MS4 SSA Materials Project-Based and Robotics Modules

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Inspiring Young People and a New STEM Culture: Battlecry WPI/Africa
Materials – The Major Driver

• Science and technology are the major engines of development
• Materials have always been a major driver in technological change...
  • Alloys
  • Semiconductors
  • Polymers
  • ...

| Hard materials |
| Soft materials |
The Evolution of Engineering Materials

What is in the future?

The diagram shows the evolution of engineering materials over time, from ancient times to modern day. It illustrates how materials have evolved from basic substances like gold, copper, and stone to advanced materials like super alloys and high temperature polymers. The timeline spans from 10,000 BC to 2020 AD, highlighting the chronological development of different material types and their relative importance in the engineering field.
Lead

- First discovered in Turkey more than 8000 years ago
- Easy to smelt due to low melting point
- Used essentially as the “plastic” material of the past
- Applications in lead pipes (the word plumber comes from Greek plumbum)
- Major issues with toxicity of lead – harmful to children and adults e.g. lead in wines
- Applications in radioactive shielding

Uranium

- Large amount of energy released when uranium splits
- The divisive element with many implications for nuclear power
- Largest naturally occurring element on Earth
- Breaks apart to shoot out alpha particles (bundles of 2 neutrons and 2 protons)
- Forms thorium and then protactinium and then lead
- Supplies internal heat for Earth’s magnetic field and plate tectonics
- Key element for nuclear power plants and weapons
- Abundant in Niger
Vanadium

• Vanadium is an important alloying element
• Used as an alloying element in ferrous materials for several centuries
• Sword of Damascus was developed based on alloying with V
• Henry Ford used it to make the body of his model T car lighter and stronger in 1908
• More recent applications in giant batteries

From Ford Motor Company via Wikipedia

http://news.bbcimg.co.uk/media/images/75512000/jpg/_75512448_index-large2.jpg
Silicon

- One of the most abundant elements on earth
- Present in sand and stones
- Origin of silicon revolution was of course...glass
- Glassmaking was developed more than a million and a half years ago
- Glass making then evolved from glass blowing to fiber optics
- The basis of silicon micro-chips
From Artisanal Mining to Wealth

- **Africa has a rich array of minerals and materials resources**
- **Artisanal Mining (Small-Scale)**
  - Difficult conditions
  - Limited profits
- **Industry (Mid- to Large-Scale)**
  - Africa’s richest man (Aliko Dangote) manufactures cement from African raw materials
  - Value addition to people, minerals and natural products
The Materials of Africa

• Africa is a continent that is rich with mineral/material deposits

• These include minerals that are rich in gold, uranium, chromium, platinum and copper

Africa’s Richest Man - Aliko Dangote
(Biggest Producer of Cement)

https://en.wikipedia.org/wiki/Aliko_Dangote

http://poslovnisvijet.ba/prljave-igre-oko-cistih-izvora/
The Energy Sources of Africa

- Africa is rich in energy resources
- The energy resources of Africa include
  - Fossil fuels
  - Solar energy
  - Hydro power
  - Wind energy
  - Geothermal energy
- These can be harnessed to produce and store energy in rural/urban areas
  - Energy generation
  - Energy storage
Background and Introduction to Materials Science and Engineering Modules

• Africa is rich in mineral and materials resources
• However most students in Africa have never heard about materials science and engineering
• Hence most of their knowledge of math and science is abstract and not connected to the materials opportunities around them
• Furthermore most students do not know much about how to add value to natural resources through materials processing
• There is therefore a need to introduce students to materials science and engineering modules
• Such modules could increase the pipeline of future materials scientists and engineers or applied scientists and engineers
Materials Science and Engineering

- Science: Knowledge-driven exploration of materials
- Engineering: Application-driven development of materials
Project-Based Materials Science and Engineering Modules

• WPI Team (Materials Science & Engineering), ASM International, MPI, Pete Gange and Robotics Team
  – Projects to promote creativity, understanding and problem solving
  – Modules for the teaching of materials science and engineering in African primary and secondary schools

• The initial modules are presented at a level that can be taught to students in secondary school

• The modules include lecture materials, homework questions, quizzes, answer keys and project-based modules
  – Lecture materials (structure, properties, processing, materials selection and design)
  – Interdisciplinary project-based approach to solving African problems (clean water, clean energy)
Outline of MS4SSA Lecture Modules

• Introduction to materials science and engineering
• Crystal structure and crystallography
• Materials processing and characterization
• Introduction to mechanical properties
• Plasticity and deformation
• Fracture and fatigue
• Phases and phase diagrams
• Materials and their mechanical properties
• Electrical properties of materials
• Biomaterials and bio-inspired design
• Materials selection and design
• Project-based modules – renewable energy/clean water/housing/transportation
Atomic Structure

Bohr model

wave-mechanical model

The Periodic Table

- The periodic table is rich with metallic elements
- Combinations of metals with nonmetals yield ceramics
- Organics are mainly based on covalently bonded carbon structures held together with weak interactions

Crystal Structure of Materials

- Repeating units (lego pieces) that can be used to build up the structure of materials
- Seven basic types of crystal systems
  - From cubic to monoclinic
  - Variations in symmetry
- Simple hard sphere ideas can be used to estimate
  - Atomic packing Factor
  - Density
Microscopic Techniques

- Differences in crystallographic orientation affect surface texture at micro- and macroscopic scales.


Grains as they might appear when viewed with a microscope.
Yield Stress & Deformation

- Associated with the transition from elastic to plastic deformation:

Stress vs. Strain Diagram:
- Elastic deformation:
  1. Initial
  2. Small load
  3. Unload
- Plastic deformation:
- Elastic means reversible!
Tensile Strength

- Tensile strength associated with the maximum of the stress-strain curve:

- Not used for design purposes since structures compromised after such large deformations
Materials Property Charts

“The main problem of materials selection in mechanical design is the interaction between function, material, shape and process.”

“Function dictates the choice of both material and shape.

Process is influenced by the material.

The process determines the shape, the size, the precision and, of course, the cost.”

Adapted from Ashby, Michael F. "Materials selection in mechanical design." Metallurgia Italiana 86 (1994): 475-475
Projects – Affordable and Sustainable Materials for Buildings

• Features for reducing cost:
  – Low interest loan (PRGF)
  – Subsidized land
  – Ceramic water filters
  – Solar energy
  – Contractor’s profit 24.17%
  – $75/month 30 yr mortgage
Brittle and Ductile Materials

- Energy absorbed by the material up to the point of failure:
- Brittle materials stretch uniformly up to a certain point and then rupture
- A brittle material does not have a plastic region

Ductile materials will withstand large strains before the specimen ruptures

Ductile materials often have relatively small Young’s moduli and ultimate stresses

Ductile materials exhibit large strains and yielding before they fail
So the real question is whether we can use the same zeal that we use in developing new high tech products to find solutions to global problems of eco-friendly affordable housing?

As with the other examples – the answer is yes

However we must adopt a holistic framework that spans the complete range from concepts to reality

- Non conventional materials
- Water collection and purification
- Energy (active and passive solar, wind, hydro, biomass)
- Integrated rural and urban plans
- Initial and life cycle costs
Non-Conventional Materials

- Conventional materials represent 70% of the cost of an unaffordable building
- Many of these are imported in developing countries thus making the homes even more unaffordable
- Yet all these countries contain earth, natural fibers, industrial/home/agricultural wastes
- Objective is to develop non conventional materials via intrinsic and extrinsic modification
Typical Matrix and Fiber Materials

- Sisal
- Polypropylene
- Phylite
- Metakaolin
- Eucalyptus
Alternative Eco-Friendly Materials

- All countries have industrial and agricultural wastes that can be combined with earth or cement based materials to make building elements

- Examples include straw-reinforced earth, cementitious composites reinforced with natural fibers and polymers reinforced with wood chips

- Such reinforcement gives rise to toughening by crack bridging which increases durability and earthquake resistance of homes and roads

Resistance-curve behavior in natural fiber composites

Backscattered electron image showing cracks and composite bridges. Fibers are seen in dark gray
Background to Bamboo Applications

The chart shows that bamboo, which is a very cheap and fast growing material, is the closest material to carbon fiber reinforced plastic in performance for bike frames.

With this information, we felt we could build a high performance bicycle without paying the large expense of having a carbon fiber frame.

The chart expresses the desire for materials with high Young’s modulus and critical stress while having a low density, since in bicycling, light weight is extremely important for high velocity
Project - Bamboo Bicycle
Bamboo as a Material - Plantation of Moso Culm and FGM Cross Section
Scanned Images of Functionally Graded and Intelligently Adapted Bamboo Structures

(a) L-R Cross section of the culm wall
(b) L-C Cross section of the diaphragm

Radial Bundles
Circumferential Bundles
AFM Scans of the Fiber Bundles

(a) Surface of vascular bundles in 2-D image

(b) Surface of vascular bundles in 3-D image
Design Objective

• The objective of this project was to make a bamboo fixed gear bicycle at low cost that would be strong and durable while providing a comfortable ride.

The frame must be light, stiff, and comfortable. The optimization of these three variables is crucial for the design of a successful racing bike or a comfortable road machine.
Gathering the Bamboo

• Bamboo was collected from Pennsylvania along the Delaware River

• When cut down, the bamboo is full of water so experimentation was necessary to determine the best drying technique
Treating the Bamboo

- Baking the bamboo in an oven helped to remove water but caused cracking at the nodes.
- After trying many techniques, we found the most effective approach was to first use a blow torch on the bamboo to seal the nodes and then bake it in an oven.

Testing the baking of bamboo with a fresh piece, a piece that was previously blowtorched, and a fresh piece wrapped in aluminum foil.
Frame Geometry

Bamboo Bicycle Geometry Sketch, MAE 561

Notes:
1) 110mm rear hub spacing (track standard)
2) English-thread 68 mm BB shell (standard) Arms 6061 aluminum
3) 1.5" I.D. headtube, approx. 200mm w/hatset inserted
4) 27.2 O.D. seatube w/machined aluminum sleeve epoxied. (No front derailleur w.)
Cutting The Bamboo

- The first step was to cut the tubes to a ballpark length to fit the jig
- The tubes were then mitered with a large end mill, roughly the size of the head tube and BB shell to which they mate
- A Dremel was then used to miter the small diameter chainstays and seatstays as well as perfect the miters of the larger tubes
The Jig

- A key piece to putting the frame together was first building a jig.
- The jig keeps the tubes together in a specific geometry while being wrapped with carbon tape and epoxy before curing.
Wrapping the Tubes

• To connect the tubes together, we used unidirectional carbon fiber tape

• The tape was dipped in an epoxy and wrapped around each joint

• After curing, the joints were extremely sturdy

• Special attention was paid to area going to experience higher stresses, applying extra wrapping
Bamboo Frame Bicycle

WPI

Nick Frey, Will Watts, Douglas Wolf, Tom Yersak
Ezekiel Odeh
Bamboo Applications

Bamboo Racing Bicycles

Pictures by courtesy of Princeton University Website

Bamboo People Mover
Patrick Kiruki

Bamboo Solar Vaccine Refrigerator

Bamboo Wind Turbine
Ting Tan – University of Vermont
The problem of contaminated water is the single biggest cause of the steep decline in life expectancy in Africa
  – Impact bigger than that of HIV
  – Example of Nigeria
  – 5000 lives lost per day

Major problem is due to microbial pathogens (E.Coli)

Other global challenges due to water contamination include chemical contamination (fluoride, arsenic and heavy metals) in Asia, Africa, Latin America

Holistic approach needed to develop solutions from science to technology & evidence-based policy & entrepreneurship
# Water Treatment Methods

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Water</td>
<td>- 100% potable if boiled for at least 20 min.</td>
<td>- Requires time to gather fuel (fire wood)</td>
</tr>
<tr>
<td></td>
<td>- Can be done in the home all year round.</td>
<td>- Requires time for heating and cooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Causes a Change in the taste of water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Method does not remove turbidity</td>
</tr>
<tr>
<td>Adding Chlorine</td>
<td>- Effectively kills bacteria</td>
<td>- Affects the taste of water</td>
</tr>
<tr>
<td></td>
<td>- Simple to use</td>
<td>- Must be applied periodically</td>
</tr>
<tr>
<td></td>
<td>- Can be used anytime</td>
<td>- Does not remove turbidity</td>
</tr>
<tr>
<td></td>
<td>- Low cost technology</td>
<td>- Most be purchased and transported</td>
</tr>
<tr>
<td>SODIS</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>- Low cost</td>
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<tr>
<td></td>
<td>- Can be large or small</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Remove turbidity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can be used</td>
<td></td>
</tr>
<tr>
<td>Bio Sand Filter</td>
<td>- Can be large or small</td>
<td>- Does not work in shade, night or rainy season</td>
</tr>
<tr>
<td></td>
<td>- Easy to use</td>
<td>- Requires 4-6 hours to reach required to heat</td>
</tr>
<tr>
<td></td>
<td>- Local materials</td>
<td>- Requires Time for water to cool</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Change in the taste of the Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Does not remove turbidity</td>
</tr>
<tr>
<td>Filtrón Water Filter</td>
<td>- Kills bacteria 99%</td>
<td>- Cost, US$ 7.50 to $25.00 (depending on country)</td>
</tr>
<tr>
<td></td>
<td>- Easy to use</td>
<td>- Heavy compared to the other systems</td>
</tr>
<tr>
<td></td>
<td>- One time transportation</td>
<td>- Fragile, easy to break</td>
</tr>
<tr>
<td></td>
<td>- No change of taste</td>
<td>- Periodic cleaning is required (turbid water clogs the filtering element).</td>
</tr>
<tr>
<td></td>
<td>- Culturally acceptable</td>
<td>- Combustion for the production process</td>
</tr>
<tr>
<td></td>
<td>- Self-encased water Container permits serving.</td>
<td>- Should be replaced after two years</td>
</tr>
<tr>
<td></td>
<td>- Made locally</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Works all year around 24 hours a day.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Low cost</td>
<td></td>
</tr>
<tr>
<td>PuR (P&amp;G)</td>
<td>- Effective</td>
<td>- Expensive (US$ 4.20 a month)</td>
</tr>
<tr>
<td></td>
<td>- Good for emergencies</td>
<td>- US$ 0.14 cents a day for 20 liters</td>
</tr>
</tbody>
</table>
Materials Science: Surface Morphology and Chemical Composition - SEM/EDX

Sawdust (Woodchips)  Clay (Redart)

Porous Ceramic
Sliced View
Schematic Diagram

- Pathogen
- Ag+ Particle Lining
- Pores
Size Comparison

Figure 2. Comparison of relative sizes of various contaminants in water. Based on these, the pore size of the ceramic filter, at 0.2 μm, would be about the size of a full stop on this page.
**E. coli** Filtration Tests of Non-Coated Ceramic Water Filters

<table>
<thead>
<tr>
<th>Volume Fraction Clay:Sawdust</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Average ± Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>45:55</td>
<td>99.97</td>
<td>99.85</td>
<td>99.91 ± 0.06</td>
</tr>
<tr>
<td>50:50</td>
<td>99.99</td>
<td>99.93</td>
<td>99.96 ± 0.03</td>
</tr>
<tr>
<td>55:45</td>
<td>99.52</td>
<td>99.84</td>
<td>99.68 ± 0.16</td>
</tr>
<tr>
<td>65:35</td>
<td>99.99</td>
<td>99.99</td>
<td>99.99 ± 0.00</td>
</tr>
</tbody>
</table>

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Microbial and Fluoride Removal

• High fluoride content can cause serious health problems\(^1\)
  - Occurs naturally in deep bore holes
  - Groundwater with high fluoride concentrations can be found in many areas of the world, including large parts of Africa, China, Mexico, the Middle East and southern Asia (India, Sri Lanka)\(^1\)
    - Example: A “national health problem” in India
      - 17 out of 32 states and territories have naturally high concentrations of fluoride (UNICEF, 1999). As high as 48 mg /L in Rewari District of Haryana. \(^2\)
      - 60–70 million people in India are at risk

• High fluoride intake causes dental and skeletal fluorosis; osteoporosis; nausea; adverse effect on kidneys

• The question is – can we combine fluoride and microbial removal?

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1: UNICEF Handbook on Water Quality, Released: 16\(^{th}\) April, 2008
Clay/Hydroxyapatite Filters for Fluoride Removal

Hydroxyapatite (HA): $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$
- Made from simple acid/base reaction
- Mechanism of removal involves:
  - Crystal substitution ($\text{OH}^-/\text{F}^-$)
  - Fluorite précipitation ($\text{CaF}_2$)
  - Surface sorption

Redart Clay
- Previously used to remove bacteria and microbial organism in the form of frustum-shaped filter

Mixing of Clay with HA
- “A combo” with the potential to remove both Fluoride and Bacteria
- Ease of forming
- Cost

Strategy
- Fundamental Study (Adsorption study)
- Proof-of-concept
  - Disc-shaped filter
  - Frustum-shaped filter

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Results

Effect of sintering temperature of the adsorbent on the amount of fluoride that is adsorbed from water with an initial fluoride level of 10mg/L. Results was obtained for other fluoride concentration.

An overall picture of the adsorption capacity of the C-HA adsorbent using the Freundlich isotherm constant.
Filter Processing - From Ideas to Markets
Motivating Technological Independence in Africa: Solar Energy
Mpala Project-Based Module

- **49,107 acres** of savannah and dry woodland, 1 hour from Nanyuki, on the Laikipia Plateau in North Central Kenya
- MRC staff members and immediate families housed in various community villages
  - Homes were generally a **single 20-ft diameter room**. People used old bed-sheets to partition the space to create a living room and 1-2 bedrooms. Household sizes ranged from 1-8 persons.
- Because it is in a remote area, **access to basic necessities is a challenge**.
  - **Clean drinking water** is available to staff and researchers through boreholes and purified rainwater collection.
  - **Electricity**, however, is only provided to the research community, through a combination of solar panels and generators.
Project-Based Module on Clean Energy

Project-Based Approach

- Identify societal problem and/or developmental need
- Explore possible solutions within a scientific and engineering framework
- Develop and test potential solution
- Propose potential strategies for going from ideas to markets/policy

From Problem to Solutions

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Innovation for STEM to Young People

- Robotics is a source of inspiration for young people to pursue STEM
- This has been recognized Dean Kamen (WPI Alum) and founder of FIRST Robotics ...

- Alloys
- Semiconductors
- Polymers

...
WPI Robotics Modules

- Project-based extra-curricular program designed to inspire students
- Promote experiential learning and creativity within a team-based friendly competitive framework
- Modules integrate mechanical design, electronics and motors, and computer science
- Scope of Program
  - Mechanisms and motors
  - Programming
  - Three-dimensional printing
Summary and Concluding Remarks

• This lecture presents an introduction to the MS4SSA materials, project-based and robotics modules.

• Project-based approach is proposed to motivate the students to learn and integrate concepts.

• Materials science and engineering projects enable students to have better understanding of concepts while applying them to real world problems and opportunities.

• Robotics inspire young people to explore STEM fields while developing a culture of intelligent engineering.

• Look forward to working with individual African Governments and African Nodes on the implementation of the project-based modules.

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FOR TEACHING & LEARNING

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MS4SSA
Math and Science for Sub-Saharan Africa

THANK YOU!