Stadelhofen Station

Zurich

Santiago Calatrava Valls

Image courtesy of Per Waahlen, photographer, and Structurae

concrete and composites

1. Introduction
    - practice
    - research
2. Concrete Issues
    - ductility
    - CO_2 generation
    - durability
3. Improved Structural Materials
    - substitution
    - dematerialization
    - technology transfer
4. Material Selection and Evaluation (CES)
    - multi-objective optimization
    - material indices/ CES software
5. New and Emerging Materials
    - new concretes
    - composites
6. Architectural Form and Research Priorities
    - research development: NFRC
    - design

concrete and composites

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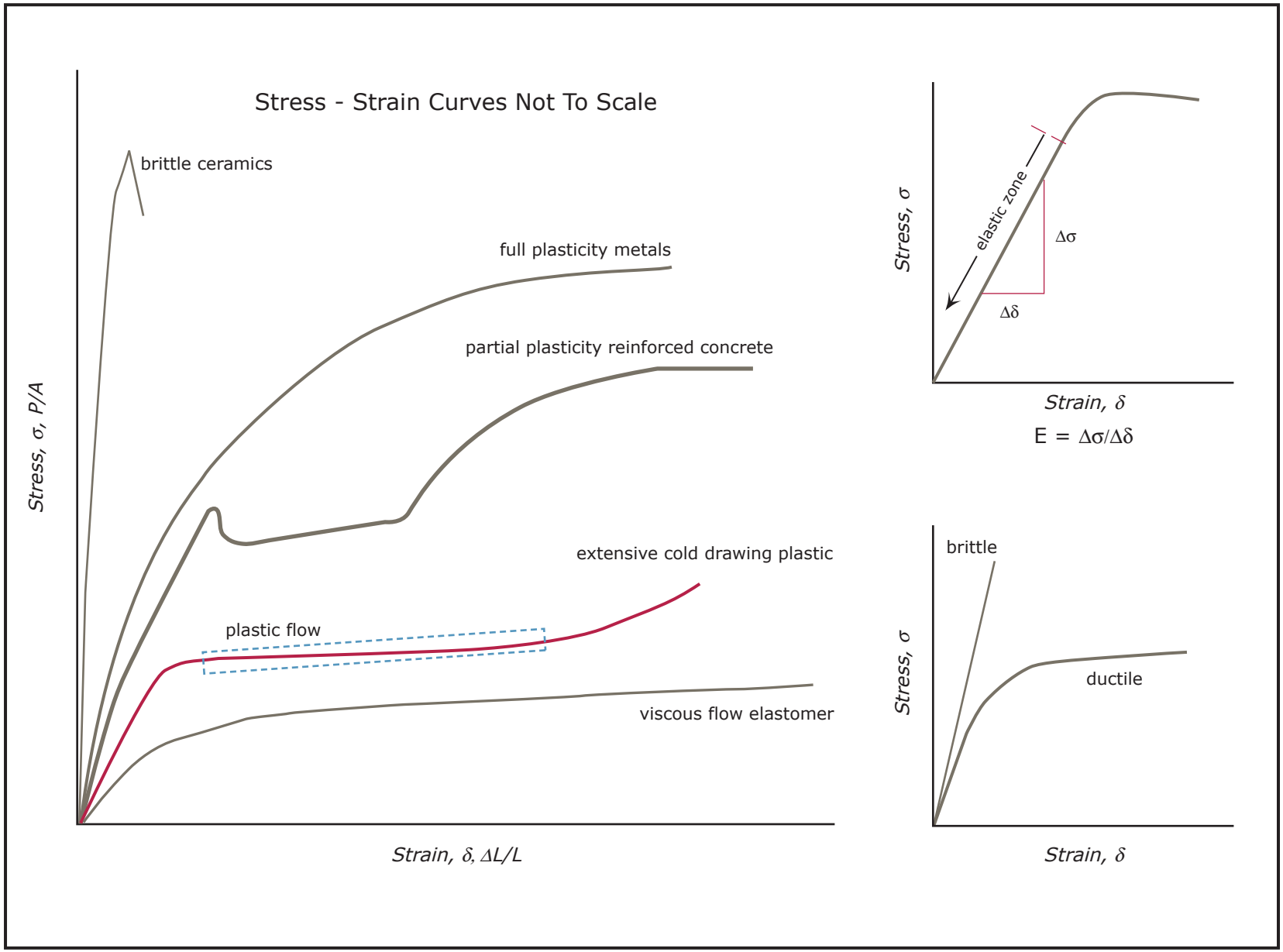


Image by MIT OCW.

Failure strain, ϵ_f

ϵ_f - measure of the deformation of the material at final fracture stress

Ceramics

Fracture and failure is unpredictable

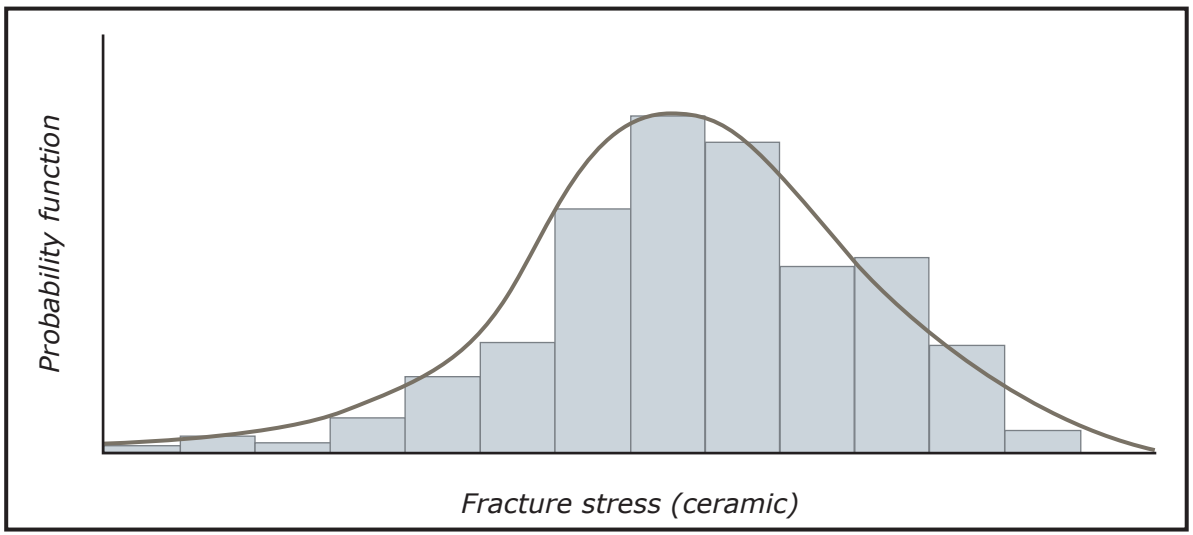


Figure X

Material	ε_f
concrete, unreinforced (compression)	0
concrete, reinforced	0.02
soda glass	0
low-alloy steel	0.02-0.03
mild steel	0.18-0.25
carbon steel	0.2-0.3
stainless steel, austenitic	0.45-0.65
stainless steel, ferritic	0.15-0.25
cast irons	0-0.18
iron	0.3
aluminum	0.5
copper	0.55
brasses and bronzes	0.01-0.7
natural rubber	5.0

Tensile Ductility, ε_f (except for certain materials such as concrete, unreinforced)

Images by MIT OCW.

Toughness, G_f, and

Fracture toughness, K_c

measures of energy absorption potential through resistance to crack propagation.

G_f (toughness), K_c (fracture toughness) -

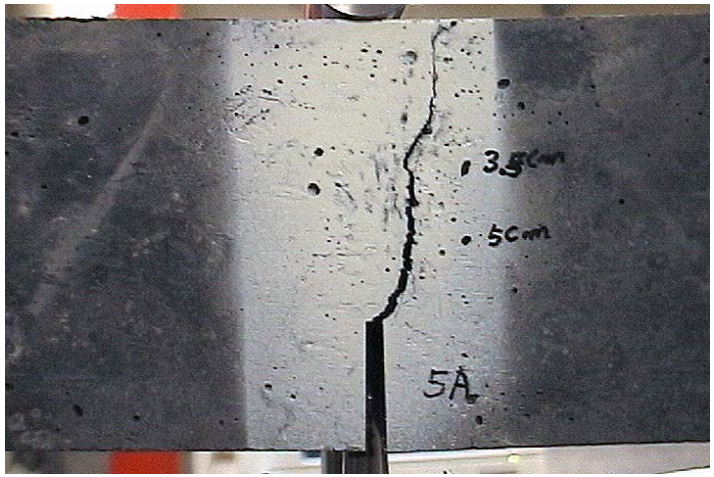
both material properties.

G_f = energy per unit of crack area

Various ways of measuring depending on the material.

Therefore, search for materials that have high resistance to cracks that are formed through loading or other lifecycle stresses.

Sometimes toughness is also referred to as the area under the stress-strain curve.

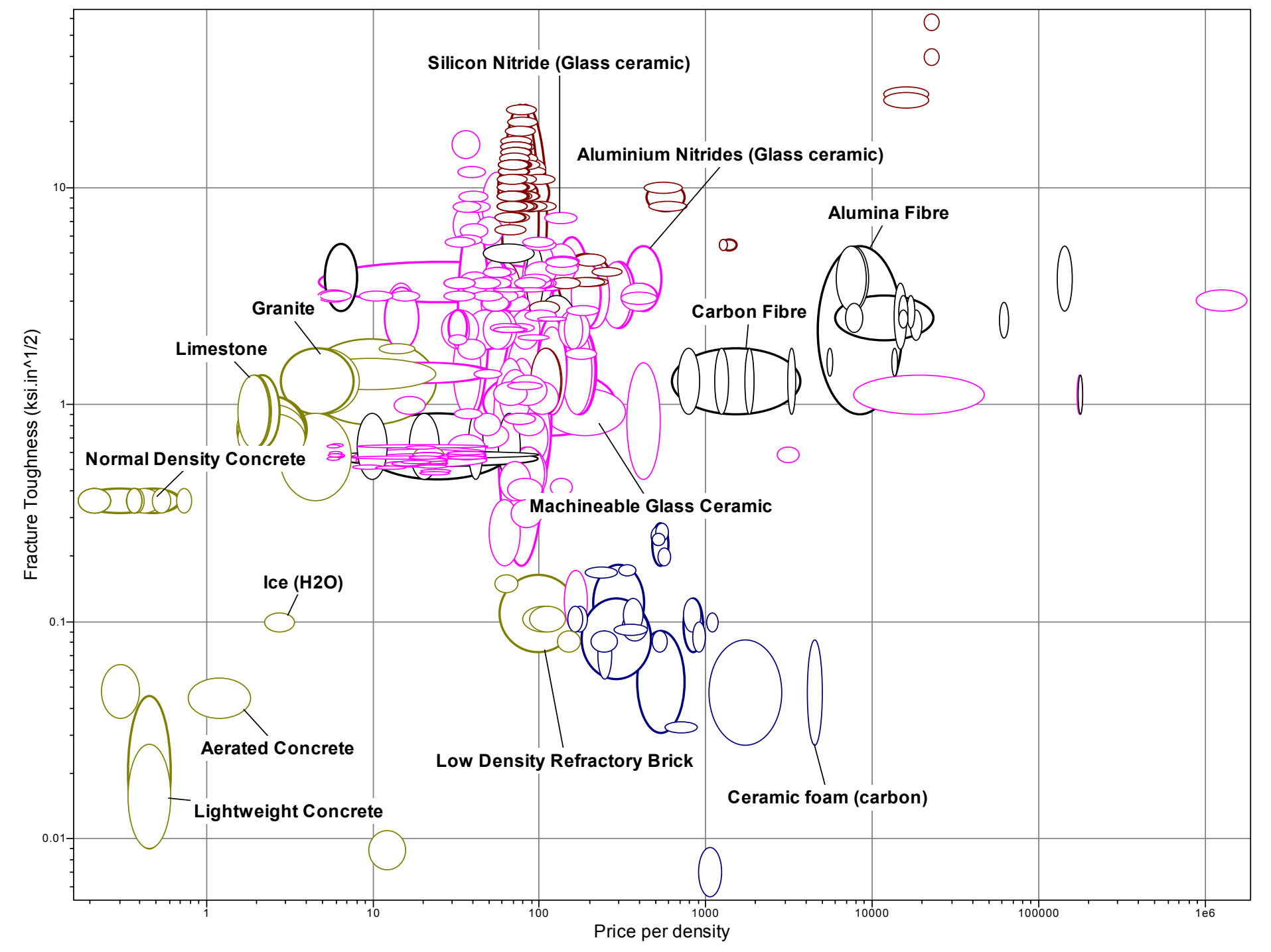


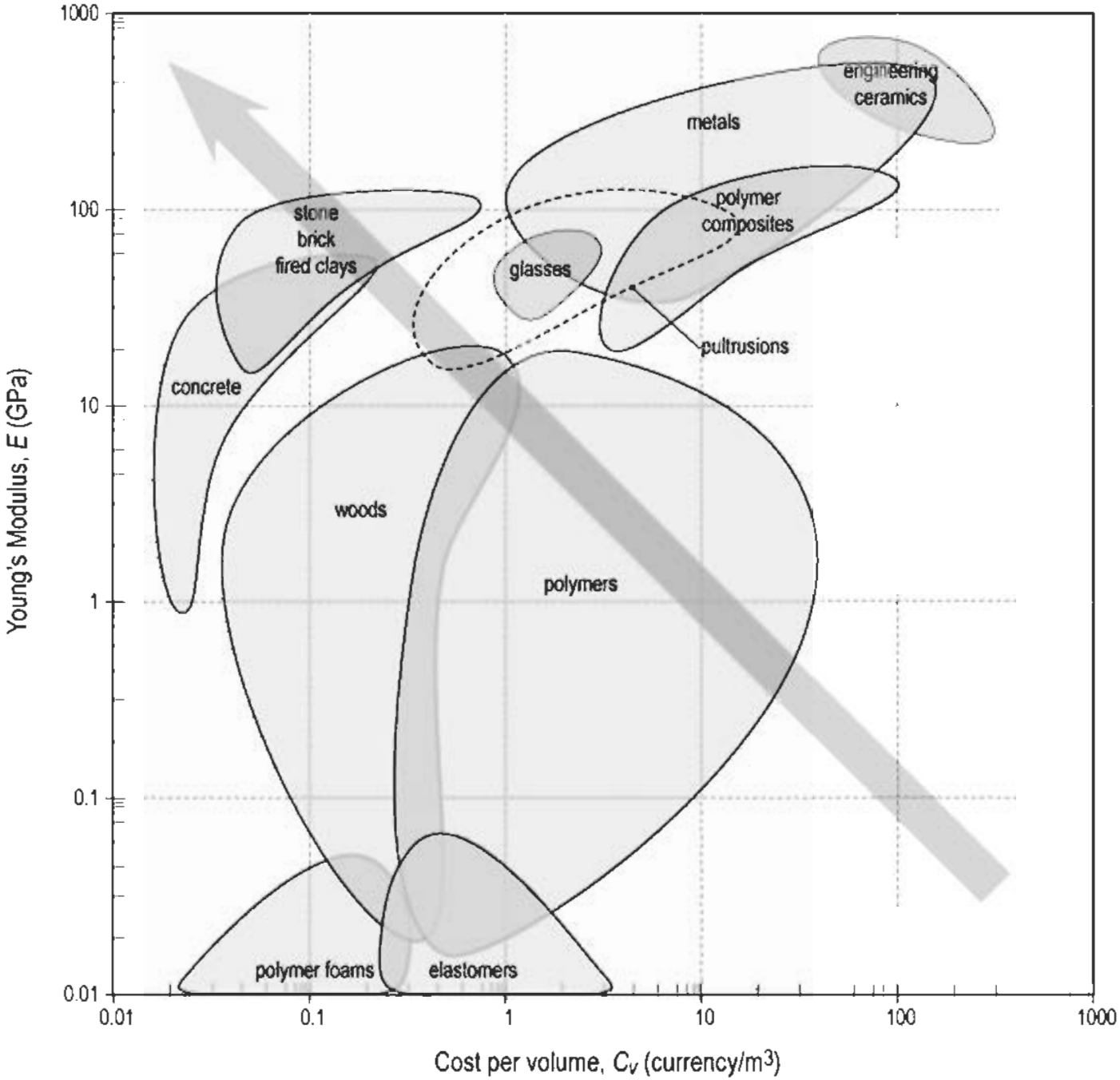
Material	G_f (kJ/m^2)	K_c (MN/m$^{3/2}$)
concrete, unreinforced	0.03	0.2
concrete, reinforced	0.2-4	10-15
soda glass	0.01	0.7-0.8
mild steel	100	140
medium carbon steel	13	51
high strength steel	15-118	50-154
cast irons	0.2-3	6-20
aluminum alloys	8-30	23-45
pure ductile metals Cu, Ni, Al	100 -1000	100-350
GFRP	10-100	20-60
CFRP	5-30	32-45
fiberglass	40-100	42-60
common woods ‖ to grain	0.5-2	0.5-1
granite	0.1	3
polypropylene	8	3
polyethylene (low density)	6-7	1
polyethylene (high density)	6-7	2

Figure X

Toughness, G_f, and fracture toughness, K_c, for a variety of materials.

Source: Ashby, Engineering Materials I


Silicon Nitride (Glass ceramic)
Aluminium Nitrides (Glass ceramic)
Alumina Fibre
Granite
Carbon Fibre
Limestone
Normal Density Concrete
Machineable Glass Ceramic
Ice (H2O)
Aerated Concrete
Low Density Refractory Brick
Ceramic foam (carbon)
Lightweight Concrete
Fracture Toughness (ksi.in^1/2)
10
1
0.1
0.01
1
10
100
1000
10000
100000
1e6
Price per density


1000
100
10
1
0.1
0.01
Young's Modulus, E (GPa)
0.01
0.1
1
10
100
1000
Cost per volume, C_v (currency/m^3)
engineering ceramics
metals
polymer composites
stone
brick
fired clays
glasses
pultrusions
concrete
woods
polymers
polymer foams
elastomers

Ecological Issues

Concrete production contributes 8% of world's total CO_2 emissions.

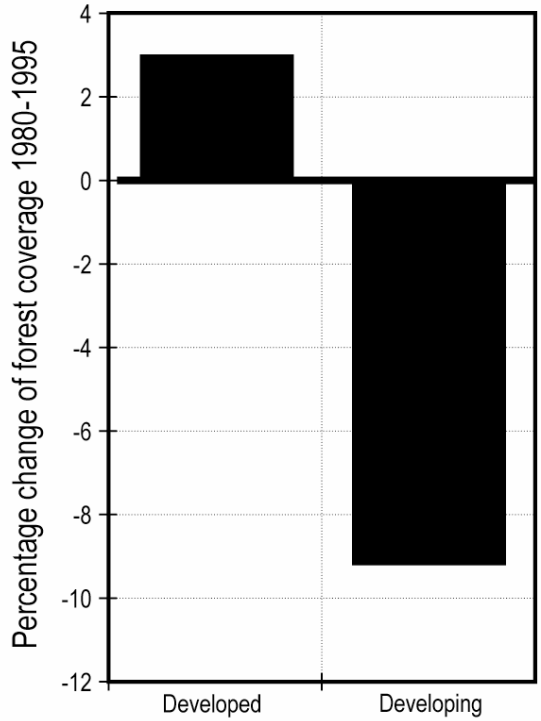
Research in building materials for the developing world is a moral obligation.

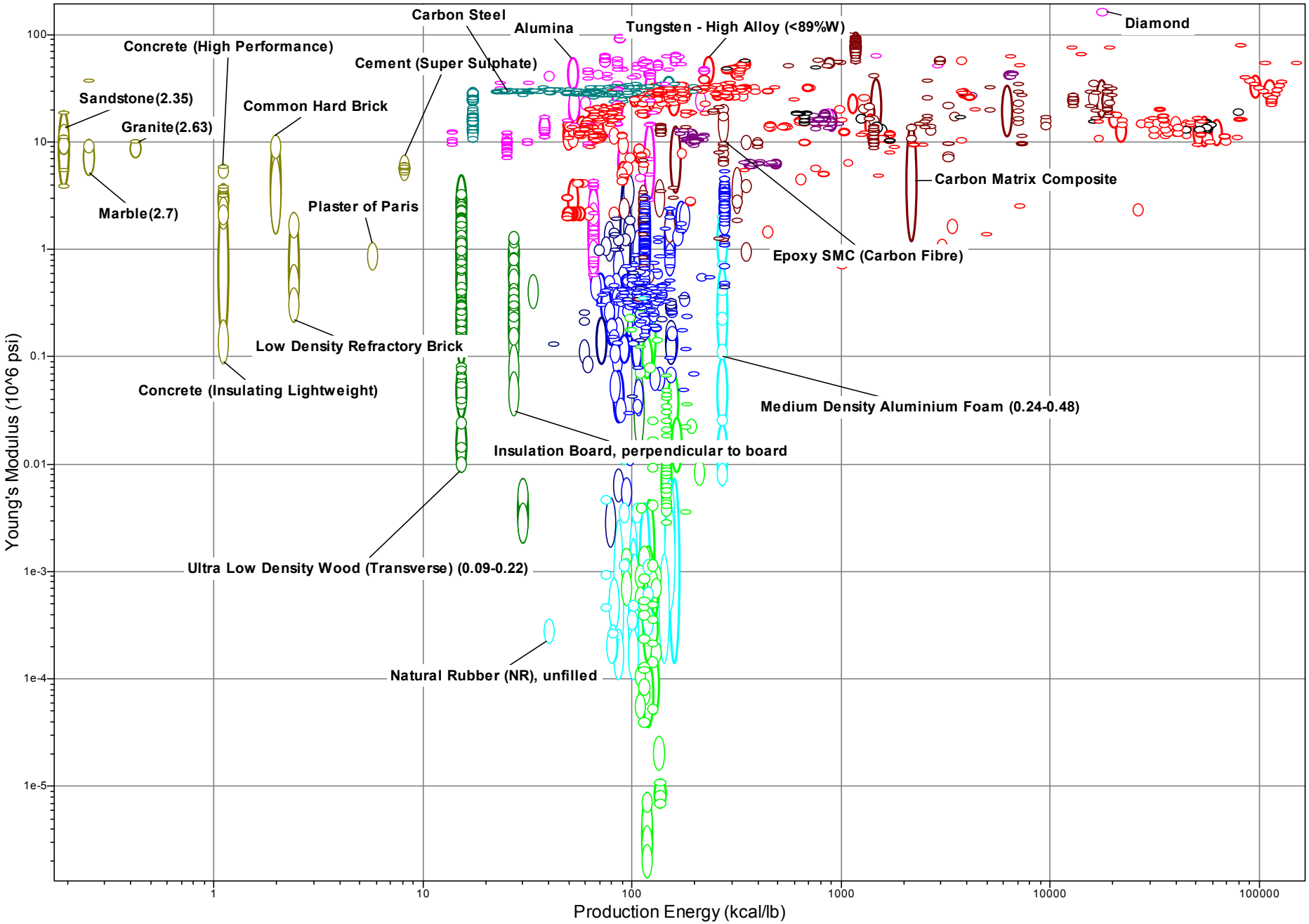
Issues

- **Poverty allevation**
- **Safety**
- **Health (IAQ, toxicity)**
- **Resource Management**

Cultural Issues

- **Form (resonance with place)**
- **Process (acknowledges local skill set)**
- **Material (regional resources)**

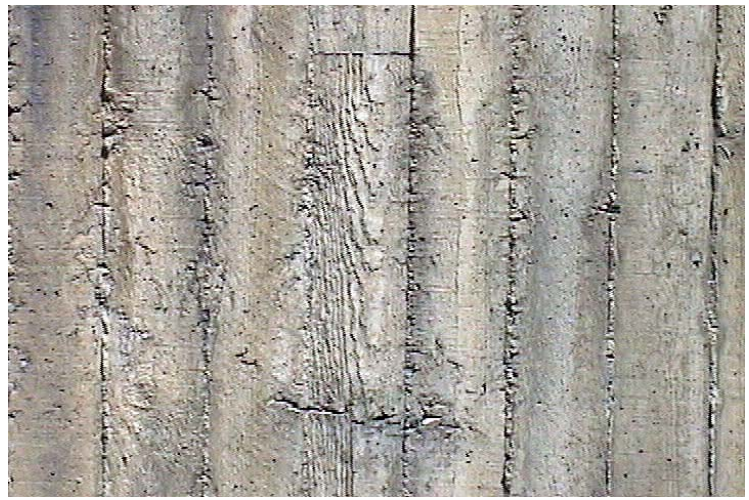



Young's Modulus (10^6 psi)
Production Energy (kcal/lb)
100
10
1
0.1
0.01
1e-3
1e-4
1e-5
1
10
100
1000
10000
100000
Carbon Steel
Alumina
Tungsten - High Alloy (<89%W)
Diamond
Concrete (High Performance)
Cement (Super Sulphate)
Sandstone(2.35)
Common Hard Brick
Granite(2.63)
Carbon Matrix Composite
Marble(2.7)
Plaster of Paris
Epoxy SMC (Carbon Fibre)
Low Density Refractory Brick
Concrete (Insulating Lightweight)
Medium Density Aluminium Foam (0.24-0.48)
Insulation Board, perpendicular to board
Ultra Low Density Wood (Transverse) (0.09-0.22)
Natural Rubber (NR), unfilled

Concrete

Need for durable reinforcing and water impermeable concrete matrix

Especially for freeze/thaw climates



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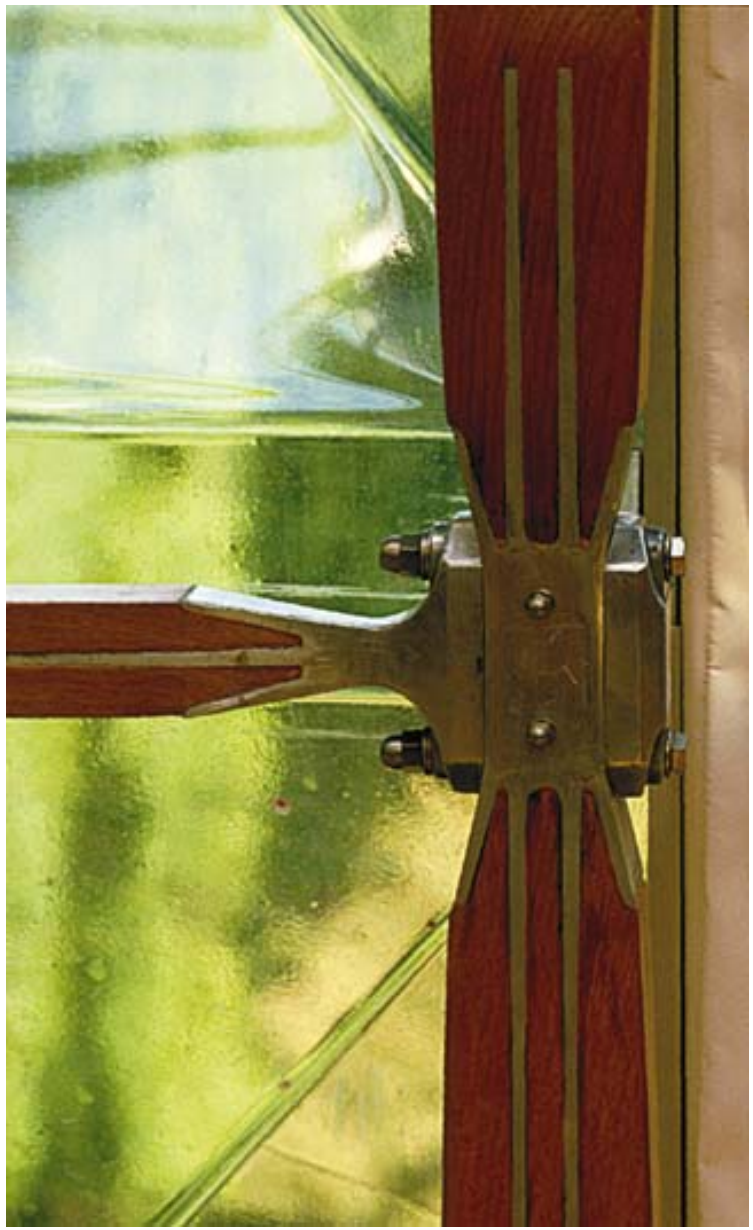


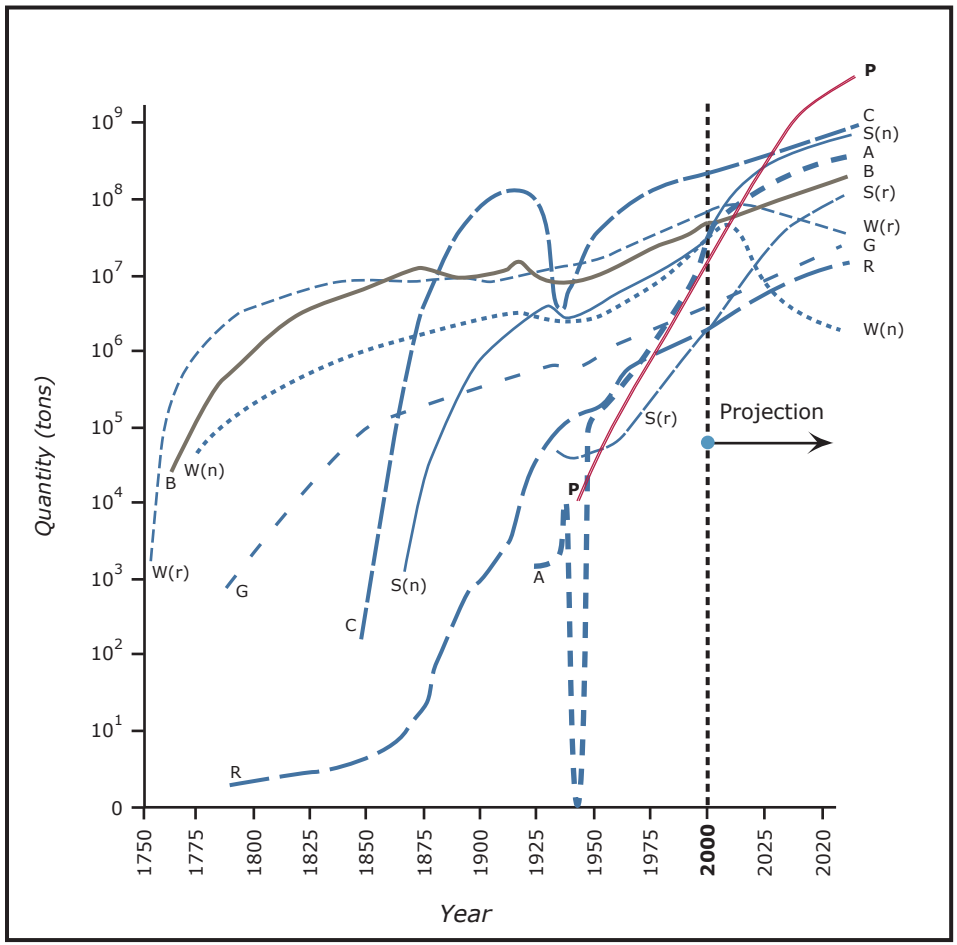


Image by MIT OCW.

US materials use in construction

A:	aluminum	R:	copper
B:	brick	S(r):	steel
C:	concrete	S(n):	steel, non-residential
G:	glass	W(r):	wood, residential
P:	polymers	W(n):	wood, non-residential

Assembled with data from the following sources:

Moavenzadeh: pg. 517.
USGS Reports
US Minerals Reports
NAHB
Others

Common abbreviations

Polymers (homopolymers)

CA	cellulose acetate
CN	cellulose nitrate
CSF	casein-formaldehyde
EP	epoxide
PA	polyamide
PA66	polyamide 66
PAN	poly(acrylonitrile)
PBA	poly(butylacrylate)
PC	polycarbonate
PCTFE	poly(chlorotrifluoroethylene)
PE	polyethylene
PE-HD	high-density polyethylene
PE-LD	low-density polyethylene
PEEK	poly(etheretherketone)
PET	poly(ethyleneterephthalate)
PF	phenol-formaldehyde
PI	polyimide
PIB	polyisobutylene
PIR	polyisocyanurate
PMMA	poly(methylmethacrylate)
PP	polypropylene
PS	polystyrene
PSU	polysulfone
PTFE	poly(tetrafluoroethylene)
PU	polyurethane
PVB	poly(vinylbutyral)
PVC	poly(vinylchloride)
PVC-P	plasticized poly(vinylchloride)
PVC-U	unplasticized poly(vinylchloride)
SI	silicone
SP	saturated polyester
UF	urea-formaldehyde
UP	unsaturated polyester
VF	vulcanized rubber

Copolymers

ABS	acrylonitrile/butadiene/styrene
EPDM	ethylene-propylenediene
ETFE	ethylene/tetrafluoroethylene
SB	styrene butadiene

Commercial introduction of important polymers in the US

1910	-	Rayon
1924	-	Acetate
1930	-	Rubber
1939	-	Nylon
1939	-	Vinyon
1941	-	Saran
1946	-	Metallic
1949	-	Modacrylic
1949	-	Olefin
1950	-	Acrylic
1953	-	Polyester
1959	-	Spandex
1961	-	Aramid
1983	-	PBI
1983	-	Sulfar

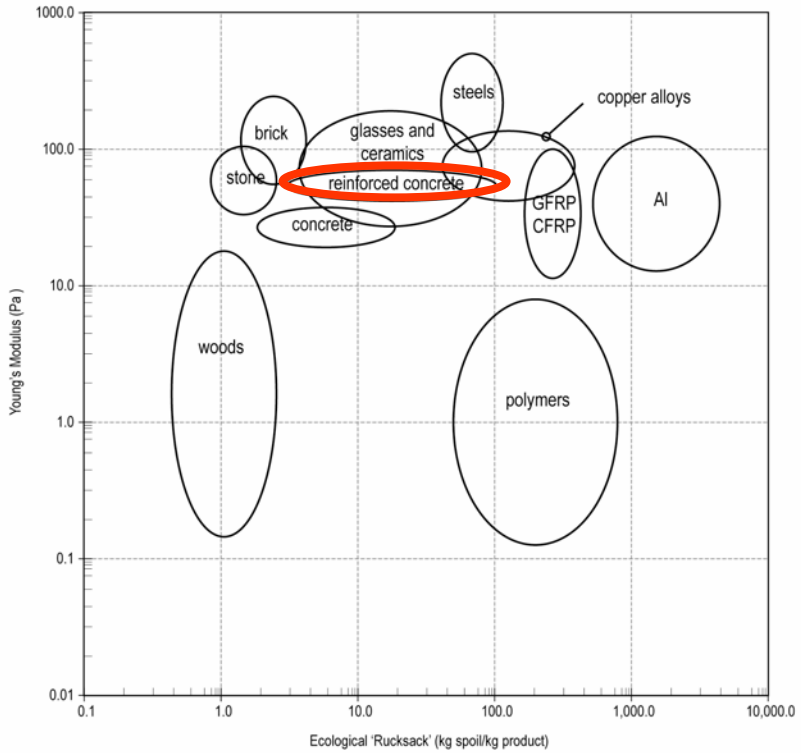
Concrete

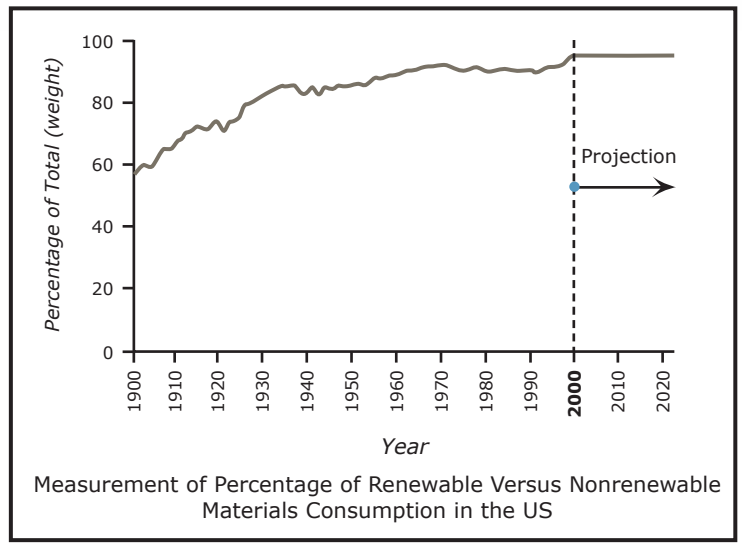
Dematerialization: a decrease in the material input per unit service

Is occurring in certain industrial sectors but 'ecological rucksack' needs to be accounted for

Substitution: substituting concrete best in situations in which safety is at high risk of compromise

Technology transfer: best employed in situations in which to lengthen lives of existing building stock (such as infrastructure refurbishment using carbon/epoxy reinforcing)





Measurement of Percentage of Renewable Versus Nonrenewable Materials Consumption in the US

Image by MIT OCW.

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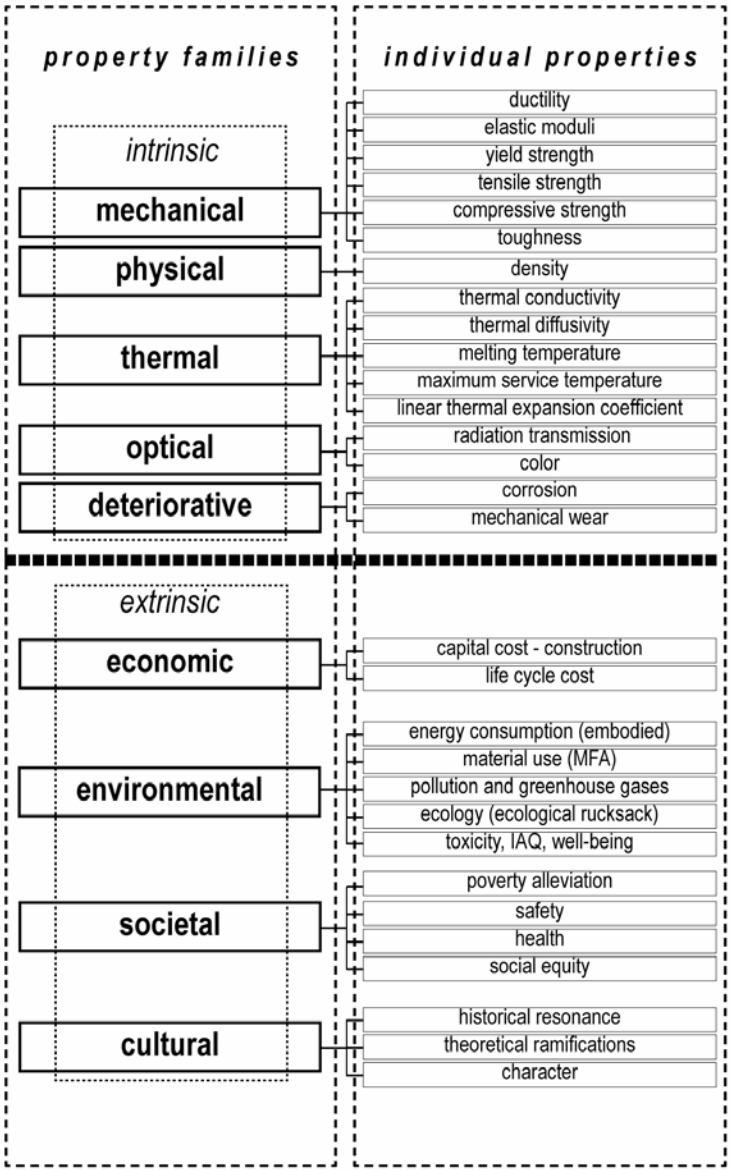
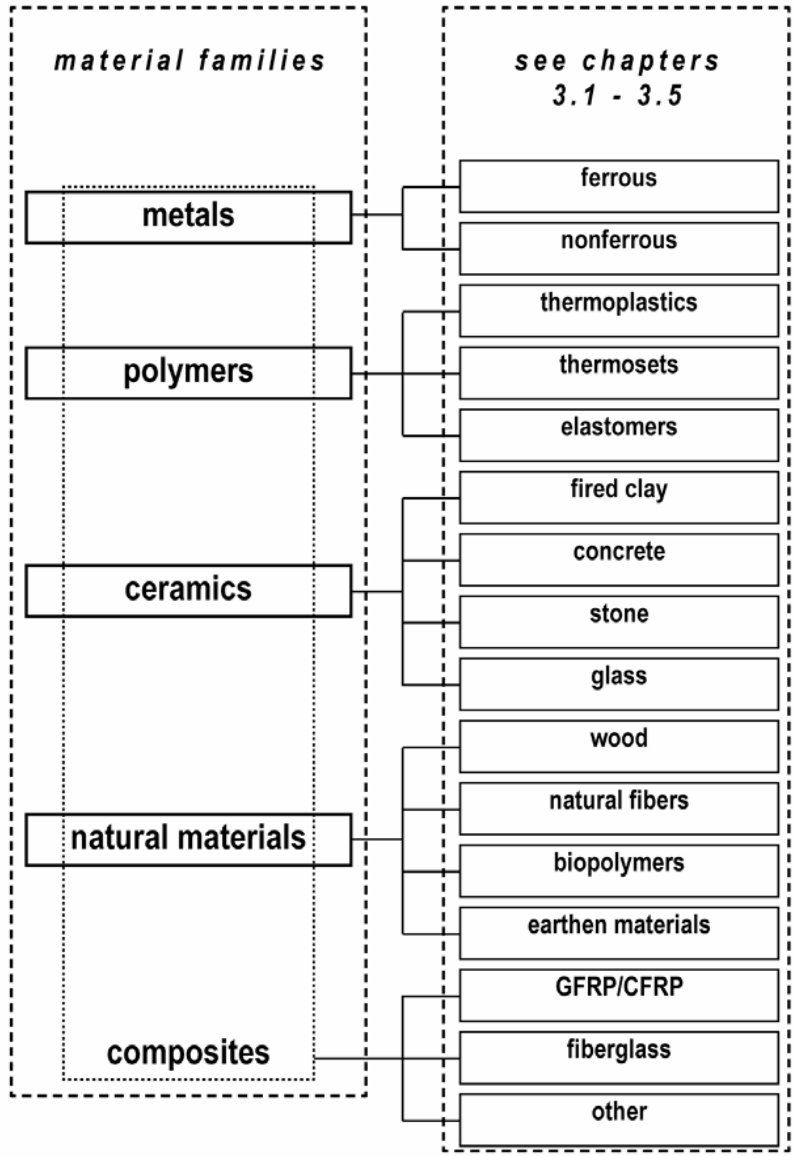
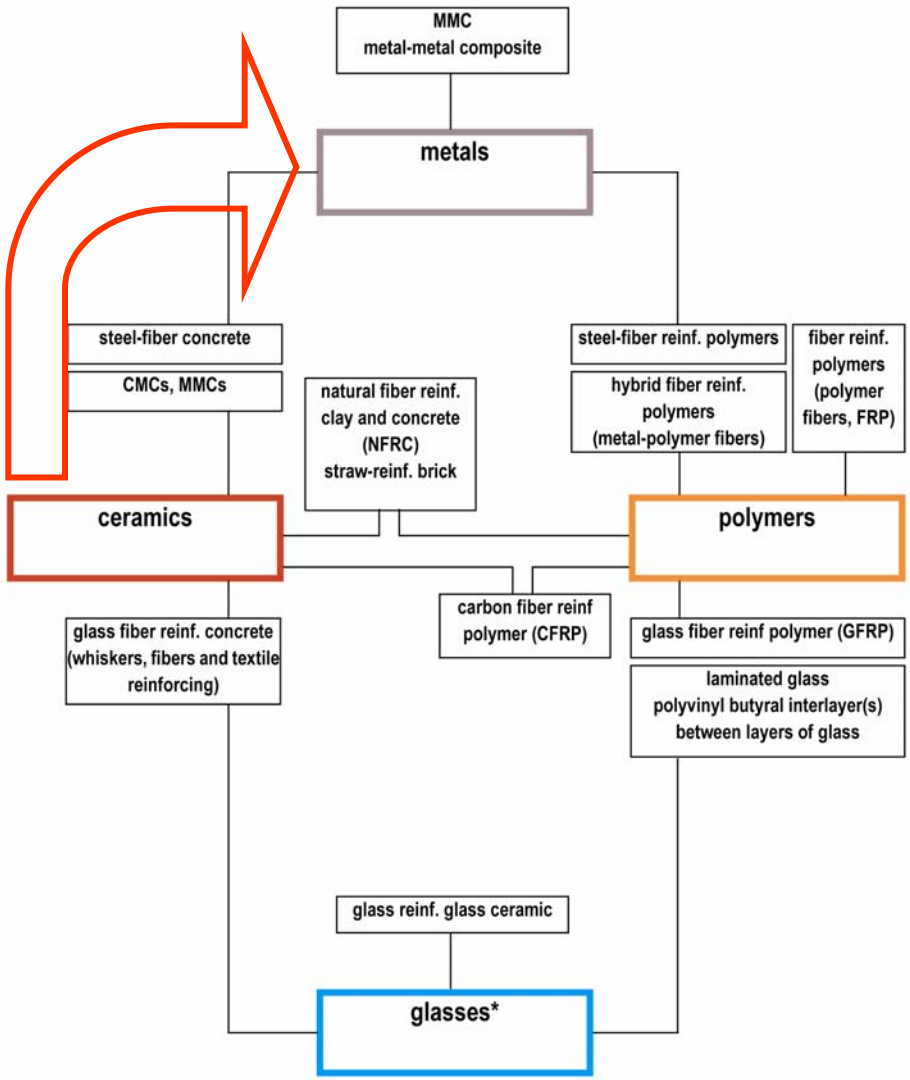
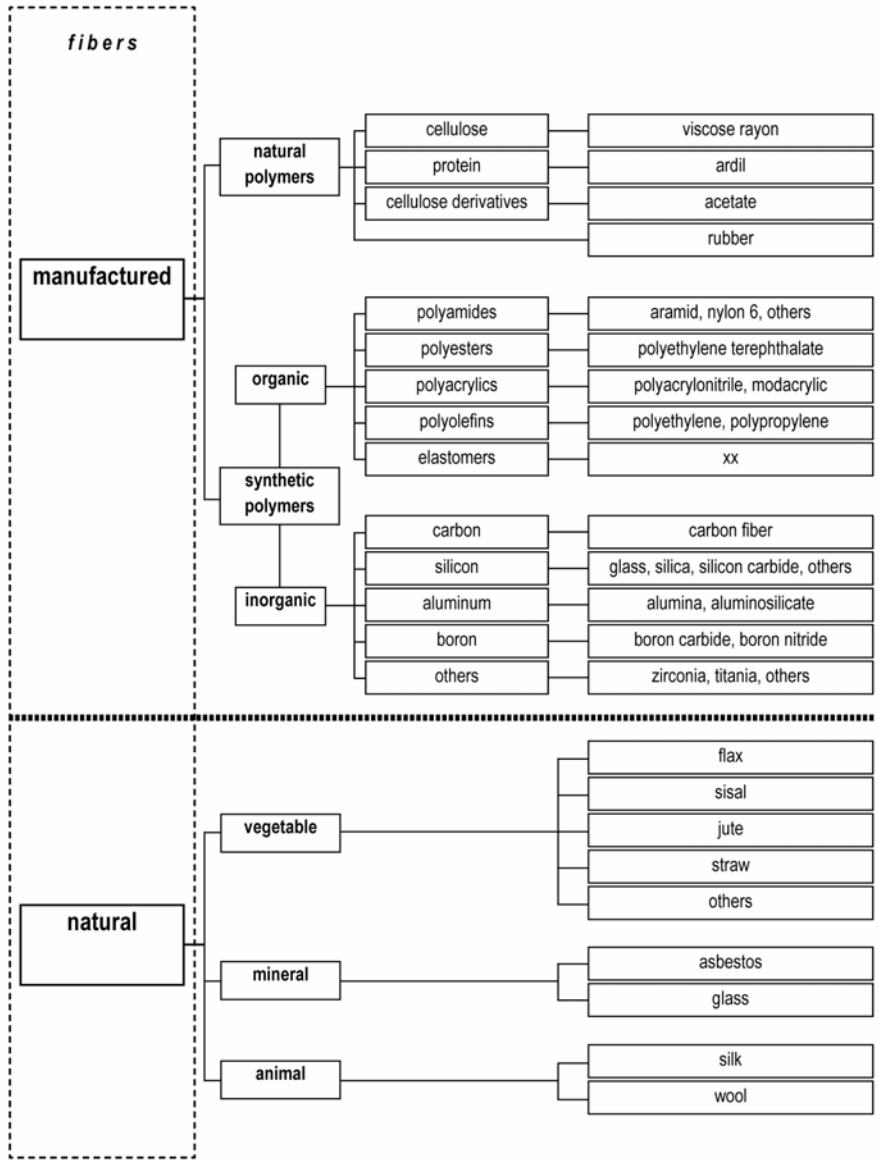
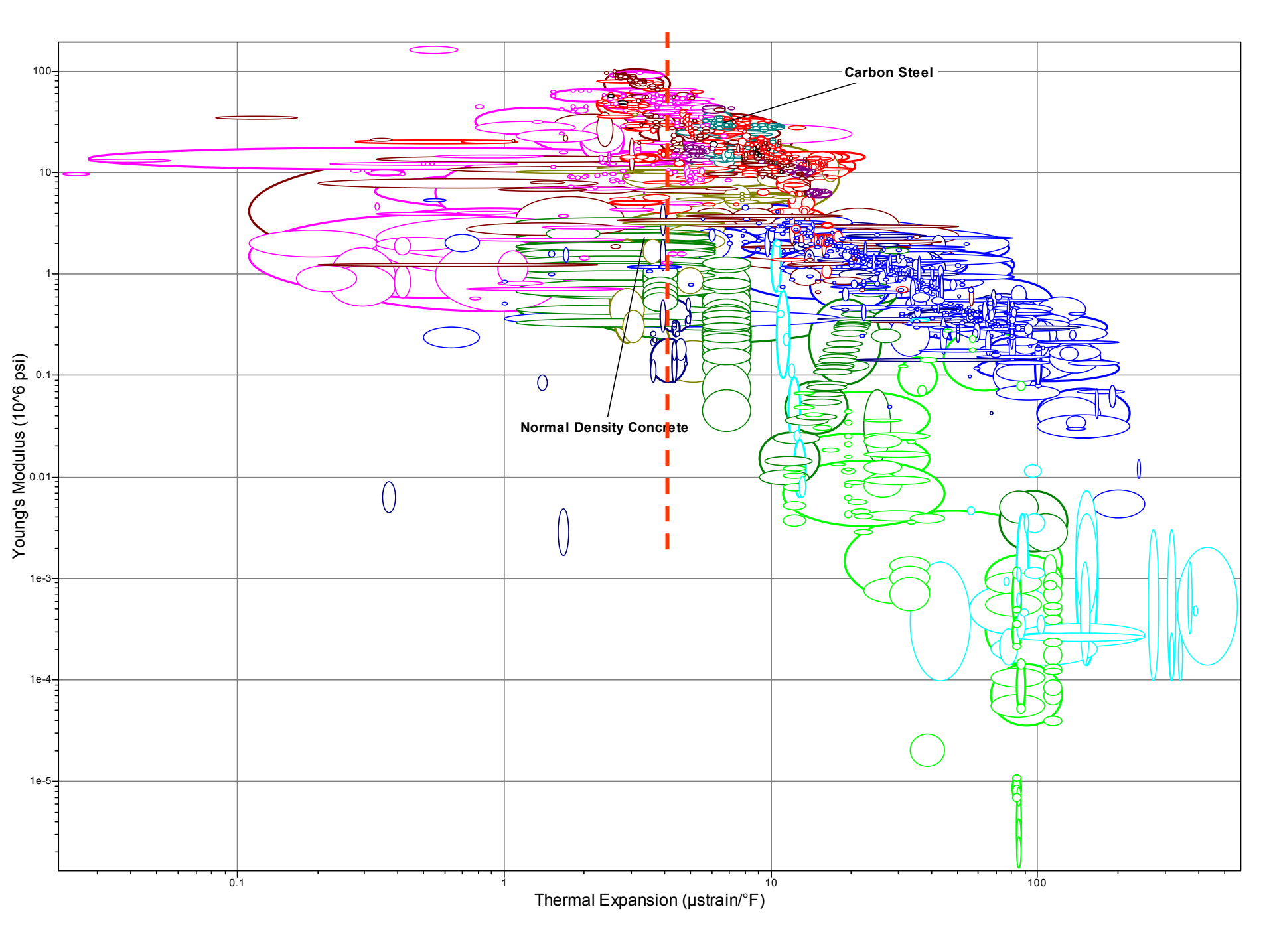

property families
individual properties
intrinsic
mechanical
physical
thermal
optical
deteriorative
ductility
elastic moduli
yield strength
tensile strength
compressive strength
toughness
density
thermal conductivity
thermal diffusivity
melting temperature
maximum service temperature
linear thermal expansion coefficient
radiation transmission
color
corrosion
mechanical wear
extrinsic
economic
environmental
societal
cultural
capital cost - construction
life cycle cost
energy consumption (embodied)
material use (MFA)
pollution and greenhouse gases
ecology (ecological rucksack)
toxicity, IAQ, well-being
poverty alleviation
safety
health
social equity
historical resonance
theoretical ramifications
character


material families
see chapters
3.1 - 3.5
metals
polymers
ceramics
natural materials
composites
ferrous
nonferrous
thermoplastics
thermosets
elastomers
fired clay
concrete
stone
glass
wood
natural fibers
biopolymers
earthen materials
GFRP/CFRP
fiberglass
other


MMC
metal-metal composite
metals
steel-fiber concrete
CMCs, MMCs
steel-fiber reinf. polymers
hybrid fiber reinf. polymers (metal-polymer fibers)
fiber reinf. polymers (polymer fibers, FRP)
natural fiber reinf. clay and concrete (NFRC) straw-reinf. brick
ceramics
polymers
carbon fiber reinf polymer (CFRP)
glass fiber reinf polymer (GFRP)
glass fiber reinf. concrete (whiskers, fibers and textile reinforcing)
laminated glass polyvinyl butyral interlayer(s) between layers of glass
glass reinf. glass ceramic
glasses*
*Glasees have been separately represented here because of the importance of glass whiskers, fibers and textiles in the reinforcement of various types of composites.


fibers
manufactured
natural polymers
cellulose
viscose rayon
protein
ardil
cellulose derivatives
acetate
rubber
organic
polyamides
aramid, nylon 6, others
polyesters
polyethylene terephthalate
polyacrylics
polyacrylonitrile, modacrylic
polyolefins
polyethylene, polypropylene
elastomers
xx
synthetic polymers
inorganic
carbon
carbon fiber
silicon
glass, silica, silicon carbide, others
aluminum
alumina, aluminosilicate
boron
boron carbide, boron nitride
others
zirconia, titania, others
natural
vegetable
flax
sisal
jute
straw
others
mineral
asbestos
glass
animal
silk
wool


Carbon Steel
Normal Density Concrete
Young's Modulus (10^6 psi)
100
10
1
0.1
0.01
1e-3
1e-4
1e-5
0.1
1
10
100
Thermal Expansion (µstrain/°F)

ceramics

- *Glass ceramics*

Machineable, good fracture toughness

- *Very HPC (Ductal)*

Ductile concrete

- *Ceramic foams*

Lightweight, structural material

- *New laminated glasses*

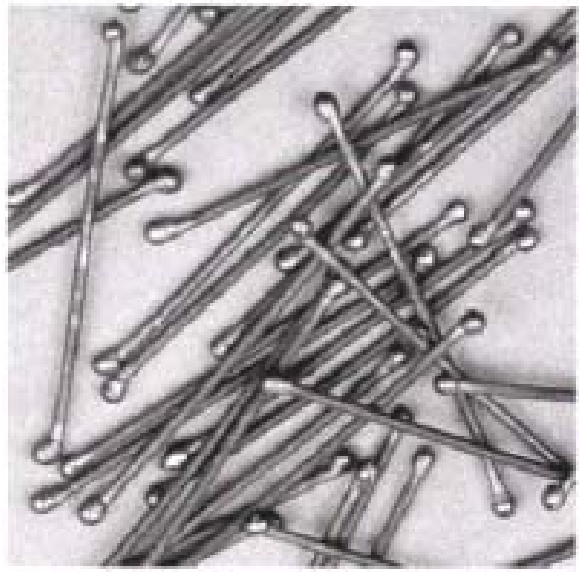
Laminated glass (Dupont SGP interlayer)

Ductile concrete

Steel whisker reinforcement

Increased toughess

Increased water impermeability (few micropores)



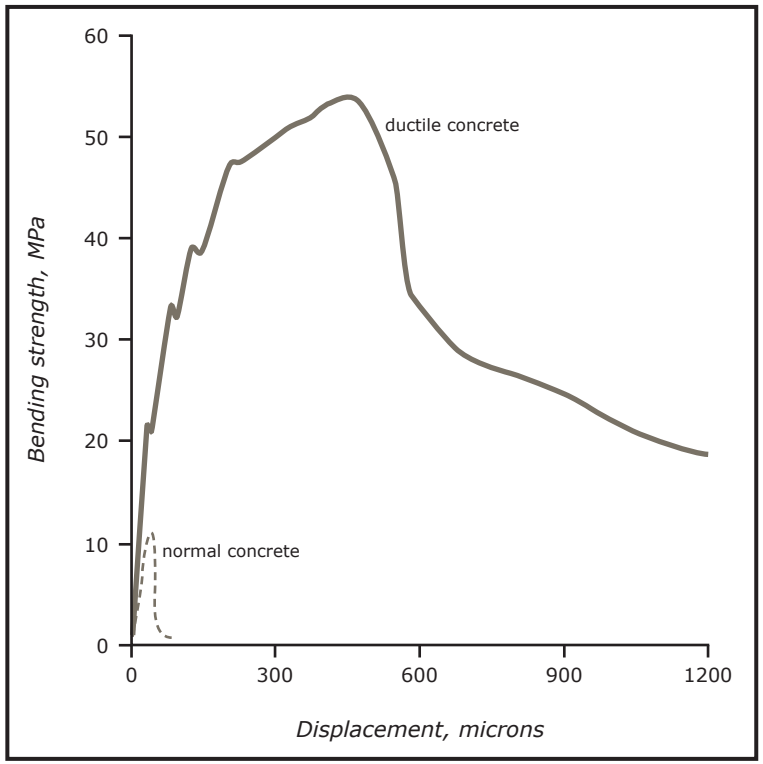


Image by MIT OCW.