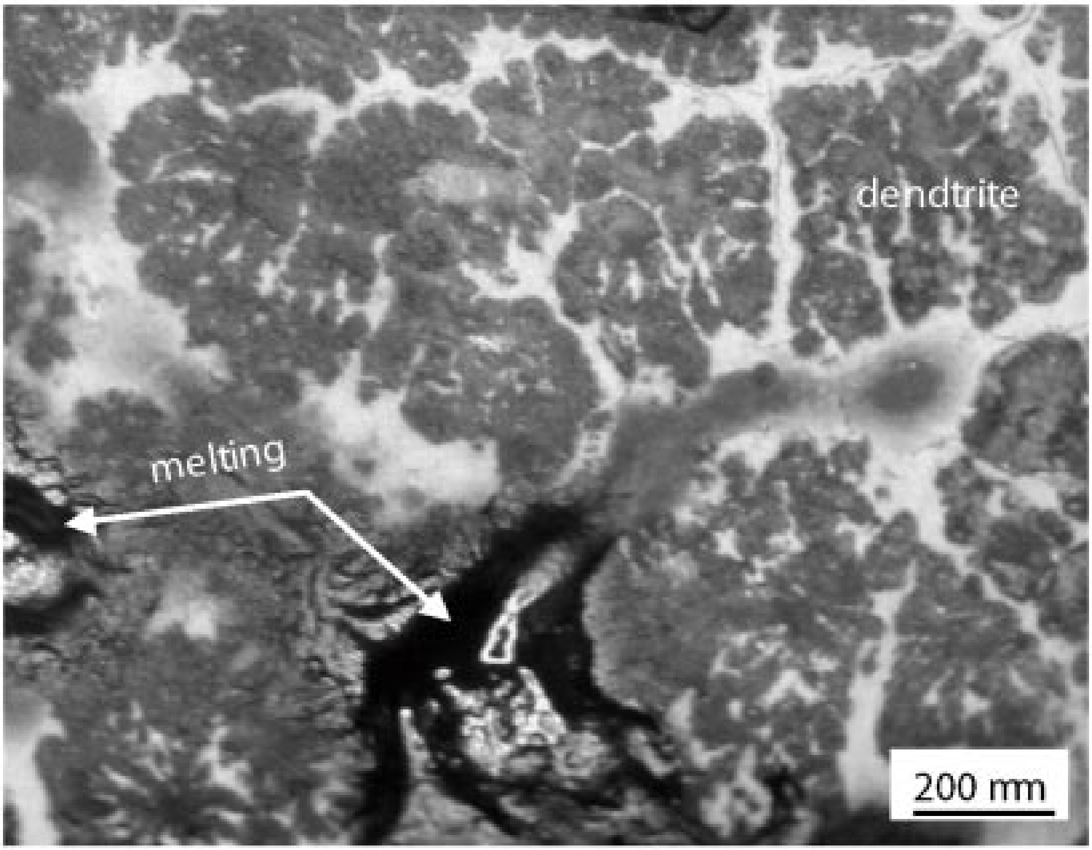

Fig. 5. Optical micrograph of as-cast surface for chocolate cooled to 22°C. Arrows indicate phase melting due to surface heating from imaging light source. Also evident in the light-coloured phase are intergranular cracks.

the chocolate cooled to ambient temperature had significant strength but was overall very brittle and in the worst cases was described as 'crumbly' by the students. The optical micrograph in Fig. 5 of the as-cast surface reveals several micrometer-sized dendritic structures surrounded by a light-coloured intergranular phase and secondary dark intergranular phase. Melting of the dark intergranular, lower-melting-point phase under the observation lighting is indicated by the arrows. Also evident in the top right corner is the brittle nature of the light-coloured phase, as cracks are observed in this phase surrounding some of the dendritic crystals. In classical solidification theory, the dendrite size is related to the solidification process, such that faster cooling can result in a greater number of nuclei, and therefore smaller-sized crystals. Small crystallites are essential for improving mechanical strength [11, 12] and toughness [13], but not necessarily taste. In chocolate terminology, the lighter phase is the unwanted fat bloom, which develops from one of the metastable chocolate phases during storage at too high a temperature. Except for care in preparing the specimens in a repeatable manner, no further attempt was made to identify the observed phases. It is interesting to note that a more rigorous explanation for the formation of this and other chocolate phases has only recently been proposed [14] after a high-resolution synchrotron x-ray study by Schwenk and Peschar [15].

ACT TWO: THE SUPPORTING PLAYERS

Design considerations

The main student goal of Strength by Chocolate was to significantly increase, and predict, the (yield) strength of chocolate with addition of a reinforcing phase. Design was limited to reinforcements that were fully biodegradable, or at least recyclable, and which occupy no more than 60 percent of the total volume. Furthermore, the design loading required only uniaxial compression and/or three-point bending. A geometrical constraint required that composite test specimens be fabricated to the same dimensions as the chocolate test specimens described earlier. With this criterion, student teams went about choosing a reinforcement, configuring the reinforcement, and determining how to fabricate the composite. Without any further suggestions, the students independently chose what could be called classical composite architectures, which include reinforcement with fibres, plates, or particles. The proposed designs are traditionally reported at the interim report stage, from which report evaluations can be used to allow or dissuade further design. In many cases, reliable mechanical data was not available for the selected reinforcements, so that independent measurements had to be carried out by the students for their predictive model. Some general comments about the students' reinforcement choices and their efforts to incorporate them into the chocolate are worth noting.

Proprietary composite fabrication (processing)

Fibres: The fibre category can be further divided into continuous-oriented and long-random fibres. The continuous-oriented fibre represented one of the more common student solutions to the composite design problem, which exploits the fact that the loading conditions are known a priori. To strengthen the chocolate in both compression and bending, continuous fibres were oriented through the matrix to maximize compressive and tensile strengths, respectively. Fibre reinforcements chosen by the students included food-based ones such as Super Nibs®, beef jerky, and Tootsie Roll®, and more structural ones such as oak or bamboo wood dowels. Most fibres had fairly large diameters relative to the volume they occupied in the matrix, with length to diameter aspect ratio no larger than 40:1; the term 'short' fibres is justified only if the ratio is considered, and not the specific diameter size as used to describe fibre reinforcements [16]. In all cases, the fibres were laid-up inside the split-mould, sometimes with an applied compressive stress, the mould closed, and the molten chocolate poured into the mould. The students tended to overfill the mould to account for shrinkage during solidification. Figure 6a illustrates a generic bi-directional solution and 6b an actual as-cast composite. For a pure bend-loading design, the students considered using very fine, randomly oriented, tangled fibres to strengthen the chocolate in tension, and reduce the chance of forming a catastrophic crack. Fibre materials considered included hemp or cotton, but only cotton is described here. Cotton fibres were extracted from a generic brand of cotton ball. The students elected to stir-cast the composite instead of the more challenging squeeze infiltration. The cotton was slowly added to the melted chocolate and hand stirred until the fibres were saturated with chocolate. Stirring subsequently became more difficult with addition of cotton. The chocolate-impregnated fibres had a higher density then the chocolate and were observed to sink to the bottom of the reaction container. The solution was difficult to keep homogeneous, and cotton addition was stopped when all of the liquid chocolate had been absorbed. The chocolate–cotton mixture was then manually 'injected' into the top of the mould until no more could be added. Figure 13 shows the as-cast composite. Visible at the corners are large surface voids that were caused by the difficulty of filling the mould with the high viscosity melt.

Plates: In this example students used oriented plate-shaped Gypsona® or silica glass as reinforcements. Though not biodegradable, the glass was accepted as being recyclable. Gypsona®, a plaster-of-paris material used in making casts, was chosen as the reinforcement by the students because it is easy to mould when wet and quickly hardens (sets)

Fig. 6. (a) Generic bi-directional fibre lay-up for tensile/compressive and compressive loadings. (b) Example of bittersweet chocolate reinforced with Super Nibs® fibres.

as it dries. A lattice, or pre-form, was fabricated and oriented either orthogonally or diagonally into the mould and the mould was filled with chocolate. Two millimetre-thick slabs of silica glass were cut to the width and height dimensions of the mould, and four slabs were positioned in parallel. Molten chocolate was poured in between the slabs and cooled. Some difficulty was encountered keeping the spacing between the glass plates equi-distance during the pouring, because the chocolate did not wet the glass, and the resulting vapour-liquid interfacial force could pull the glass plates out of alignment.

Particles: Particles chosen by the students as reinforcements could be classified as either chemically inert or reactive. Inert silica glass was ground into different particle sizes. Equivalent volume fractions were added to a fixed volume of molten chocolate and stir-cast into the moulds. In contrast, L-phenylalanine or gelatine was used as the particle reinforcement. Both were available as fine powders, which was amenable to creating a more homogeneous and isotropic reinforcement distribution. Both are food-based chemicals, which were expected to react chemically with the molten chocolate as a liquid solution. Gelatine is a polymeric material valued for its biocompatibility and environmental friendliness. Gelatine can exist as a sol at room temperature and exhibits properties of both a solid and a liquid. Mechanically, gelatine is visco-elastic and displays strong time-dependent deformation behaviour [17, 18]. Knox® gelatine was dissolved in boiling water as per the manufacturer's instructions, and then combined with the molten chocolate. Almost instantaneously, and to the surprise of the students, the mixture became very viscous and difficult to stir, and heat was released from the reaction. The composite solution was then frantically squeezed into moulds and allowed to cool. L-phenylalanine is the major constituent of the well-known sweetener, aspartame. It was combined with the melted chocolate in a ratio of one gram of L-phenylalanine to 10 ml of chocolate, or about 10% by volume. After stirring, the mixture was poured into the moulds and stored at –12°C. Separate L-phenylalanine compacts were isostatically pressed from the raw L-phenylalanine powder for evaluation of its compression and flexure properties.

ACT THREE: DEDUCING EACH PLAYER'S ROLE

Testing the rule of mixtures (properties–performance)

Each team discovered during mechanical testing whether their reinforcing design had the predicted effect, i.e. increasing the strength of the as-cast chocolate. It was not until final oral presentations that one team could assume bragging rights for 'strongest chocolate composite'. It became immediately obvious to the students that the rule of mixtures was applicable in most cases to estimate the maximum strength of their composite materials. In cases where the overall strength of the chocolate was significantly less than the pure chocolate, students realized that they could weaken the chocolate by introducing new reinforcement/chocolate interfaces, which would require a different predictive law. Explaining why the rule of

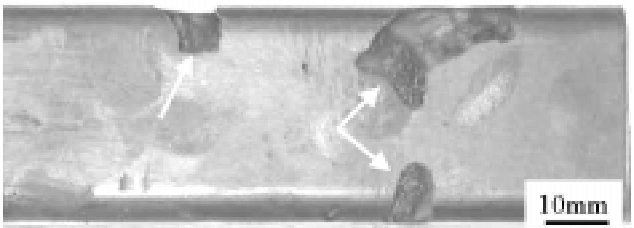

Fig. 7. Example of cast surface for bittersweet chocolate–cotton fibre composite specimen cooled to –25°C. The arrows indicate unwanted surface porosity at the corners.

mixtures does not work was the more difficult challenge and is not discussed further here.

Characteristic behaviour (structure–properties)

Many of the deformation and failure behaviours observed during testing of the chocolate-based composites can be compared to textbook treatments such as Hull and Clyne, *An Introduction to Composite Materials* [16]. Though this was not the objective of the project module, it was reassuring that the student-made materials behaved in an expected manner! The opportunity to carry the students' analysis to a higher level is a result of the open-endedness of this project, which only becomes limited by time and the students' abilities. This scientific approach also completes Olsen's description of the central paradigm of materials science and engineering [2], by connecting the cause-and-effect relationships between processing and performance. Two examples taken from the continuous oriented and the randomly oriented fibres are presented here. A complete analysis of the other composites behaviour is presented elsewhere [9].

In the cases using continuous oriented fibres, the tests can be separated into the imposed loading states, the types of reinforcements used, and the interfacial bond formed between the matrix and reinforcement. For example, chocolate infiltration into the Tootsie Roll® reinforcement during processing appears to have wet the reinforcement to form a significant bond. This is evident after the flexure experiments, which revealed failure in the matrix and not at the interface (Fig. 8a). Failure of this composite resulted from propagation of one major crack in the matrix, which is bridged by the fibres. Figure 9 displays the characteristic stress versus platen behaviour for the test indicating three regions: (i) loading of composite till debonding occurs between the fibre and the matrix; (ii) further debonding along the fibre/chocolate interface; (iii) pull-out of fibre from matrix. In contrast, the wooden reinforcements were not as well bonded to the chocolate, with the worst being the bamboo, with its very smooth surface (Fig. 8b).

Reinforcing the chocolate matrix with randomly oriented cotton fibres did not improve the measured yield strengths, but in fact decreased the overall performance. Instead of contributing to the yield strength, the fibres helped bridge the evolving damage and reduce the stress intensity at the cracks. The result was a composite material that was very, very tough, and able to sustain many small cracks without catastrophic failure. Figure 10 is a fractograph taken from the tensile side of the three-point bend specimen. It was not until the students looked through the microscope at the fracture surface that they fully understood why their composite was not only weaker but considerably more ductile (the composite never experienced macroscopic fracture) than the pure chocolate. Visible in Fig. 10 are cotton fibres dangling from the matrix fracture surface in various conformations; the white arrows indicate two straight segments which could have severed from each other during the test. The benefit of the cotton fibres was not in the strengthening, but toughening, since the fibres deflected cracks and held the composite together after fracture.

Such student-driven investigations offer nice examples of composite materials behaviour for students to take home and ponder. Encouraging self-learning to continue outside the classroom is another important aspect of any successful teaching exercise, but it is difficult to ascertain how and why this happens. Below we rationalize what the students (and the author) actually learned, how it was learned, and if possible whether the exercise has further impacted student learning. Finally, we ponder on how to attract students into the MSE discipline.

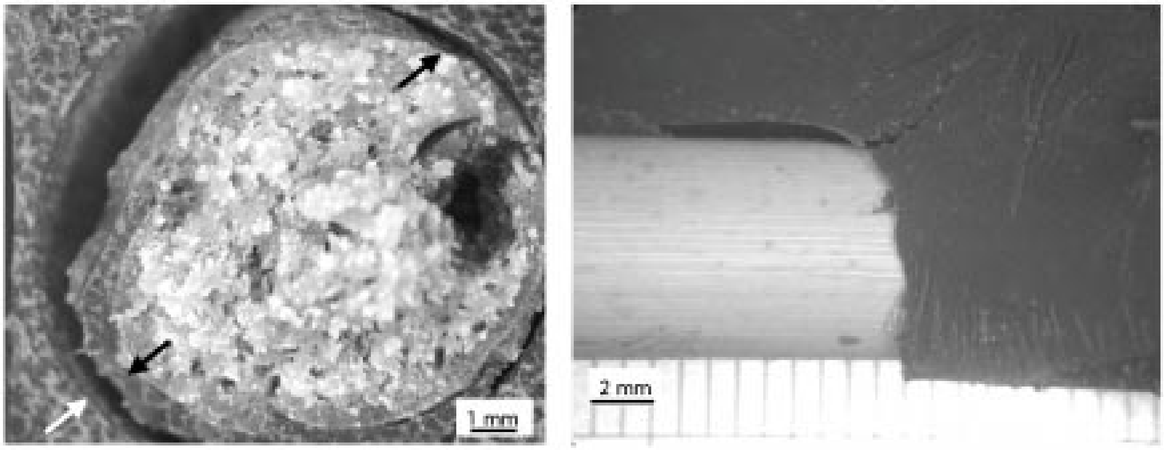

Fig. 8. (a) Fractograph of the interface failure between the Tootsie Roll® reinforcement and chocolate matrix taken from the tension side of the neutral axis after flexure. Note that most of the fibre contains a chocolate coating (black arrow), and the failure occurs at the interphase boundary (white arrow). Near the top right the black arrow indicates failure at the fibre/matrix interface. (b) Chocolate/bamboo composite after flexure exposing bamboo fibre. Note the visibly clean surface of the bamboo, indicating weak chocolate adhesion, and the gap between the matrix and fibre.

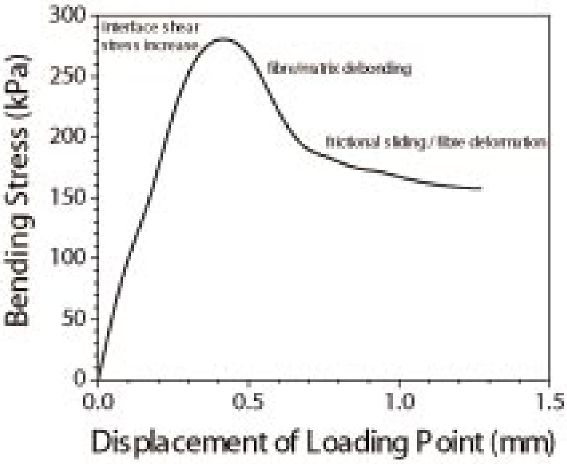

Fig. 9. Bending stress versus platen displacement for Case I, Tootsie Roll® reinforced chocolate undergoing three-point bending, illustrating the classic load-displacement behaviour for fibre pull-out (c.f. Hull and Clyne, p. 141 [14]).

DISCUSSION

Lessons learned

1. One of the main objectives of Strength by Chocolate was to introduce students to materials science and engineering using the central paradigm of materials science and engineering. No student could state the paradigm then nor now, because the paradigm was never formally defined, but the project operated using its premise; the students understand the connectivity between what they did, and observed materials processing, properties, structure and performance. Interestingly enough, when asked in question 8 of the post-project survey, 'What does **structure–property relationship** mean . . . in the context of materials engineering?' students in higher-year non-materials disciplines were unable to offer a reasonable answer.
2. Phase transformations are a difficult concept to comprehend without some grounding in chemical thermodynamics. Complete knowledge of the chocolate-phase systems present in the composites is important, but was not completely necessary for study. However, students realized that the internal structure of the chocolate changed after processing for several different reasons: the surface of the cast chocolate changed from the starting material; the apparent melting temperature of the chocolate changed, as detected by simple handling of the specimens; and the measured mechanical properties correlated to the casting process. It was therefore felt that heating the chocolate after testing to determine its melting point

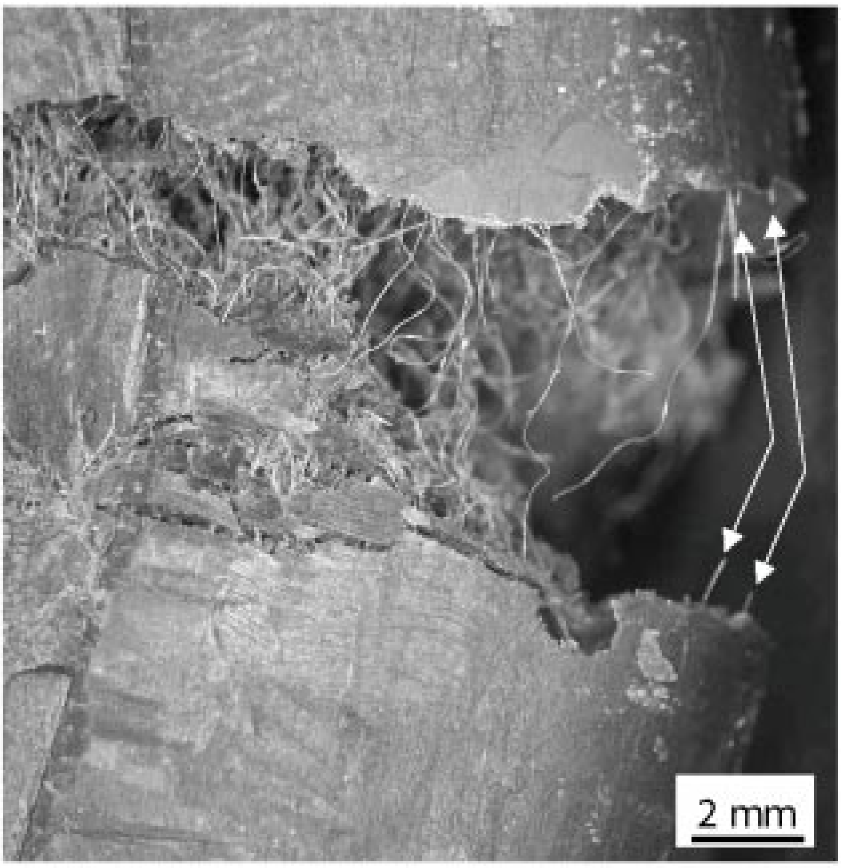

Fig. 10. Fractograph of cotton-reinforced chocolate composite having undergone three-point bending. Clearly visible are the white cotton fibres in various conformations. The arrows indicate possible matching fibre ends that have been severed during the bending test. The direct observation of the fibre pull-out helped make a memorable connection between the theory and the experiment.

could better identify the metastable form of the chocolate processed by the students.

3. 'Composites' are of strong interest for many students, and it is relatively easy to introduce the concepts of structure–property relationships using composite materials.
4. Choosing the reinforcement in most cases was done in a brainstorming session between the students, which resulted in some unorthodox reinforcements—i.e. gelatine—but was believed a better process than supplying a master list to work from. This approach encouraged students to think on their own, and resulted in greater student interest over the duration of the project.
5. In the era of fast internet data access, it was surprising to students that little information was available on the materials properties of their self-created composite systems; hence the empowerment of making their own measurements.
6. The design properties of interest were mechanical—i.e. strength or toughness—so it was very useful for the students to directly observe the mechanical behaviour of their composites in uniaxial (compressive) or bending (tensile/compressive) stress states. The concept of stress and strain is often inadequately introduced in engineering, and the concept of multiaxial stress–strain states is very difficult to illustrate. Incorporating these concepts into a first-year design project seems to help tremendously. Several students in second-year Mechanical or Civil Engineering programs reported an advantage in their studies of mechanics and strength of materials that they attributed to Strength by Chocolate.
7. Many students felt that fabricating more specimens would improve the statistics of the study, but this was unattainable due to time constraints.
8. Mathematical modeling is an important aspect of MSE research. The simple rule of mixtures enabled first-year engineering students to design and predict the behaviour of a composite structure. Interestingly, one student who has gone on to the Applied Math Program at Queen's clearly identified this project as helping him realize the need and beauty of mathematical relationships to predict natural behaviour.
9. Are students directly out of high school prepared for higher learning? We would hope so, but some students in their first term of first-year engineering found the introductory lecture too complex and academic and the Ashby paper too intimidating to be useful. In contrast, students participating in the project in their second term of first-year engineering did not have this concern.
10. Students realized that processing and not measurement (of properties) was the raison d'être for the limited success of their design; compare to more traditional labs which emphasize results.
11. The full benefit of a Strength by Chocolate type of project is only realizable if someone fully knowledgeable in MSE, such as senior lecturers or advanced graduate students, is present to guide students towards the nuggets and away from general misconceptions about materials. This approach goes against usual practices of MSE laboratories, which are repeat exercises designed to illustrate specific concepts and which are usually presented by less-experienced graduate students. When lab results do not work out, the learning tends to stop, because the explanation needed does not fit the objectives.
12. It is always challenging to assess group projects, because there is always the danger that someone does not contribute equally, and so evaluations tend to be averaged. The other danger to unequal participation is providing an unequal learning advantage to some. In this project, those team members who were 'stuck' with the numerical analysis of the stress–strain data using the canned spreadsheet program said in the post-project survey that their efforts paid off in upper years by boosting their confidence in doing this type of work.
13. When the student teams did not pursue post-deformation analysis using microscopy, they were unable to offer realistic suggestions to improve the fabrication process of their composite.
14. A noticeable benefit of open-ended project-based learning is that stronger learning reinforcements can sometimes be provided by multiple case studies obtained from student teams doing their own thing on a similar task, and reconvening to give oral presentations to all teams. Past results can be easily incorporated into the fabric of the course to advance the design process or take the projects in different directions, depending upon the chosen design criteria—i.e. fracture toughness, recycling processes—but it is important to maintain a quantitative component in the design.
15. Most students reacted very positively to the concept of food-based, recycable composites, which is reflected in their choices of reinforcements, but realized there are limitations to the strengthening effect; most of the strengths measured were in the kPa and not MPa range. In this respect, some students felt the project was useless for the 'real world', because chocolate would never be used structurally. Still they did think the project provided invaluable experience in understanding the theory and applications of Materials Engineering in a hands-on way.

Epilogue: attracting students into MSE

A materials person developed Strength by Chocolate for first-year engineering students in a common program year. A general belief in MSE departments is that students know little about the MSE discipline before they enter university. The post-project survey supports this thinking; most students entering first-year engineering do not know what MSE is about. A first-year project can provide students with their first sense of the MSE discipline, but it should be presented in an open yet challenging manner follow the paradigm of MSE. This paper describes one such example.

In the greater context of attracting excellent students into MSE programs, doing so in first-year studies is probably too late, particularly if the program does not already have a high profile. Outreach programs to grade school students might be one way to correct this deficiency.

CONCLUSIONS

The design module Strength by Chocolate offered to first-year engineering students offers a safe, creative, and progressive way to introduce them to composite materials and the materials paradigm. From the introduction of the materials paradigm to composite fabrication, property prediction, mechanical property measurement, and failure analysis, this module can be used by course coordinators to grow student interest, and help introduce them to foundation-level materials concepts. An 'open-ended' but theoretically well-grounded project offers first-year engineering students a valuable environment for higher learning.

Acknowledgements—The author would like to acknowledge the indirect influence in 2003 of the UK Centre for Materials Education's Composites Tour. The author is very grateful to the dedicated assistance from his APSC100 Project Managers, E. Secord and D. Yokom. A special thanks is offered to S. Ancic for his conceptualization and fabrication of the split moulds. The author would like to extend a very special thank you to all the students who participated in Strength by Chocolate and contributed their ideas and specimens for this paper. Finally, the author would like to thank the reviewers for their critical comments on the original manuscript.

REFERENCES

1. G. B. Olson, Computational design of hierarchically structured materials, *Sci.*, **277** (1997), pp. 237–1242.
2. G. B. Olson, Brains of steel: Mind melding with materials, *International Journal of Engineering Education*, **17**(4 and 5) (2001), pp. 468–471.
3. M. C. Flemings and S. Suresh, Materials education for the new century, *MRS Bulletin*, **26**(11) (2001), pp. 918–924.
4. A. W. Cramb, What is the future direction for undergraduate education in materials departments? *MRS Curriculum Crossroads*, March 23, 2005, http://www.mrs.org/connections/curriculum/tomorrow/cramb.html.
5. Queen's University, *Applied Science Undergraduate Calendar*, http://www.queensu.ca/calendars/appsci/APSC.htm#APSC100.
6. M. F. Ashby, Criteria for Selecting the Components of Composites, *Acta Metall. Mater.*, **41** (1993), pp. 1313–1335.
7. P. Fryer and K. Pinschower, The materials science of chocolate, *MRS Bulletin*, **25**(12) (2000), pp. 25–29.
8. M. L. Herrera and R. W. Hartel, Effect of processing conditions on crystallization kinetics of a milk fat model system, *J. Amer. Oil Chem. Soc.*, **77** (2000), pp. 1177–1187.
9. B. J. Diak, to be published.
10. B. Chalmers, *Physical Metallurgy*, John Wiley & Sons (1959), pp. 277–281.
11. E. O. Hall, The deformation and ageing of mild steel, *Proc. Phys. Soc.*, **B64** (1951), pp. 747–753.
12. N. J. Petch, The cleavage strength of polycrystals, *J. Iron Steel. Inst.*, **174** (1953), pp. 25–28.
13. A. N. Stroh, A theory of the fracture of metals, *Adv. Phys.*, **6** (1957), pp. 418–465.
14. R. Peschar, M. M. Pop, D. J. A. De Ridder, J. B. van Mechelen, R. A. J. Driessen and H. Schenk, Crystal structures of 1,3-distearoyl-2-oleoylglycerol and cocoa butter in the beta(V) phase reveal the driving force behind the occurrence of fat bloom on chocolate, *J. Phys. Chem. B*, **108** (2004), pp. 15450–15452.
15. H. Schwenk and R. Peschar, Understanding the structure of chocolate, *Rad. Phys. Chem.*, **71**(3–4), pp. 829–835 (2004).
16. D. Hull and T. W. Clyne, *An Introduction to Composite Materials*, 2e, Cambridge Press (1996).
17. A. Courts and A. G. Ward (eds.), *The Science and Technology of Gelatine*, Academic Press, London (1977).
18. A. A. Apostolov, D. Bonev, E. Vassileva, J. E. Mark and S. Fakirov, Mechanical properties of native and crosslinked gelatines in a bending deformation, *J. Appl. Polymer Sci.*, **76** (2000), pp. 2041–2048.

APPENDIX 1: EXAMPLE SCHEDULES USED FOR APSC-100 MODULE STRENGTH BY CHOCOLATE.

Week 1	Orientation Meeting with Manager	Orientation Meeting with Manager
Week 2	Introduction Lecture	Introduction Lecture
Week 3	Cast Pure Chocolate	Evaluate Chocolate Literature
Week 4	Test Pure Chocolate / Select Reinforcement from Literature	Test Reinforcement / Upper Bound Calculations
Week 5	Interim Presentations / Test Reinforcements	Interim Presentations /Fab. Composite
Week 6	Interim Reports / Fabricate Composite	Interim Reports / Test Composite
Week 7	Test Composite	Improve Composite Fab.
Week 8	Test Composite / Fractography	Test Composite
Week 9	Final Presentation	Final Presentation
Week 10	Final Report Due	Final Report Due

APPENDIX 2: POST-COURSE SURVEY ADMINISTERED TO APPLIED SCIENCE UNDERGRADUATE STUDENTS IN THEIR SECOND OR THIRD YEAR, AFTER THEY HAVE ENTERED THEIR CHOSEN DISCIPLINE.

1. What is your strongest memory about the module? Like, and dislike?
2. Were you interested in materials engineering before the module? Why?
3. Were you **more** interested in materials engineering after the module? Why?
4. What discipline did you finally choose in second year?
5. What new did you learn about materials after the module?
6. If you had more time in APSC100, what more would you have done with your Strength by Chocolate design?
7. Did any of your experimental results surprise you?
8. What does **structure–property relationship** mean to you in the context of materials engineering?
9. At the completion of the module did you feel you understood the stress–strain (mechanical) behaviour of materials?
10. Do you think food-based composites will ever become useful to our society?

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