Granta EduPack White Paper

Bio Engineering Database. Part 1: Introduction to Biological and Bio-medical materials

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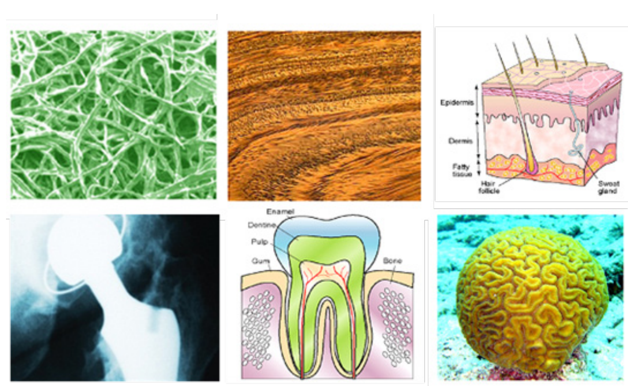


Summary

Engineering and Materials Sciences are becoming increasingly interdisciplinary. The contributions that these can make to the Bio-sciences are of particular interest at present, for a number of reasons. One is the emergence of new experimental techniques for visualizing the structure and measuring the properties of biological materials. Another is the realization that the modeling and simulation methods of the physical sciences can contribute also to bio engineering and bio-processing. Yet another is the belief that, even now, nature can suggest ways to make new, useful, materials. A fourth is the nature of the healthcare industry, one that is under constant pressure to develop new procedures and more effective treatments. Most of the materials of nature perform more than one function. A remarkably large number have, as one of their functions, that of providing stiffness, strength, elasticity, resilience, toughness, and thermal protection and to do this efficiently (a term defined in a moment). These are words familiar to a student of engineering, even in the first year of their studies. The logical starting point for a biomaterials database aimed at engineering students would seem to be one which captures the mechanical and thermal properties of biological materials and allows comparison of these with the equivalent properties of the engineering materials with which they are already familiar.

That is what the Granta EduPack Bio Engineering Database does. It is a biomaterials database and contains records for some 177 biological, bio-derived, and bio-medical materials. Biological materials have widely varying properties. Storing records for each variant is impractical; instead, representative data are presented, usually as a single record. The database also contains records for 100 standard metals, polymers, ceramics, and composites of engineering, same as the Level 2 in the Standard or Design Editions. The ensemble enables a number of interesting investigations of which we list a few here:

Simple retrieval of the properties of natural and man-made materials, in a consistent framework.

- The construction of material property charts for biological materials in the manner of those introduced by Ashby et al (1995) and developed further by Wegst and Ashby (2004).
- Exploration of the ways in which the basic structural building blocks of the natural world (minerals, polysaccharides, and proteins) combine to give the great diversity found in biomaterials.
- Comparisons of the properties of natural and man-made materials, revealing their comparative efficiencies.
- Substitution studies exploring the potential for one to substitute for another, suggesting where man-made bio-medical materials might best be used for implants and organ replacement.

The rest of this White Paper describes the database in more depth, documenting the nature and content of the records and illustrating the ways in which it can be used to introduce the concept of Biomaterials and their use for medical applications. This paper is Part 1 of two papers that accompany the Granta EduPack Bio Engineering Database Level 2. This paper will focus on general introduction to Biomaterials and specifically to bio-medical materials uses. The other white paper titled The Granta EduPack Bio Engineering Database. Part 2: Bio-derived materials and applications, deals with bio-derived materials and non-medical applications. For consistency throughout both papers and when using the Bio Engineering Database, please find key definitions of terms used in Box 1.

The Bio Engineering Level 2 database was restructured, revised, and enlarged in 2014. One of the enlargements is the inclusion of bio-derived materials and of bio-medical materials. Also, the structure of the folder tree has changed, following Design Level 2, with the same families of materials. Biomaterials can easily be accessed by the subset of materials, read Box 2 to find out how to access these sub-groups of materials.

1. Introduction

Natural materials are remarkably efficient. They fulfill the complex requirements posed by the way plants and animals function and that they do so using as little material as possible. Many of these requirements are mechanical in nature: the need to support static and dynamic loads created by the mass of the organism, by blood pressure, by the acts of eating and fighting and so on. The same is true of plants: they must support themselves, tolerate wind and snow loading, and resist (where possible) attack by creatures keen to eat them. Some are thermal or electrical: the need to insulate, transpire, sense, and actuate. And most natural materials are sustainable, recyclable, and—when disposal is necessary—biodegradable.

Almost all natural materials are composites or hybrid materials. They consist of a relatively small number of polymeric and ceramic components or structural building blocks, which often are composites themselves. Wood, bamboo and palm consist of cellulose fibers in a lignin / hemicellulose matrix, shaped to hollow prismatic cells (Figure 1). Collagen is the basic structural element of soft tissues like tendon, ligament, skin, blood vessels, muscle and cartilage. Mineralized tissues—e.g. antler, bone, dentine and enamel—are mainly composed of hydroxyapatite with varying degrees of residual collagen. Hair, horn, wool, and reptilian scales are made of keratin. Insect cuticle contains chitin in a matrix of protein. From a mechanical point of view, there is nothing very special about the structural building blocks. It is the structure and arrangement of the components that give rise to the striking efficiency of natural materials.

Texts and other sources for the materials of nature generally take a biological view, focusing on their structure and physiology. It is interesting, instead, to think of them in the framework of engineering design—they have, after all, evolved to meet a set of design requirements, as have engineering materials. This allows exploration of the ways they fulfill mechanical or thermal functions, and suggests ways to create man-made replacements when they fail. It also hints at how the ways in which nature achieves efficiency might be harnessed to create better man-made bio-inspired materials.

Relevant Bio- terminology used in this paper

Terminology involving the prefix “Bio” can be confusing. In this White Paper we adopt the following terms.

Biological materials are natural materials, those produced by biological systems. Thus skin, bone, wood, shell, hair are biological materials.

Bio-derived materials are those synthesized from natural biological materials. Thus paper, plywood, twine, and rope are bio-derived materials.

Bio-medical materials are materials synthesized for tissue engineering or to replace or support body parts; they have to be compatible with the human body. Thus bio-glass, alumina bio-ceramics, titanium grade F67(B652), silver amalgam, and ultra-high molecular weight polyethylene (UHMWPE) are bio-medical materials.

Bio-inspired materials and structures are those that mimic nature and biological materials. Thus high performance silk, Velcro, adhesive-free (“Gecco”) adhesion, and water-repellant (“Lily-pad”) surface texturing are bio-inspired materials and structures.

The blanket-term ***Biomaterials*** is used here to mean biological, bio-medical, and bio-derived materials.

Box 1. Bio-terminology used in white paper

The database described in this paper, available with the Granta EduPack Bio Engineering Edition, is an educational tool to support teaching of bio engineering. It seeks to capture thermomechanical properties and design-related properties of natural materials and present them in ways that allow direct comparison with those made by man. It is aimed at 1st and 2nd year university courses for students of engineering, introducing the materials of nature alongside those of conventional engineering—a context familiar to an engineer, which enables exercises in substitution and in material design.

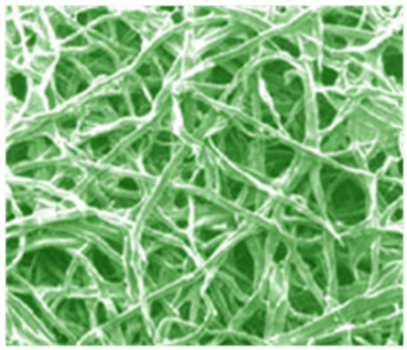


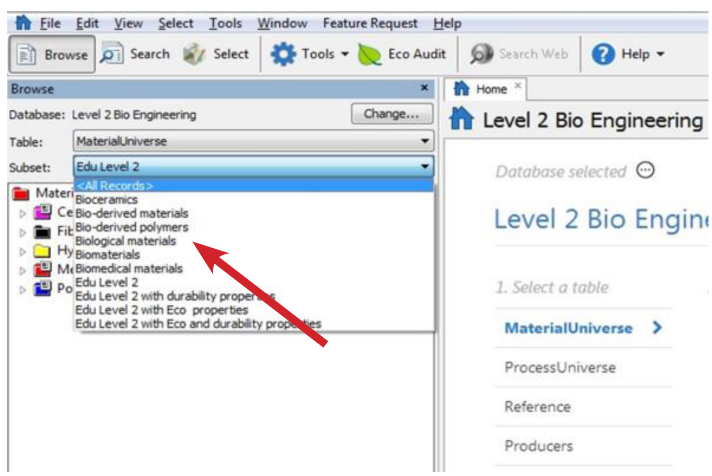
Figure 1. Cellulose, one of the building blocks of nature.
(Image courtesy of the Concord Consortium).

Biomaterials subset in Bio-Engineering Level 2

Biomaterials and their sub-groups can easily be accessed by pre-defined subset of materials. Filters in the Browse and Select functions allow subsets of biomaterial, biological, bio-medical, and bio-derived materials to be isolated, hiding all other records.

Access To access these subsets, in Browse mode, open the drop-down menu for Subset on the left pane, and select the relevant subset of interest.

You can now only browse the tree among the relevant materials.



Box 2. How to easily access biomaterials subsets. As described in Box 1

2. The materials

The natural and biomaterials in the database are representative of six groups, described below. The first group contains records for the “building blocks” of the natural world: the proteins, polysaccharides, and minerals from which they are assembled. Groups 2 to 5 contain records for natural materials made from these building blocks. Group 6 contains records for representative biomedical material—materials made by man to replace those of nature.

2.1 Group 1. The basic structural building blocks of nature: proteins, polysaccharides, and minerals

Proteins.

These are complex organic macromolecules that contain carbon, hydrogen, oxygen, nitrogen, and usually sulfur. Proteins are fundamental components of all living cells. They carry out most of the chemical processes and make up the majority of cellular structures. Protein chains in nature are all synthesized from just 20 amino acids. Nineteen of these contain the same two functional groups: an amino group -NH2, and a carboxylic acid group, -COOH. In all 20 the two functional groups are attached to the same carbon atom. This carbon is also attached to a hydrogen and a side group, -R, as in Figure 2 below. The 20 amino acids differ in the nature of the side group, ranging from a single H atom in glycine or single methyl (CH3) group in aniline to complex aromatic groups. The amino acids polymerize, releasing water (a “condensation reaction”) to form long-chain proteins. The figure shows part of a chain.

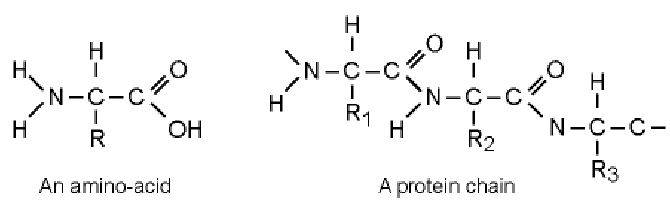


Figure 2. An amino acid and a protein chain made by polymerization of amino acids.

The database contains records for four structural proteins: the natural polymer, keratin, and the natural elastomers elastin, resilin, and abductin.

Glycoproteins and Proteoglycans.

These are covalently-linked protein-polysaccharide complexes where sugars are added as post-translational modificiations (chemical modification of a protein after its translation) to a core protein. The sugars in glycoproteins include galactose, glucose, mannose, xylose, acetylglucosamine, and acetulgalactosamine. The sugars assist in protein folding and can improve the protein stability (resistance to enzymatic degradation); they frequently bind water and control local water concentration. Examples of glycoproteins include collagen, serving as a natural structural molecule, and antibodies, which serve as immunologic molecules.

Proteoglycans are a special class of sulfated and negatively charged glycoproteins with critical extracellular matrix functions. The polysaccharide in proteoglycans is typically chondroitin sulfate, dermatan sulfate, heparan sulfate, or keratan sulfate.

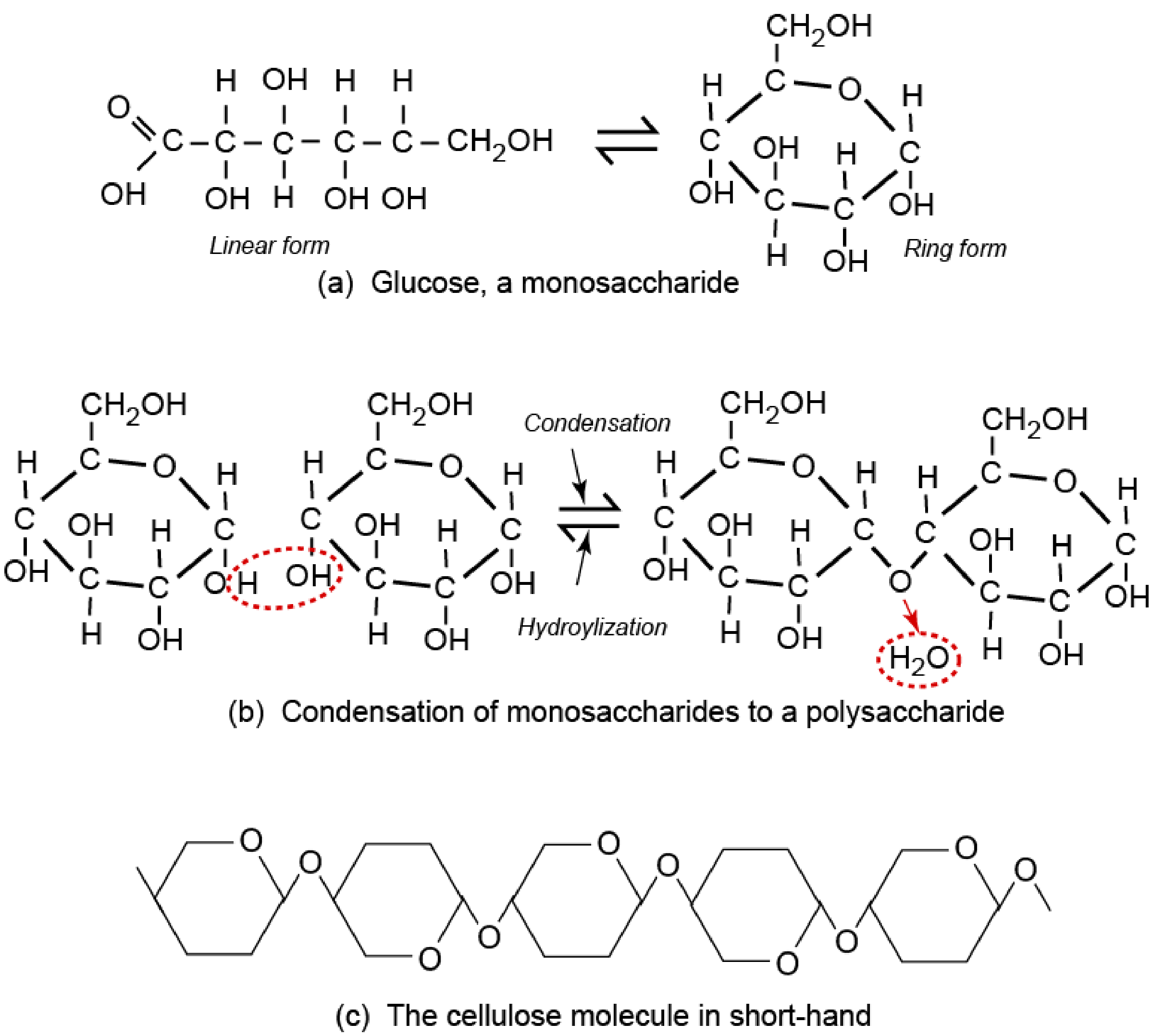


Figure 3. (a) The two forms of glucose, a monosaccharide. (b) The polymerization of monosaccharides to make polysaccharides. (c) The configuration of the monosaccharide rings in cellulose.

Polysaccharides.

Polysaccharides perform two essential functions. Some, such as starch and glycogen, store energy in a way that can be retrieved when the organism needs it. Others, such as cellulose, lignin, and chitin, are structural. It is these that are of interest here. The first two are the structural materials of the plant world, and because of this are the most prolific polymers on earth. The third is the structural material of the exoskeleton (the exterior shell) of insects and other arthropods—crustacea, arachnids (spiders), centipedes, and other bugs—and it, too, is widespread.

Polysaccharides are made by polymerizing monosaccharides—sugars—typified by glucose (Figure 3 (a)). Glucose, a 6-carbon saccharide, exists in two structural forms: as a linear molecule or as a ring. In the ring-like form it has the ability to polymerize by a condensation reaction (one releasing water) to give stiff, straight polysaccharide chains (Figure 3 (b)). The process is reversed by hydrolyzation. In the cellulose molecule, which can have many thousand monosaccharide units, the units are arranged such that the bonding oxygens are staggered (Figure 3 (c)), in which only the oxygen atoms are identified). Chitin is chemically related to cellulose, but the monomer from which it is built is a glucosamine unit—glucose with one –OH unit replaced by--HCOCH3. The molecules of both cellulose and chitin are straight and stiff. The molecules hydrogen-bond together to form microfibrils which hydrogen-bond in turn to form fibers of great strength, comparable with that of steel. The database contains records for cellulose, lignin, and chitin.

Minerals.
Minerals are ceramics. Natural materials use few structural ceramics, but they use them in ingenious ways. Those of principal importance are calcite, aragonite, hydroxyapatite, and bio-silica. Mineralized tissue is tissue that incorporates these, but in widely varying degrees (from as little as 1% to as much as 99.9%). It is these that give stiffness, hardness, and strength to bone, teeth, and shell. In the plant world it is bio-silica that makes some so abrasive that they can be used to clean metals, and provides others with needle or dagger-like protective armor. All four are chemically simple. Figure 4 shows the formulae and—since the first three are crystalline—the shape of the unit cell that describes the positions of groups of atoms in the structure. Bio-silica is amorphous—its structure is like that of glass. There are records for all four, listing their properties.

2.2 Group 2. Soft tissue

Soft tissue (e.g., Figure 5) is tissue that has not been mineralized. Many have mechanical functions. There are two broad groups, distinguished by type of mechanical function: active (muscle) and passive (connective tissues). Muscle fibers are very large specialized cells containing protein fibers for voluntary contraction (the biceps, for example) or involuntary contraction (the heart) depending on the muscle type. Connective tissues—ligament, tendon, cartilage— are predominantly acellular composite materials assembled from proteins, polysaccharides, and glycoproteins, with a substantial fraction of water. The molecules are generated, organized, and remodeled by living cells typically of a fibroblast (type of cell in connective tissue that produces collagen and other fibers) morphology. Differences between tissues arise from compositional variations and variations in component organization and alignment. Keretinized tissue (hair, horn, hoof, the shells of turtles and tortoises) is much stiffer and stronger than those based only on collagen and elastin.

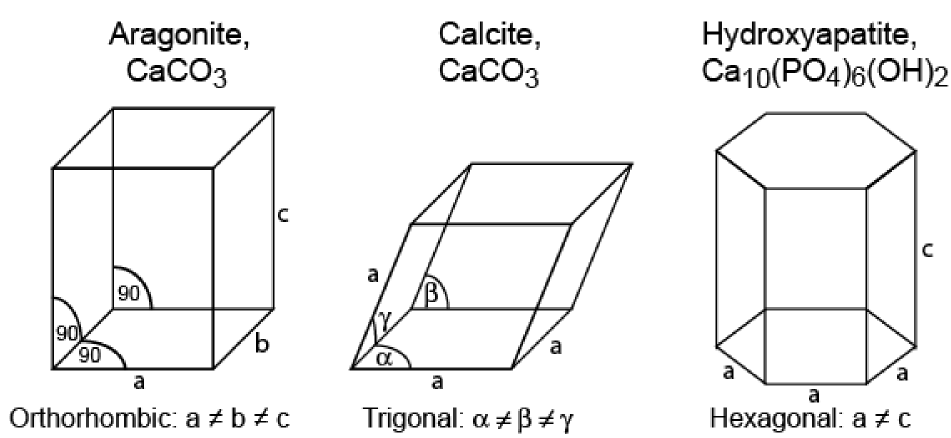


Figure 4. Three of the principal structural minerals of biological systems. The fourth, bio-silica, is amorphous.

The database contains ten records representative of soft tissues:

- Artery and vein
- Muscle
- Tendon
- Ligament
- Cartilage
- Skin
- Hair
- Hoof
- Horn
- Tortoise shell

2.3 Group 3. Mineralized tissue

Bio-mineralization is the process by which living tissues deposit minerals within their structure, creating composites of organic and inorganic materials. The soft tissue forms first; mineralization occurs as it grows and matures. The key minerals involved are those described in the records for "Basic structural building blocks": calcite, aragonite, hydroxyapatite, and bio-silica.

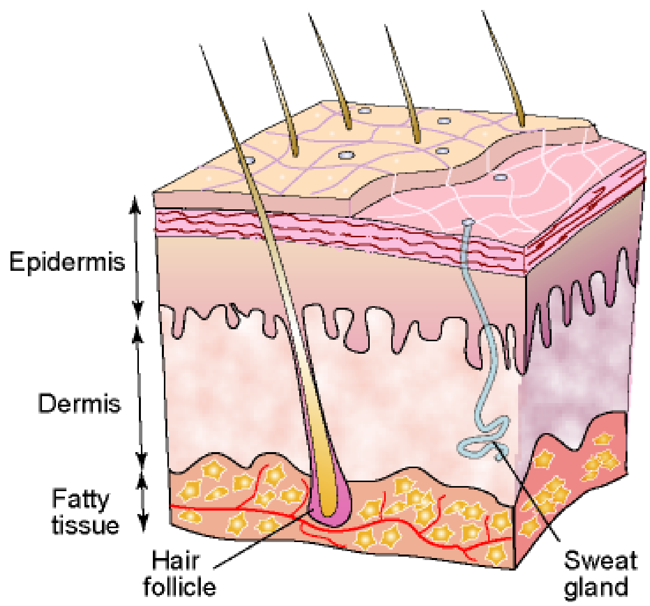


Figure 5. Skin, an example of soft tissue.

Bio-mineralization gives organisms competitive advantage. It allows them to become mobile, supporting their own weight. It gives a rigid framework to which muscles and tendons can be attached. As exo-skeletons and shells, it gives protection from predators. Bio-mineralization also contributes to the survival of plants, allowing them to grow taller (capturing more light) and to survive aggression. It is bio-silica that gives the nettle its sting, the cactus its spines, and bamboo its ability to grow so tall yet remain so thin. Almost all our knowledge of life on earth in earlier eras, meaning millions, tens, and hundreds of millions of years ago, is through fossil records—the embalmed remains of organisms, of which only the mineral component survives. Flesh decays. Minerals are immortal.

The database contains records for a number of families of mineralized tissue, listed below.

Dentine and enamel. Dentine and enamel are the material of teeth and tusk, as shown in Figure 6. Enamel—the outer layer of tooth—is the most highly mineralized of all natural tissues.

Bone. Bone is living tissue. Like all natural materials, it does several things:

- It provides mechanical support and protection for the soft tissue of the animal's body.
- Articulated bone structures (with associated cartilage and tendon) provide the basis of movement and the leverage to make it possible.
- Bone acts as a storage-reservoir for salts, particularly calcium.
- It provides a steady supply of new blood cells, generated by the bone marrow.

Bone is made of living bone-cells in a hard matrix of hydroxyapatite bonded with collagen fibers (see "Basic structural building blocks" for information about both). There are two types of bone: compact (or dense) bone and spongy (trabecular or cancellous) bone. Compact bone is deposited in shells or lamellae arranged in nesting concentric cylinders. The lamellae of spongy bone are arranged in a sponge-like lattice resembling that of a foam.

Antler. Antler is less highly mineralized than bone, giving it greater flexibility and toughness.

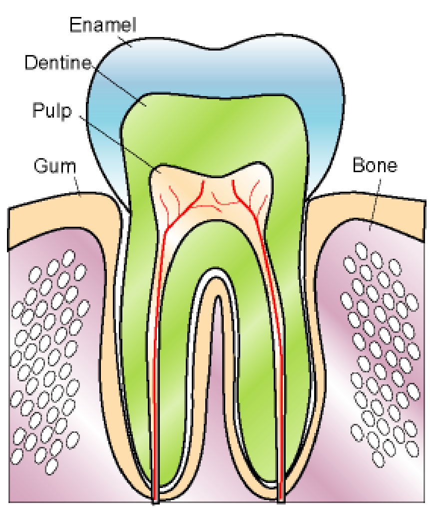


Figure 6. Enamel and dentine are examples of mineralized tissue.

Shell. Shell is a form of exoskeleton. The database has records for eggshell and mollusc shell. Each is representative of its family, but the families are large and the true range of properties very wide.

Coral. Corals, like shells, are exoskeletons. The number of coral types is large. The record, like the others in this part of the database, describes a representative example.

2.4 Group 4. Woods and wood-like materials

All woods and wood-like materials rely on cellulose for their mechanical stiffness and strength (see the introduction to "Basic structural building blocks" for information about it). See Figure 7 for an example. They offer a remarkable combination of properties. They are light, and, parallel to the grain, they are stiff, strong, and tough—as good, per unit weight, as any man-made material except CFRP. They are cheap, easily machined, carved, and joined, and— when laminated—they can be molded to complex shapes. And they are aesthetically pleasing, warm both in color and feel, with associations of craftsmanship and quality.

Tree-wood. All tree-woods have broadly the same chemical composition: 40-50 wt% crystalline cellulose fibers in a matrix consisting of 20-25 wt% partly-crystalline hemi-cellulose and 25-30 wt% amorphous lignin; in addition there is 0-10% oily extractives (terpenes and polyphenols) that give the wood its color and smell. The great range of properties exhibited by different woods is largely due to the difference in structure and relative density, which ranges from 0.1 to 0.85.

Like most natural materials, wood is multifunctional. Three functions are of primary importance: to support the crown, to conduct water and minerals from roots to crown, and to store energy as carbohydrates until required. Three features characterize the microstructure:

- Elongated cells that make up the bulk of the wood, called tracheids in softwoods and fibers
- in hard woods.
- Rays, radial channels connecting the inner part of the trunk to the thin outer region or cambium.
- Sap channels, which are enlarged cells with thin walls and large pore space that conduct fluids up the tree, driven by osmotic pressure.

The main part of the trunk—the part from which we derive what we call "wood" and "timber" — performs the mechanical function. The other two are provided by a thin outer region or cambium, which is enclosed in a bark that may contain a layer of cork. Trees are dicots. The primary growth is upwards, seeking more light. The secondary growth is radial, in seasonal surges, creating the growth rings.

Figure 7. Wood: here, Hardwood (Oak) (Image: Shutterstock)

Palm. Palms are monocots, more closely related to grasses and ferns than to trees. Unlike tree-wood, they lack a cambium through which radial growth takes place to support the increasing height. Some palms grow to a considerable height, supporting it by increasing the thickness and amount of lignin in the older cell walls, giving the stems a gradient structure, densest at the outside. These differences give palm wood a structure and properties that differ from those of tree wood.

Bamboo. Bamboos are grasses. The hollow, cylindrical stem derives its strength and stiffness from its tube-like shape, reinforced by parallel fiber-bundles that occupy about 50% of the cross section. Like palms, bamboos do not thicken by secondary growth and show no growth rings. Some are mineralized with silica.

Cork. Many trees have a thin layer of cork just below the outer bark. The cork tree, Quercus suber, is unique in that, at maturity, the cork forms a layer several centimeters thick around the trunk. Structurally, it is a low density, polymeric closed-cell foam. Cork contains suberin, a fatty acid, and waxes that make it impervious to air, water, and alcohol (think of the cork in a wine bottle). Its function in nature appears to be to protect the tree from heat, loss of moisture, and, perhaps, from damage by animals (suberin tastes unpleasant).

Nut. Most nut shells are made up of a network of fiber tissues with a composition close to that of wood, but with an approximately random 3-D fiber lay-up (unlike woods, in which the fibers are highly oriented). The database contains records for 40 woods and wood-like materials.

2.5 Group 5. Natural fibers

Natural fibers derive from the world of mammals, that of insects, and that of vegetables. Many have evolved to carry loads (though they perform other functions too), with the result that they are optimized for strength and stiffness at minimum weight. Others have evolved to insulate and provide warmth, giving them exceptional thermal properties. Fibers are elongated, tapering, thick-walled cells that give elasticity, flexibility, and tensile strength. Fibers of the mammal and insect world are based on proteins such as keratin. Those of the vegetable world are based on cellulose and are found in the stem, the leaf, and the seed pod. The database contains records for the fibers listed below.

Mammalian fibers: wool. Wool is the fiber derived from the fur of animals of the Caprinae family, principally sheep, but the hair of certain species of other mammals such as goats, llamas, and rabbits may also be called wool.

Insect fibers: silk-worm silk. Silk is a natural protein fiber, some forms of which can be woven into textiles. The best-known type is that obtained from the cocoons of the larvae of the silkworm, Bombyx mori, which is farmed for its fiber.

Arachnid fibers: spider silk. Spiders are not insects, yet the silk they spin has a protein structure very like that of the silk worm. The spider is able to adjust the properties of its silk to meet particular requirements. Records for drag-line silk and spiral-silk bring out the differences.

Stem fibers: flax, hemp, jute, kenaf, ramie. The stems of fibrous plants contain cellulose fiber bundles, each containing individual fiber cells or filaments. The filaments are made of cellulose and hemicellulose, bonded together by a matrix of lignin or pectin. The pectin, which surrounds and binds the bundles, is removed by a process called retting or by boiling in alkali, separating the bundles from the rest of the stem.
Flax, which can be grown in a temperate climate, gives strong and stiff fibers. These can be spun to fine yarns for textile (linen). Other stem fibers grow in warmer climates. The most common is jute, which is cheap and has a reasonable strength and resistance to rot.

Leaf fibers: sisal, palm. Leaf fibers are generally coarser than stem fibers. Within the total production of leaf fibers, sisal is the most important. It is obtained from the agave plant. The stiffness and strength are relatively high.

Seed fibers: cotton, coir. Cotton is the most common seed fiber, used worldwide for textiles. Other seed fibers are used in less demanding applications such as stuffing for upholstery. The exception is coir, the fiber of the coconut husk – thick and coarse, but exceptionally durable, it is used for ropes, matting and brushes. See Figure 8.

The database contains records for fifteen natural fibers.

Figure 8. Coir, fiber derived from the coconut palm.
(Image courtesy of the Natural History Museum of Victoria, Australia.)

2.6 Group 6. Bio-medical materials

A number of materials have been developed to allow repair or replacement of tissue. They must meet demanding requirements. They must be bio-compatible and, in some cases, able to stimulate cell growth. They must resist attack by body fluids or, if attacked, it must be in a way that allows the body to absorb the corrosion products benignly. And they must also meet demanding mechanical constraints: particularly the ability to carry the cyclic loads imposed on them by the normal functioning of the body, and to do so for many years.

Materials drawn from all of the main material classes have been developed to fill these roles. They carry FDA and other approvals to permit their use.

Bio-metals. Most metals, if implanted in the body, corrode, releasing chemical species that damage cells. A few based on nickel, cobalt, titanium, or precious metals (platinum, gold, silver) release ions so slowly that the body can tolerate them indefinitely. Figure 9 gives an example. The database contains records for representatives of these families.

Figure 9. Ultra high molecular weight polyethylene and
cobalt-chrome alloy forming an artificial a knee-joint.

Bio-polymers. The least toxic polymers are the polyolefins, consisting only of carbon and hydrogen and with properties that more nearly match those of tissue than they do the properties of metals. Principal among them is ultra-high molecular weight polyethylene, UHMWPE. Acrylics find use both as contact lenses and as cements for bone hip and other joint replacements. Silicone elastomers are used for cosmetic implants.

Bio-ceramics and glasses. Ceramics and glasses are much more stable than metals or polymers. Many are oxides, chemically inert, and perform useful mechanical functions. A few have a further feature: their chemistry is like that of bone, stimulating cell growth or permitting re-sorbance. The database contains records for typical bio-ceramics.

3. Typical records

The Bio Engineering level 2 database was revised and enlarged in 2014. One of the changes is the inclusion of bio-derived composites materials. As in other Granta EduPack databases, records can be examined at two levels: Level 2 (Introductory) and Level 3 (Advanced). Figure 10 show typical Bio Engineering Level 2 records, for cancellous bone and zirconia bio-ceramic.

Data for natural materials are difficult to locate and are not always reliable. The data themselves show much natural variability and are often incompletely documented. There are no handbooks or other sources that compile data for a broad range of natural materials in a uniform format. For this reason the main sources from which the data for each record are drawn are listed explicitly in the record itself under mechanical, thermal, and electrical properties.

The tree structure of the database follows the families of materials as in the Standard Edition. The record format will be familiar to Granta EduPack users: a description with an image, followed by table listing general, mechanical, thermal, electrical, and optical properties. Four attributes have been added (biomaterial, bio-medical material, bio-derived material, biological material) to easily filter and select from these group of materials. Two bio-medical attributes are included, identifying whether the material is bio-compatible, or is of medical grade. The record ends with text listing uses. Each property is stored as a range, as in other Granta EduPack databases. Data from reliable sources are un-starred. Data that, for one of several reasons, could be unreliable, yet meets credulity checks, are included with a star (*). When no direct measurement is available it is sometimes possible to estimate a value, using standard procedures (see the Granta EduPack documentation). Estimated data, too, are starred. The rationale for including uncertain or estimated information is that, in introducing students to natural and biomedical materials, comparisons are the most effective way of highlighting their qualities. For this, approximate information is a good deal better than none at all—there is still enough real resolution to bring out characteristics. Sometimes, however, neither a direct measurement nor an acceptable estimate is available. This database (unlike other Granta EduPack databases) has holes—fields that, for some materials, are unfilled. When performing a selection such field, the materials without a value will not appear.

Do not imagine, though, that un-starred data is “accurate” in the sense that data for conventional engineering materials attempts to be. The variability of natural materials is great. If the data ranges encompassed this variability in full, the overlap in comparison plots like those in the next section would be confusing. Hence, the records describe “representative” examples of the material, presenting a set of properties more or less in the middle of the range that the material. Most are described by a single record. Two records are used when:

- the material is extremely anisotropic; records are provided for the stiffest and the least stiff direction (e.g., cortical bone and all woods);
- the property spread is so great that a single record would be misleading; separate records represent materials with high / low properties in this spread (e.g., cancellous bone, silks).

The database contains record-sets for engineering materials as well as biomaterials and those of nature. The uniform format and units allows direct comparison between these sets. Examples are presented in Section 4, which also illustrates other uses of the database.
Bio-medical materials, some, like the body itself, are polymeric, others are metallic or ceramics. The database contains records for 40 bio-medical materials of which 10 are metals, 23 polymers and 7 ceramics. They are listed in Table 1 below. Case studies are described below in Section 4.

Cortical bone, longitudinal

Layout: Edu Level 2 Show/Hide

Description

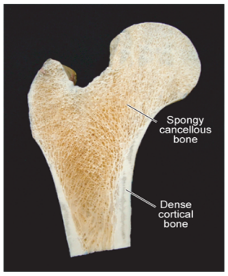
The material

Bone, the principal structural material of the animal kingdom, is a composite of the ceramic hydroxyapatite and the polymer collagen. It performs a number of functions, among them that of carrying the working loads of the body. The bones of the scull and limbs generally take the form of bi-structured shells or tubes with an outer layer of dense, cortical (or compact) bone surrounding a foam-like structure of cancellous (trabecular or spongy) bone.

Composition (summary)

A hydroxyapatite - collagen composite (see the records for both of these).

Image



Caption

Cortical (dense) and cancellous (spongy) bone. The data in this record refer to cortical bone.

General properties

Density	1.8e3	-	2.08e3	kg/m^3
Biomaterial	✓			
Biological material	✓			

Mechanical properties

Young's modulus	18	-	26	GPa
Shear modulus	4.5	-	6.7	GPa
Bulk modulus	* 12.1	-	27	GPa
Poisson's ratio	0.13	-	0.3	
Yield strength (elastic limit)	* 90	-	144	MPa
Tensile strength	135	-	167	MPa
Compressive strength	130	-	250	MPa
Elongation	0.6	-	1.4	% strain
Hardness - Vickers	50	-	80	HV
Fatigue strength at 10^7 cycles	* 23	-	80	MPa
Fracture toughness	3.5	-	6.1	MPa.m^0.5
Mechanical loss coefficient (tan delta)	0.01	-	0.02	

Notes on mechanical properties

The properties listed here are for wet cortical bone. The ranges are large because bone is anisotropic, stiffer and stronger in some directions than in other.

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Thermal properties

Maximum service temperature	* 127	-	227	°C
Thermal conductor or insulator?	Poor insulator			
Thermal conductivity	0.41	-	0.63	W/m.°C
Specific heat capacity	1.1e3	-	1.26e3	J/kg.°C
Thermal expansion coefficient	* 15	-	18	µstrain/°C

Notes on thermal properties

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Lundskog, J. (1972) "Heat and bone tissue. An experimental investigation of the thermal properties of bone and threshold levels from thermal injury", Scand J Plast Reconstr Surg., 6 (Supple), pp. 5-75

Electrical properties

Electrical conductor or insulator?	Poor insulator			
Electrical resistivity	4.5e9	-	1.4e10	µohm.cm
Dielectric constant (relative permittivity)	14.5	-	32	

Optical properties

Transparency	Translucent

Notes on electrical and optical properties

J Siepowska, M A Hakulinen, J Töyräs, J S Day, H Weinans, J S Jurvelin and R Lappalainen, Prediction of mechanical properties of human trabecular bone by electrical measurements, Physiol. Meas. 26 (2005) S119-S131

Ewa Marzec and Leszek Kubisz, Electric properties of non-irradiated and gamma-irradiated bone, Journal of Non-Crystalline Solids, Volume 305, Issues 1-3, July 2002, Pages 333-338

Values marked * are estimates.
No warranty is given for the accuracy of this data

Zirconia bio-ceramic

Layout: Edu Level 2 with Eco and durability properties Show/Hide

Description

The material

Zirconia, along with alumina, are the technical engineering ceramics that are well suited as bio-materials. Yttria-toughened zirconia (Y-ZTP) has an excellent combination of strength and toughness together with bio-inert properties and low wear rate. It is now displacing alumina in applications such as femoral heads for total hip replacements. The zirconia heads display double the strength of comparable alumina heads and consequently the diameter of the femoral head can be reduced to < 26mm, leading to a reduction in patient trauma during the hip replacement operation.

Composition (summary)

Zirconia, ZrO_2, stabilized in its tetragonal form by a small addition of yttria, Y_2O_3.

Image

Caption

Left: zirconia tooth implant compared to metallic tooth implant. Zirconia makes the replacement tooth appear more similar in colour to neighbouring teeth compared to the dark appearance of metal implants (image from maxillofacialcostrica.com).
Right: zirconia used for the ball and acetabular cup of a hip implant. Polished ceramics offer very low friction surface couples in addition to low wear, however they risk brittle fracture (image from implants-event.com).

General properties

Density	5.85e3	-	5.9e3	kg/m^3
Price	* 11.8	-	17	GBP/kg
Biomaterial	✓			
Biomedical material	✓			

Mechanical properties

Young's modulus	205	-	212	GPa
Shear modulus	* 82	-	88	GPa
Bulk modulus	* 140	-	160	GPa
Poisson's ratio	0.24	-	0.26	
Yield strength (elastic limit)	* 750	-	850	MPa
Tensile strength	* 750	-	850	MPa
Compressive strength	1.9e3	-	2e3	MPa
Elongation	0			% strain
Hardness - Vickers	1.2e3	-	1.25e3	HV
Fatigue strength at 10^7 cycles	* 550	-	640	MPa
Fracture toughness	9	-	10.5	MPa.m^0.5
Mechanical loss coefficient (tan delta)	* 5e-4	-	0.001	

Notes on mechanical properties

Park, J. and Lakes, R.S. (2007) "Biomaterials, and introduction", 3rd edition, Springer Science and Business Media, NY, USA. ISBN 978-0-3873-7879-4.

Thermal properties

Melting point	2.55e3	-	2.7e3	°C
Thermal conductor or insulator?	Poor insulator			
Thermal conductivity	1.6	-	1.8	W/m.°C
Specific heat capacity	* 425	-	445	J/kg.°C
Thermal expansion coefficient	10.5	-	11.5	µstrain/°C

Electrical properties

Electrical conductor or insulator?	Good insulator			
Electrical resistivity	* 1e17	-	1e18	µohm.cm
Dielectric constant (relative permittivity)	* 20	-	22	
Dissipation factor (dielectric loss tangent)	* 0.001	-	0.002	
Dielectric strength (dielectric breakdown)	* 4	-	6	1000000 V/m

Optical properties

Transparency	Transparent			
Refractive index	2.1	-	2.2	

Supporting information

Medical applications

Femoral heads for total hip replacements, knee joints, shoulders, phalangeal joints and spinal implants.

Tradenames

Y-ZTP

Bio-data

Biocompatible	✓
Medical grades	✓

Links

ProcessUniverse

Values marked * are estimates.
No warranty is given for the accuracy of this data

Figure 10. A record for the longitudinal properties of cortical bone longitudinal and Zirconia bio-ceramic.

4. Case studies: examples of the ways the database can be used

4.1 The big picture: modulus - strength charts for natural and engineering materials

Figures 11 and 12 introduce the database. The first shows the tensile strength, σ_{ts}, of engineering materials plotted against Young's modulus, E. Each small bubble encloses the range of σ_{ts} and E for one material. Large envelopes enclose material classes: metals, polymers, elastomers, ceramics, and foams. In Figure 12 the same properties for natural materials are plotted on exactly the same axes. Again, the little bubbles describe single materials while the larger envelopes enclose soft tissue, mineralized tissue, fibers, and wood-like materials. For presentational reasons no envelope has been created for the basic structural building blocks (pink bubbles).

Charts like these allow a direct comparison of the properties of natural and man-made materials. This pair reveals that nature is able to synthesize with properties that cover a range almost as large as those of the engineering materials we use today. The Granta EduPack software allows any chosen subset of the numeric properties in the database to be plotted and compared in this way.

4.2 Soft tissue and its structural building blocks

Figures 13 and 14 show data for soft tissue and for the basic structural materials from which it is made. The first is a chart of tensile strength and elongation. Tissues that are predominantly based on keratin (horn, hoof, hair) all have strengths around 100 MPa and an elongation between 5 and 50%. Those built from collagen, elastin, and proteoglycans (cartilage, ligament, skin, artery, muscle) have lower strengths, but generally higher elongation (up to 110%).
Figure 14 is a chart of tensile strength σ_{ts} and Young's modulus E, again including the basic building blocks. The contours are lines of constant elastic energy density, W_{vol}, where

$$W_{vol} = ½\, \sigma_{ts}^{\,2} / E$$

It is a measure of the energy required to stretch the tissue to failure. The chart reveals an interesting fact: the soft tissues shown here differ greatly in strength and stiffness, but all have almost the same value of W_{vol}. The modulus increases as the square of the strength, so that the ratio of the two remains almost constant.

4.3 Elastic energy and density

Rubber bands, when stretched, store energy. The stored elastic energy per unit volume is measured by the quantity σ^2 / 2E; that per unit weight is measured by σ^2 / 2ρE. Here σ is the stress, E is Young's modulus and ρ is the density. We will identify the maximum value of the stress with the tensile strength, σ_{ts}. Then the maximum energy storage is measured by the quantity σ^2_{ts} / *2E* per unit volume or σ^2_{ts}/ *2ρE* per unit weight. High values of these quantities endow material with the ability to act as a spring and as an impact-absorbing barrier.

Figure 15 presents these two properties, the first plotted on the y axis, the second appearing as the contours. Natural materials have evolved with particularly good values of both. Spider and silk worm silk excel by both criteria. Many other natural fibers—cotton, sisal, wool, and hair among them—also have the ability to store elastic energy. Elastin, resilin, and abductin have values of strength, modulus, and density and have properties very like those of synthetic rubber.

4.4 The strength and stiffness of fibers

Fibers are, from a mechanical point of view, one dimensional: they are only ever loaded in tensional bending. Either way, it is the axial stiffness and strength that determines performance. When the fibers are polymeric (as are all natural and many manmade fibers) these two properties are maximized by aligning the C-C-C- chains of the polymer molecules parallel to the axis of the fiber. If, in addition, some ability to stretch is required, it can be achieved by crimping the molecules slightly so that, under tension, they progressively straighten out.

Nature makes use of all these strategies. The results are shown in Figure 16, which compares the specific strength and stiffness of fibers with those of man-made materials: carbon, Kevlar, glass, and heavily drawn ("patented") steel wire. A number of natural fibers perform as well or better than steel, though none quite approach Kevlar or carbon.

4.5 The dependence of the properties of woods and wood-like materials on density

Woods, as already mentioned, all have approximately the same chemical makeup. The great difference in their properties derives from the differences in their density, and, to a smaller extent, in their structure. All are anisotropic, markedly stiffer and stronger parallel to the grain than across it. We would, therefore, expect a strong correlation between stiffness, strength, and density, and a clear distinction in this correlation between the grain-parallel and the grain-perpendicular direction.

Figures 17 and 18 allow the comparison of the properties of wood with each other and with the materials from which they are principally made: cellulose and lignin. The systematic relationship between modulus and density and that between strength and density are clearly shown by the figures.

Table 1. Bio-medical materials in new Bio Engineering Level 2 database

Metallic bio-medical materials	Polymeric bio-medical materials	Ceramic bio-medical materials
Cobalt-chromium alloys (bio)	Acrylic (medical grade)	Alumina bio-ceramic
Gold	Acrylonitrile butadiene styrene (ABS)	Bioglass ceramic
Nickel-chromium alloys (bio)	Epoxies	Calcium phosphate bio-ceramic
Nickel-Titanium alloys (Nitinols), austenitic	Ethylene vinyl acetate	Glass ionomer
Nickel-Titanium alloys (Nitinols), martensitic	Natural rubber (NR)	Silicon
Precious metals implants (bio)	Nylon 11 (PA-11)	Vitreous carbon
SIlver	Polyamides (Nylons, PA)	Zirconia bio-ceramic
Silver amalgam (bio)	Polycarbonate (PC)	
Stainless steel (bio)	Polyetheretherketone (PEEK)	
Titanium (bio)	Polyethylene (PE)	
	Polyethylene terephthalate (PET)	
	Polyglycolic acid (PGA)	
	Polylactic-co-glycolic acid (PLGA)	
	Polylactide (PLA)	
	Polymethyl methacrylate (Acrylic, PMMA)	
	Polyoxymethylene (Acetal, POM)	
	Polypropylene (PP)	
	Polystyrene (PS)	
	Polytetrafluoroethylene (Teflon, PTFE)	
	Polyurethane (elPU)	
	Polyurethane (tpPUR)	
	Silicone (medical grade)	
	Ultra high mol. wt. polyethylene (UHMWPE)	

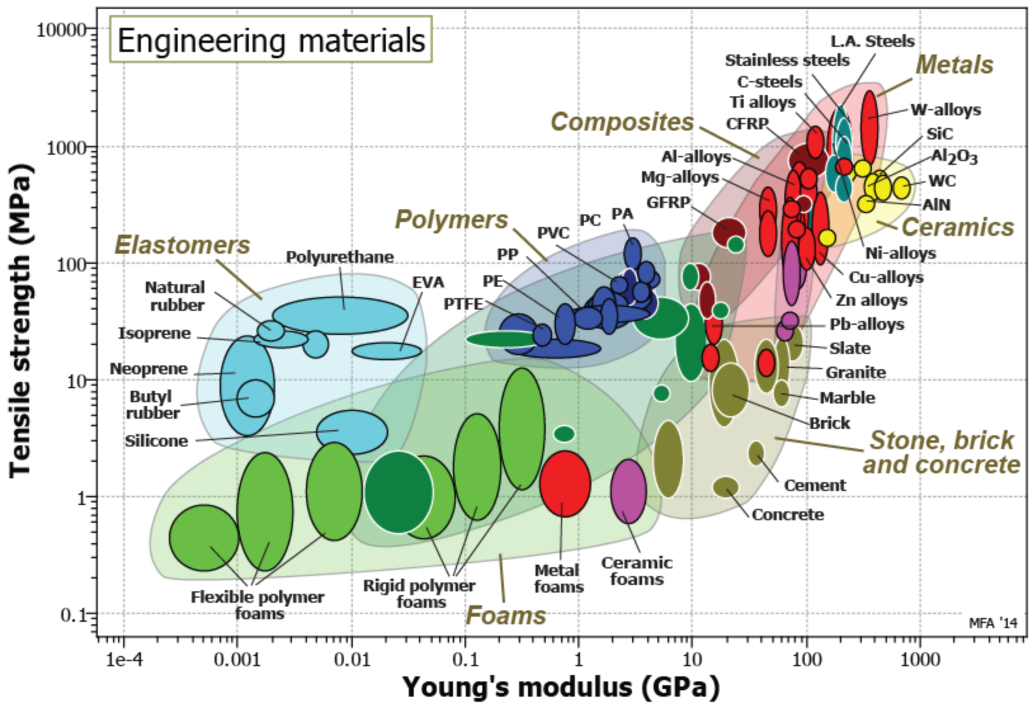


Figure 11. Young’s modulus and tensile strength of engineering material.

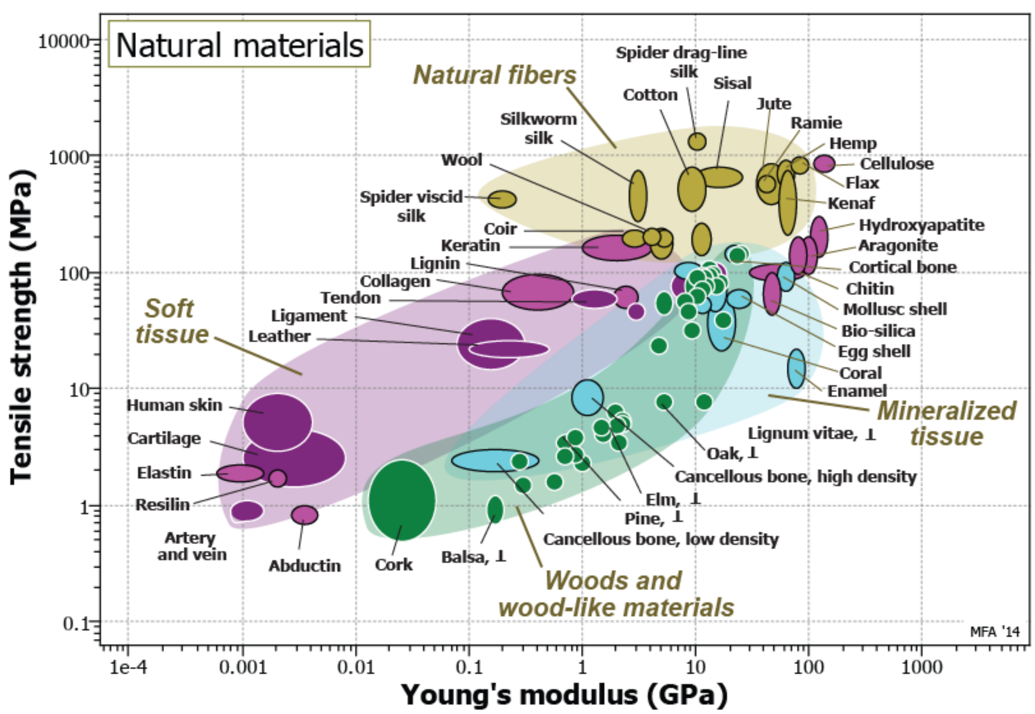


Figure 12. Young’s modulus and tensile strength of natural material on exactly the same axes as Figure 11. For clarity the basic structural building blocks (pink bubbles) are not enclosed in an envelope.

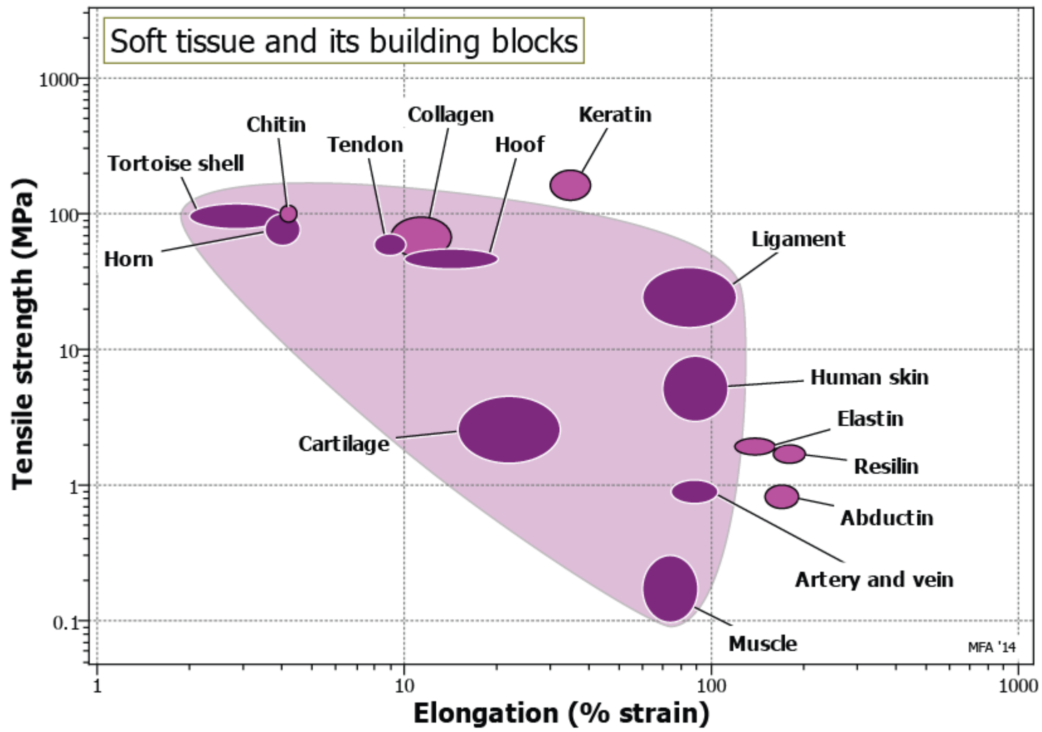


Figure 13. Strength and elongation of soft tissues compared with those of the basic structural building blocks that make them up. The greater the elastin content, the greater is the elongation.

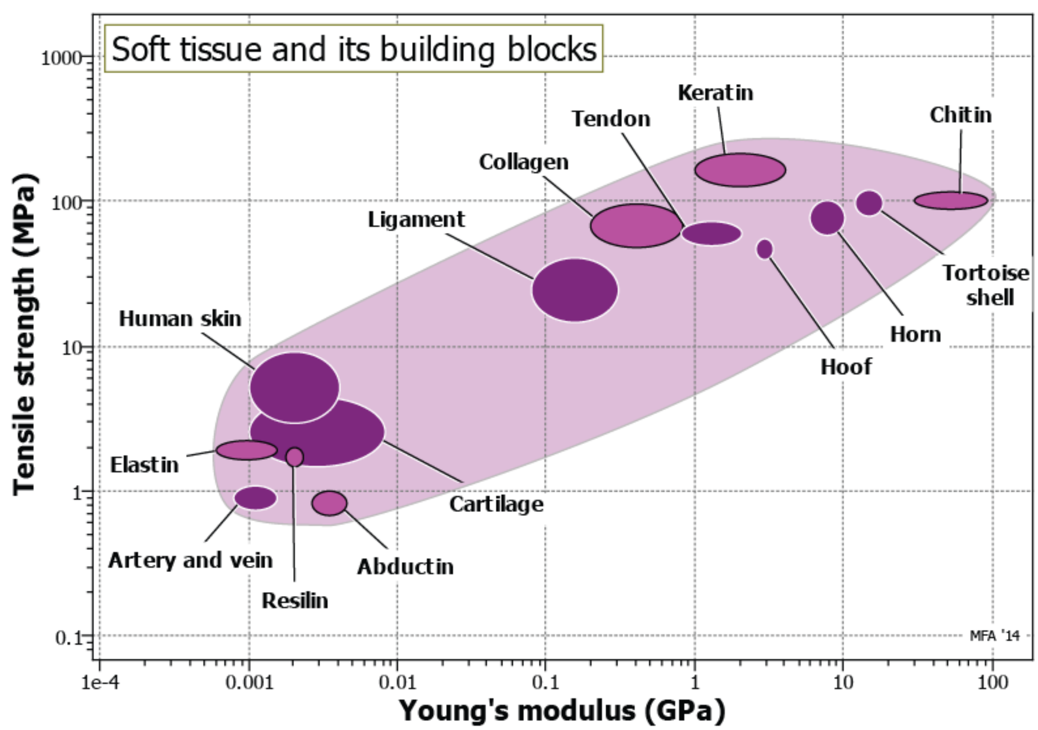


Figure 14. Strength and modulus for soft tissues and for their basic structural building blocks. The data are strung out along a band joining elastin to keratin and collagen. The contours are lines of constant elastic energy density.

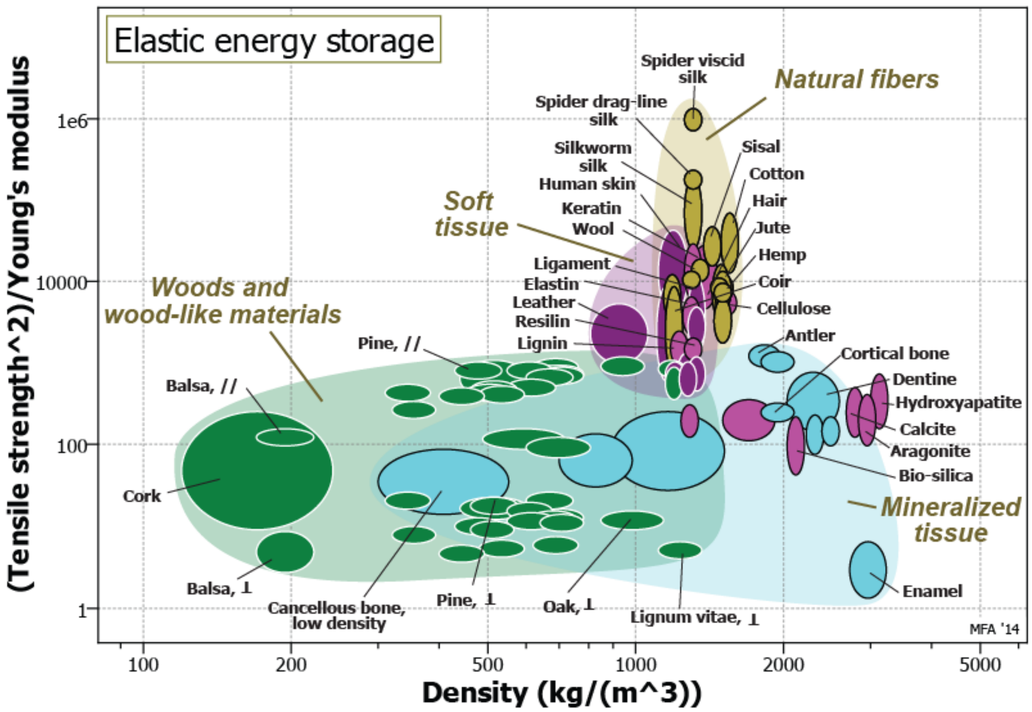


Figure 15. The maximum capacity to store elastic energy, σ2 / 2E, of natural materials. That of silk is extraordinarily high.

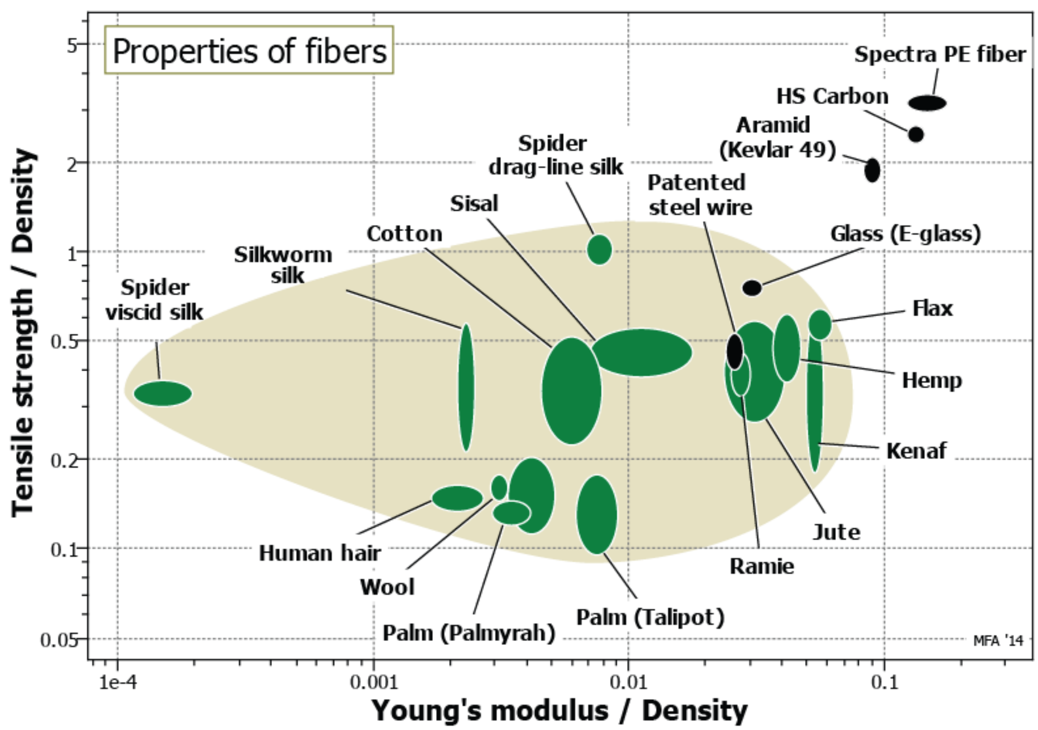


Figure 16. The specific strength and stiffness of natural fibers compared to those of the strongest man-made fibers. Several natural fibers are as good as, or better than, steel.

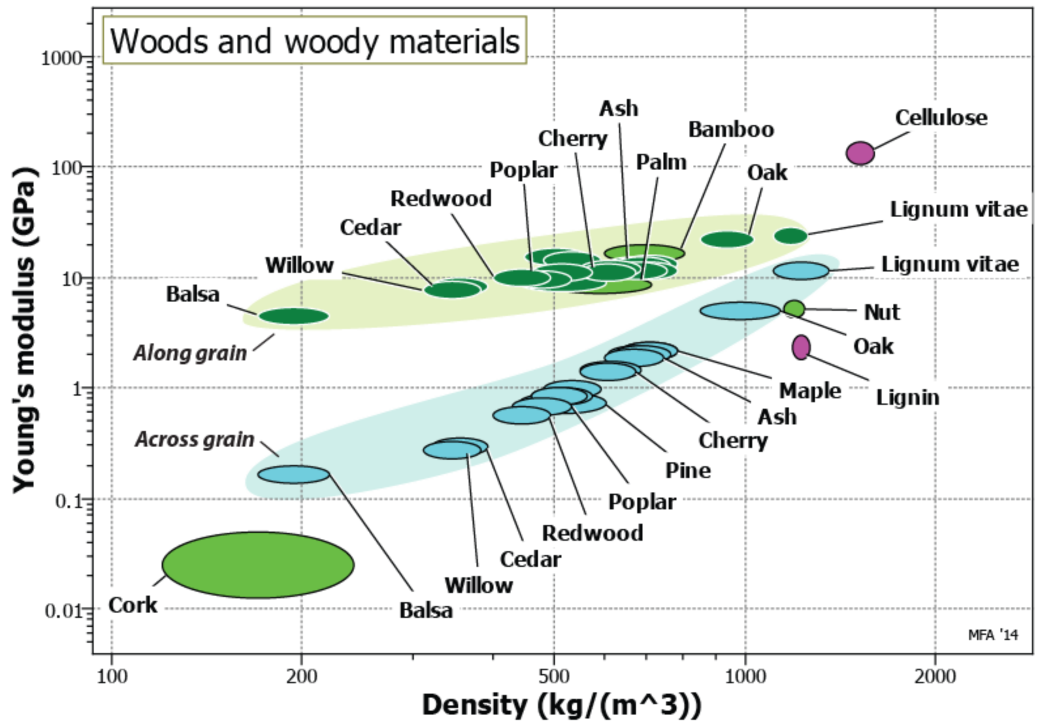


Figure 17. A comparison of the properties of woods compared with those of its constituents, cellulose and lignin: modulus and density.

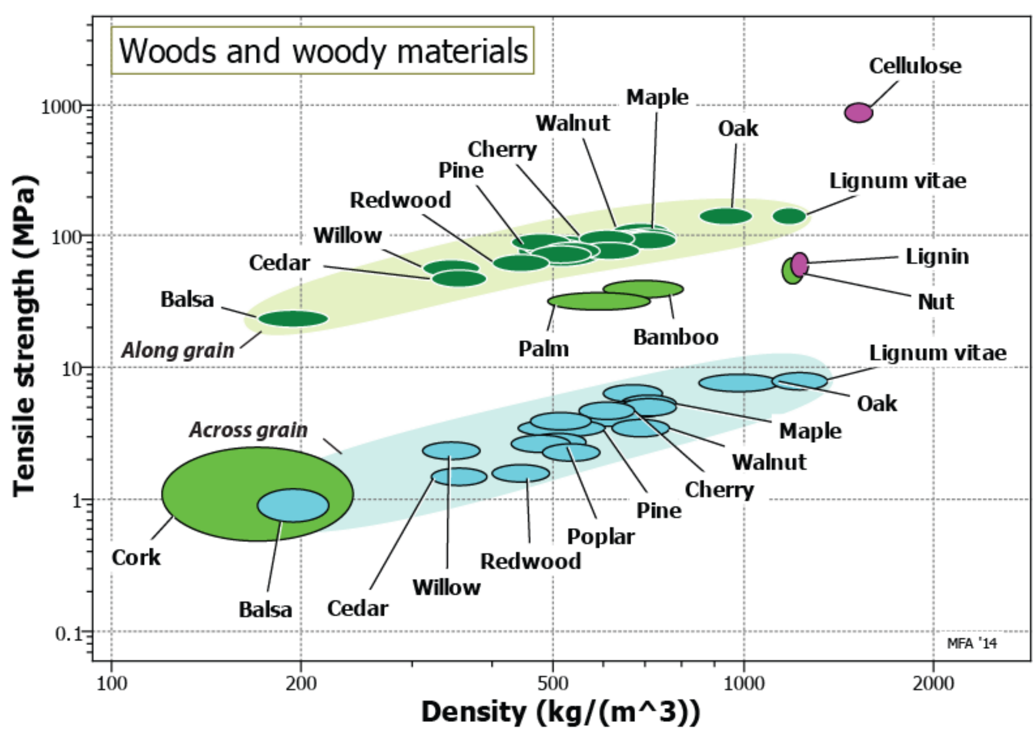


Figure 18. A comparison of the properties of woods compared with those of its constituents, cellulose and lignin: strength and density.

4.6 Comparison of the hardness and toughness of mineralized tissue with that of its mineral

The minerals of mineralized tissue are, when pure, hard and brittle. Mineralized tissue is less hard. No surprise there—all have, to varying degrees, a component of protein binding the mineral together. But many are much less brittle, indeed they are relatively tough. Toughness—resistance to cracking—is measured, in engineering, by the fracture toughness. The load needed to make a tooth or bone break or chip is proportional to its fracture toughness. The toughness has a protective role as well—tough shell, for instance, is harder for a predator to penetrate than a shell that is brittle, a strategy that molluscs, prey to sea urchins, and other marine creepy-crawlies use.

Figure 21 presents the evidence. Hardness is no surprise: the minerals are the hardest; dilute them in any way and the hardness falls. The remarkable thing is the toughness. Antlers are used for fighting; a brittle antler is not a good idea. Antler, dense bone and dentine are between three and ten times more resistant to the propagation of a crack than the hydroxyapatite with which they are mineralized. Mollusc shell, mineralized with calcite or aragonite, is remarkably high.

In all four examples the gain in toughness derives from the way the mineral is deposited and configured in the tissue. That is beyond the scope of this paper, but well documented in the references contained at the end of this paper.

4.7 Comparison of mineralized tissue with man-made bio-medical material replacements

One of the commonest mechanical interventions is that of the replacement, with biomaterials, of mineralized tissue that has become diseased. Filling, capping and replacement of teeth is an obvious example; another are the more invasive procedures that replace the joint of the hip, knee, elbow, or finger, or those of bone reinforcement with plates and pins. Secondary consequences of the intervention are reduced if the mechanical and thermal properties of the biomaterial match those of the natural one. Figure 22 shows how closely biomaterials match the properties of bone and tooth in modulus and thermal expansion coefficient. Failure to match the first redistributes in loads in ways that may limit the life of the replacement; failure to link the second can lead to thermal stress—teeth, after all, are exposed to fluids well above and below body temperature.

The figure suggests that the match is poor—more so in modulus than in expansion, but there is a mismatch there too. The best bio-match is that of calcium phosphate bio-ceramic. Not surprising—calcium phosphates are the mineral of the mineralized tissue in enamels.

4.8 Materials for Dental implants

This case study demonstrates the value of having information on biological materials and bio-medical materials alongside general engineering materials for the purpose of design in bio-medical engineering. The aim is to select a suitable material or materials for a dental implant (Figure 19). To do so we compare the properties of dentine and enamel with those of non-biological materials, exploring those where the match is good. Teeth have a hard outer coating, enamel, and a tough core, dentine. A suitable material for an implant will have the toughness of dentine (1.9 to 4.5 $MPa{\cdot}m^{0.5}$) and the hardness of enamel (95-130 HV). The compressive strength of dentine is 250 to 310 MPa.

Limiting the subset of materials to “Medical grades” returns 49 materials from the 250 in the Bio Engineering Level 2 database. The list includes dentine and enamel. Adding the below limits:

- Hardness > 90 HV and
- Fracture toughness > 1.9 MPa·m$^{0.5}$

reduces the list to 10 materials (The restriction to the hardness of dentine plus the toughness of dentine eliminates them both).

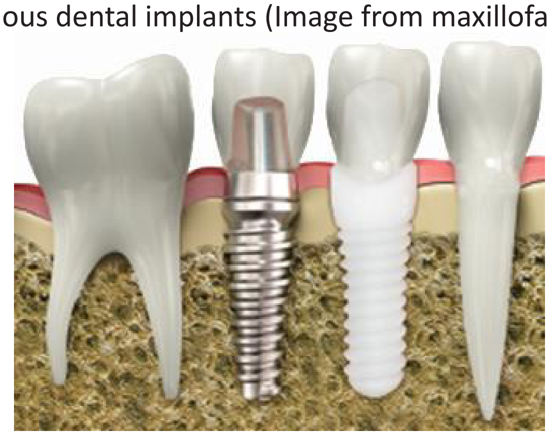
Compressive strength and price are also of interest. A dental implant has a given volume, whatever it is made from, so we want the price per unit volume (price/kg * density). Figure 23 is graph of these properties.

Using a box-selection to isolate the materials with compressive strength > 250 MPa cuts the list down to just 8 materials:

- Bioglass ceramic
- Cobalt-chromium alloys (bio)
- Nickel-chromium alloys (bio)
- Silver
- Silver amalgam (bio)
- Titanium (bio)
- Tungsten alloys
- Zirconia bio-ceramic

Most of these are familiar candidates for dental implants – six of these materials are commonly used in this application. The non-metals are quite different in character. Zirconia bio-ceramic is chemically inert in the body. It is used for white dental implants, which are aesthetically more attractive than metal (Figure 19). Bioglass ceramic is a bioactive material which encourages bone ingrowth. It has a low tensile strength and only just meets the toughness criterion.

Figure 19. Various dental implants (Image from maxillofacialcostrica.com)



4.9 Materials for Fracture Plate

A fracture plate is a fixation device that is screwed to a broken bone to facilitate healing. It is fully contained within the body, is permanent and requires open surgery on the limb in question (Figure 20). The aim is to select a suitable material or materials for a fracture plate. To do this we compare the properties of bone with those of non-biological bio-medical materials. The bones of the scull and limbs generally take the form of bi-structured shells or tubes with an outer layer of dense, cortical (or compact) bone surrounding a foam-like structure of cancellous (trabecular or spongy) bone. Ideally, the properties of the material for the plate should match those of bone, meaning a compressive strength in the range109-208 MPa and a Young's modulus in the range 10.2-22.4 GPa, typical of the femur, humerous, or tibia. Property matching is important to avoid bone resorption because an overly stiff plate will take a disproportionate fraction of the load; the body reacts by reabsorbing the lightly loaded bone – a problem encountered also with hip implants.

Limiting the subset of materials to "Medical grades" returns 49 materials from the 250 in the Bio Engineering Level 2 database. The list includes cortical bone. Applying the "ideal" limits listed above leaves only one class of material: bone itself. Using the less restrictive limits:

- Compressive strength > 120 MPa
- Young's modulus > 15 GPa

reduces the list to 19 materials. Adding the further constraint of Fracture toughness 3 - 15 MPa.$m^{0.5}$ reduces the list to just eleven materials shown in the chart of Figure 24, including:

- Cobalt-chromium alloys (bio)
- Cortical bone, longitudinal
- Gold
- Nickel-chromium alloys (bio)
- Precious metals implants
- Silver
- Silver amalgam (bio)
- Stainless steel (bio)
- Titanium (bio)
- Tungsten alloys
- Zirconia bio-ceramic

Unsurprisingly the list includes stainless steels, titanium alloys and Co-Cr alloys; all are commonly used in such devices for fracture plates. The zirconia is a particularly tough ceramic but stress concentration at the fixing screws makes the use of any ceramic material inadvisable.

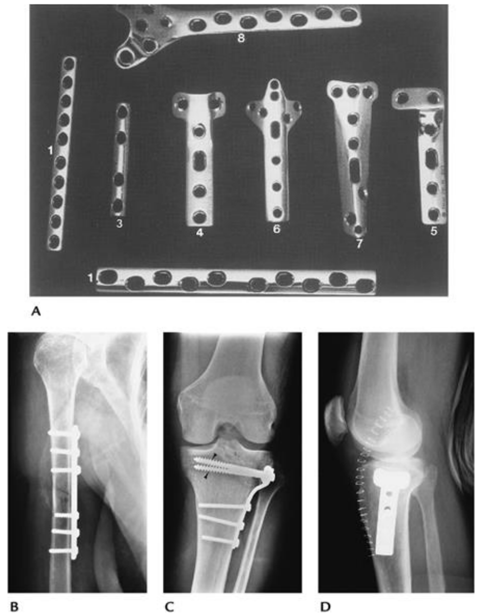


Figure 20. Plate and screw fixation.
(Image from: http://www.msdlatinamerica.com/ebooks/Muscul oskeletalImagingCompanion/sid268591.html)

5. Summary and conclusions

This paper describes a database of mechanical, thermal, and (where possible) electrical properties of representative natural and biomaterials, merged with a database of the materials of engineering. It is constructed in a unified way, using the same properties, in the same units, for all materials.

There are many difficulties, some associated with the great variability of natural materials, some with the lack of consistency in testing methods and reporting procedures. Every effort has been made to smooth these out, but it must be emphasized that the data for natural materials should not be regarded as having the same precision and reproducibility as those for the well-established materials of engineering.

Despite this, the database allows interesting and revealing comparisons. The six case studies explore these in some detail illustrating some of the following points:

- Retrieval of data for natural materials in a unified format.
- The computer based construction of material property charts for natural materials, giving a perspective of their behaviors.
- Exploration of how properties of natural materials relate to the properties of the structural building blocks from which they are made up.
- Comparison of the properties of engineering materials with those of nature.
- Comparison of the properties of biomedical materials designed for tissue replacement with those of the tissue to be replaced.

The accompanying white paper “The Granta EduPack Bioengineering Database. Part 2: Bio-derived materials and applications”, deals with bio-derived materials and non-medical applications.

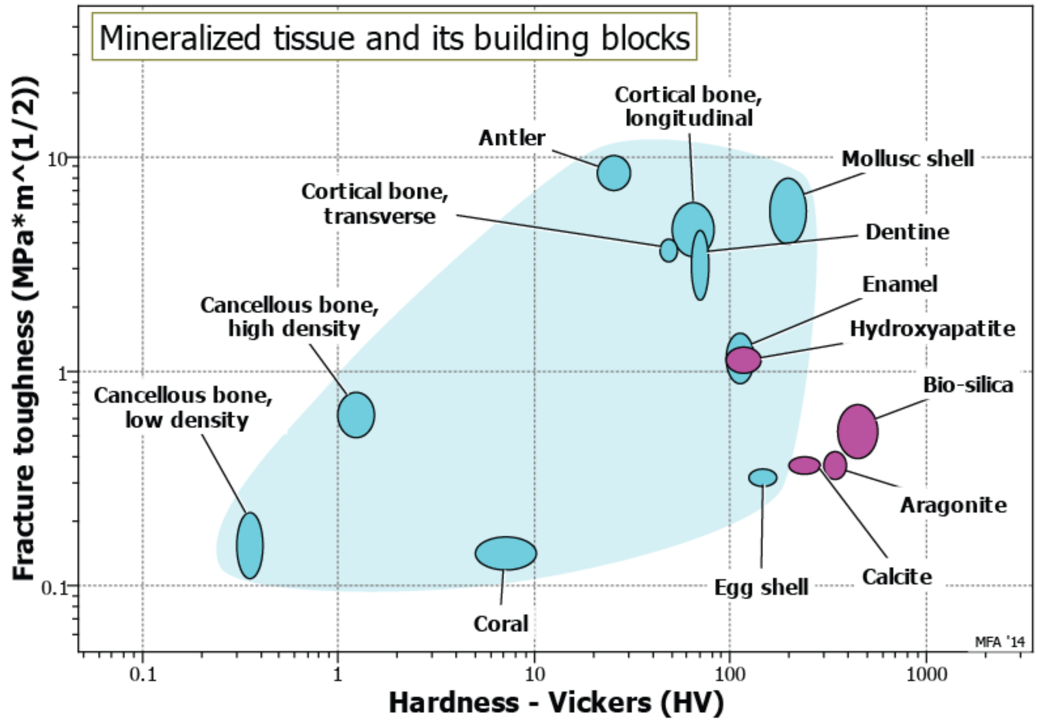


Figure 21. A comparison of the fracture toughness and hardness of mineralized tissue with those of the minerals from of which they are made.

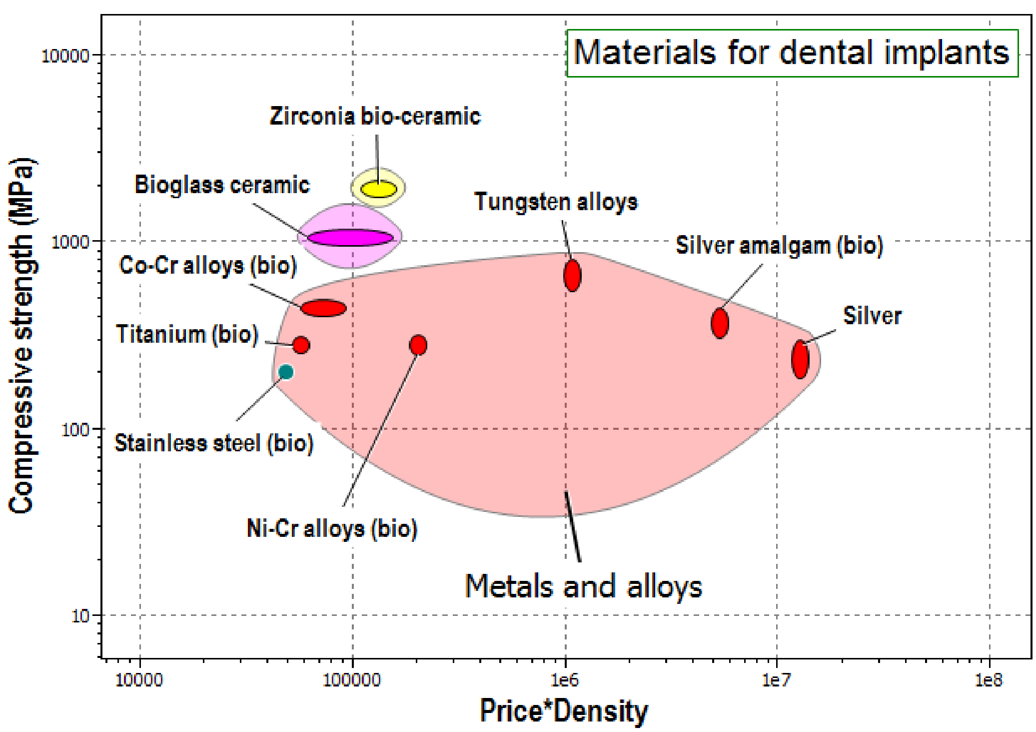


Figure 22. A comparison of the properties of bone, enamel, and dentine, and those of the materials used to replace them. There is a great mismatch in stiffness.

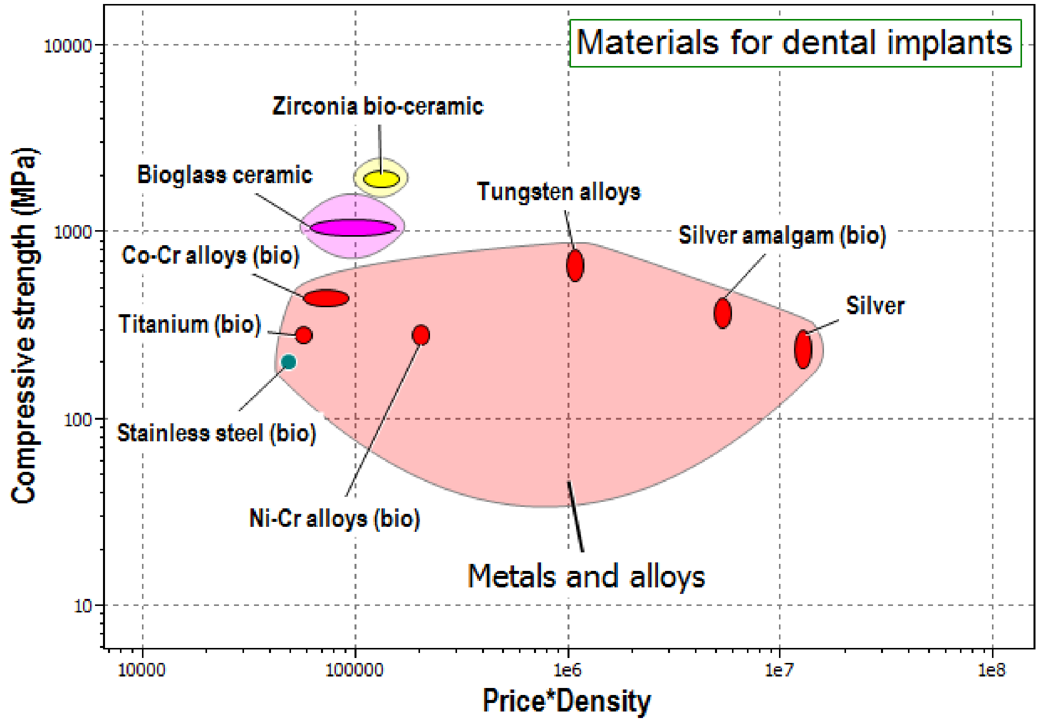


Figure 23. Compressive strength and price per unit volume of medical grade materials that meet the hardness and toughness criteria

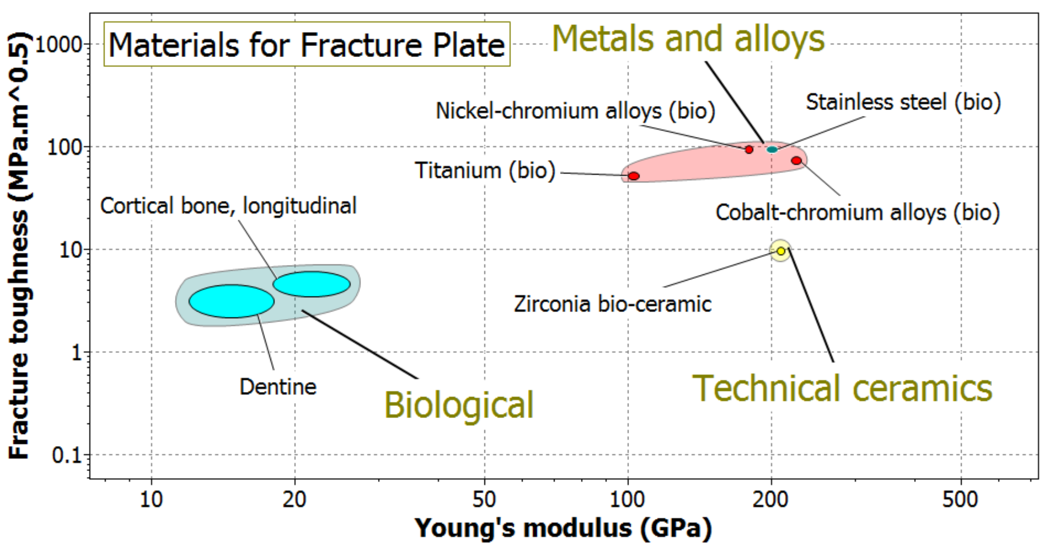


Figure 24. Compressive strength and Young's modulus of medical grade materials that meet the criteria.

Acknowledgements

We wish to acknowledge the contribution of Dr. Michelle Oyen of the Engineering Department in Cambridge, UK, in providing some guidance in identifying sources and resolving conflicts that these sometimes present.

Further Reading

The terminology on this field can become specialized. Definitions of terms can be found http://onlinelibrary.wiley.com/doi/10.1002/pol.1988.140260910/citedby

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Basic structural building blocks 3: minerals

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Biomaterials 2: Medical grade polymers (Acrylic, Silicone, Ultra-high molecular weight polyethylene)

El-Ghannam, A. and Ducheyne, P. (2005) “Biomaterials”, Chapter 11 in “Basic orthopaedic biomechanics and mechano-biology”, 3rd edition, editors Mow, V.C. and Huiskes, R., Lippincott Williams and Wilkins, Philadelphia, PA, USA. ISBN 0-7817-3933-0.

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Biomaterials 3: Metallic biomaterials (Cobalt-chromium alloys, Nickel-chromium alloys, Nickel-titanium alloys, Precious metal implants, Silver amalgam, Stainless steel, Titanium)

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