

# **AC 2009-1002: SELECTION OF MATERIALS FOR CONSTRUCTION**

**Somnath Chattopadhyay, Pennsylvania State University**

# **Selection of Materials for Construction**

## **ABSTRACT**

A systematic way of selecting materials for construction of buildings has been presented. This involves a study of relevant physical and mechanical properties, and how the deflections and stresses are related to the applied loads. The strength and stiffness characteristics are then used to determine the composite parameters based on mechanical properties and these are then input to a computerized database to facilitate the selection process. It is shown that the materials that have been traditionally used for construction are indeed the optimum materials based on the computed mechanical composite parameters and cost. A few of the unfamiliar materials used in modern construction have been mentioned and the associated design philosophy has been outlined. The computerized database is CES EduPack 2008 and this activity forms a module in a course on Strength of Materials, in the section on material selection.

## **INTRODUCTION**

Selection of materials and manufacturing processes are important activities essential for structural design. Ashby (2005) was the first to demonstrate that a wide range of material properties could be collected and plotted on the same curve, where two individual material variables appear on the abscissa and the ordinate. Using this concept Granta Design (2008) has developed a software package CES EduPack which includes a wide range of data on materials, manufacturing processes and shapes for over 3000 engineering materials. The objective of the present study is exploring the use of the software CES EduPack in the selection of material for building construction. The task of the selection process is that of matching the choice of material to the requirements of design.

The traditional materials for buildings are metallic and non-metallic. The most widely used metallic material is plain carbon steel, because it compares favorably with other materials in terms of cost per unit weight, cost per unit volume as well cost per unit of strength. The versatility of steel, and its availability in a wide range of structural forms with reproducible properties, is also among the attractive characteristics that make it a popular construction material. Non metallic construction materials include primarily stone, brick, concrete and wood. These materials have complex composite microstructures that are not easily characterized but nonetheless affect their behavior in service. Stone is largely inhomogeneous and properties of two samples can vary considerably. This feature along with its low impact strength requires a high factor of safety for design. It has good compressive strength to provide resistance against crushing.

Brick, a clay product is used for building, paving and as firebricks for fireplaces. The essential requirements for bricks in buildings are sufficient strength in crushing and bending and a pleasing appearance if it is to be used as a facing brick. Concrete is a mixture of crushed stone, gravel or similar inert material, with mortar. The cement is the most expensive ingredient in concrete. By properly proportioning the cement, water and aggregates it is often possible to affect considerable savings and still produce concrete that fulfills the requirement of durability, strength, and abrasion resistance and water tightness. Concrete is much stronger in compression than in tension. Tensile stresses when required are carried by the embedded reinforced steel bars. The typical examples are beams, footings, columns, roof slabs, and retaining walls. Wood, like stone has a very long history of use. Wood is cheaper, lighter and more easily shaped than any other construction material. However, it is subject to decay and attack by certain insects and is also flammable. The structure of wood is anisotropic and this is reflected in its physical and mechanical properties which vary along and across the grains (Farak, 2008).

The materials that are currently used in buildings are quite numerous and come in five major families (Ashby et al, 2007):

- Composites
- Concrete, stone, ceramic, brick, glass, bitumen
- Foams, fabrics and fibers
- Metals, ferrous and non-ferrous
- Polymers: elastomers, thermoplastics, thermo sets
- Wood, plywood, glulam, bamboo, straw and cork

The ones already mentioned, namely, steel, stone, brick, concrete and wood fall in the families of metals, ceramics and wood.

## **INFRASTRUCTURE**

Following Ashby et al, 2007 a building infrastructure is viewed as four semi-autonomous systems: (a) superstructure, (b) exterior envelope, (c) interior systems, and (d) building services. The superstructure transmits vertical loads to the foundation, resists the horizontal loads from wind, tornadoes and earthquakes, and provides long term service.

The exterior envelope controls heat transfer in conduction and radiation and the flow of air and water, and also provides acoustic separation. The interior systems delineate the habitable space and provide distinct climate and acoustic zones with consideration for health and safety of the occupants. Finally the building services provide ventilation, heating, lighting and water, data transmission and waste removal capabilities.

Based on the functions characterized by the above four systems, the materials are chosen. For the superstructure, the materials are concrete, cast iron and steel, timber, brick, clay-based ceramics and stone. For the exterior envelope the materials are glass, aluminum, silicone, neoprene, epoxies, insulating fibers and foams, bitumen and fiberglass.

For the interior systems, the materials are wood particle board, polymer reinforced plaster, resins and other polymers, fabrics, natural fibers, tiles, terracotta and brick. Finally for the building services a number of different materials are used: galvanized sheet metals, adhesives/tapes, polymer electrical insulators, copper and PVC piping, glass optical fiber cables along with heat exchange materials.

The materials reflect a wide range of properties which are of importance relative to the functions for which they are employed. For the superstructure, the mechanical properties of interest are strength, toughness, modulus, hardness, and mechanical loss coefficient. For the exterior envelope, the relevant properties are mechanical and thermal including coefficient of thermal expansion, thermal conductivity, flammability and hygro-thermal such as water and air permeability, along with optical and acoustical properties. Similar considerations apply for the interior systems and building services. In terms of the superstructure, the predominant properties are the mechanical properties in bending which will be the primary focus of this paper. The other properties that will be mentioned are the thermal resistivity, and thermal conductivity and its association with embodied energy.

## BEAMS AND BENDING

With our focus on the superstructure, we recognize that the structural elements must be strong, stiff and economical. The strength is desirable so that the structure does not collapse. The stiffness is desirable so that the building does not sway too much under wind, tornado and earthquake loads. We also want it to be cheap because so much material is being used and the cost adds up.

Beams of one kind or the other are used in the buildings. The most important ones are the floor joists which are loaded primarily in bending. If we consider a beam of rectangular cross section of width 'b' and height 'd', the second moment of area of the cross section, I is:

$$I = \frac{bd^3}{12} \quad (1)$$

For an applied bending moment M, the bending stress  $\sigma$  on the outer fiber located at a distance  $y_m$  from the neutral axis of the beam (which is neither in tension or compression) is given by,

$$\sigma = \frac{My_m}{I} = \frac{M}{S} \quad (2)$$

Where  $S = I/y_m$ , which is also known as the sectional modulus of the cross section.

If we denote the cross-sectional area of the beam as  $A$  and the aspect ratio by  $\alpha$ , then we have,

$$A = bd \quad (3a)$$

$$\alpha = b/d \quad (3b)$$

We also have,

$$y_m = d/2 \quad (3c)$$

The quantity  $S = I/y_m$  the section modulus can be written in terms of the quantities  $A$  and  $\alpha$  as:

$$S = \frac{I}{y_m} = \frac{A^{3/2}}{6\alpha^{1/2}} \quad (4)$$

Now we assume a beam of length  $L$  simply supported at the two ends and acted on by a central load  $F$ . Then the deflection  $\delta$  at the mid span of the beam is given by,

$$\delta = \frac{FL^3}{48EI} \quad (5)$$

And the maximum bending moment  $M$  also occurring at the mid span of the beam is given by,

$$M = \frac{FL}{4} \quad (6)$$

The bending stress  $\sigma$  on the outer fiber can now be expressed using equations (2) and (4) as:

$$\sigma = \frac{1.5FL\alpha^{1/2}}{A^{3/2}} \quad (7)$$

Also the force  $F$  can now be expressed in terms of the bending stress  $\sigma$  as;

$$F = \frac{2A^{3/2}\sigma}{3L\alpha^{1/2}} \quad (8)$$

## MAXIMUM STIFFNESS AT MINIMUM COST

If we introduce the constraint on stiffness in such a way that the beam does not deflect more than what is given by equation (5), then the stiffness  $S$  is given by the inequality,

$$S = \frac{F}{\delta} \geq \frac{48EI}{L^3} \quad (9)$$

Substituting the value of  $I$ , the above inequality becomes,

$$S \geq \frac{4A^2E}{\alpha L^3} \quad (10)$$

This upon rearrangement leads to an inequality for the area  $A$  as,

$$A \leq \left[ \frac{\alpha L^3 S}{4E} \right]^{1/2} \quad (11)$$

If the cost of the material per unit mass is  $C_m$ , and the material density is  $\rho$  then  $C$ , the cost of material for the beam of mass  $m$  is given by,

$$C = \rho A L C_m \quad (12)$$

Using equation (10) we get the inequality for cost  $C$  as,

$$C \leq \rho L C_m \left[ \frac{\alpha L^3 S}{4E} \right]^{1/2} \quad (13)$$

For a beam of fixed length  $L$  and aspect ratio  $\alpha$ , for minimum cost, the index  $M_1$  to be maximized, from the above equation is given by,

$$M_1 = \frac{E^{1/2}}{\rho C_m} \quad (14)$$

## MAXIMUM STRENGTH AT MINIMUM COST

For this purpose we use equation (8) to obtain the area  $A$  as,

$$A = \left[ \frac{3L\alpha^{1/2}F_f}{2\sigma_f} \right]^{2/3} \quad (15)$$

Note that we have used the subscript  $f$  to indicate the failure load and failure stress as  $F_f$  and  $\sigma_f$  respectively in equation (15)

Using the cost equation (12) we have, for minimum cost,

$$C \leq \rho L C_m \left[ \frac{3L\alpha^{1/2}F_f}{2\sigma_f} \right]^{2/3} \quad (16)$$

For a beam of fixed length  $L$ , aspect ratio  $\alpha$ , and failure stress  $F_f$ , for minimum cost, the index  $M_2$  to be maximized, from the above equation is given by,

$$M_2 = \frac{\sigma_f^{2/3}}{\rho C_m} \quad (17)$$

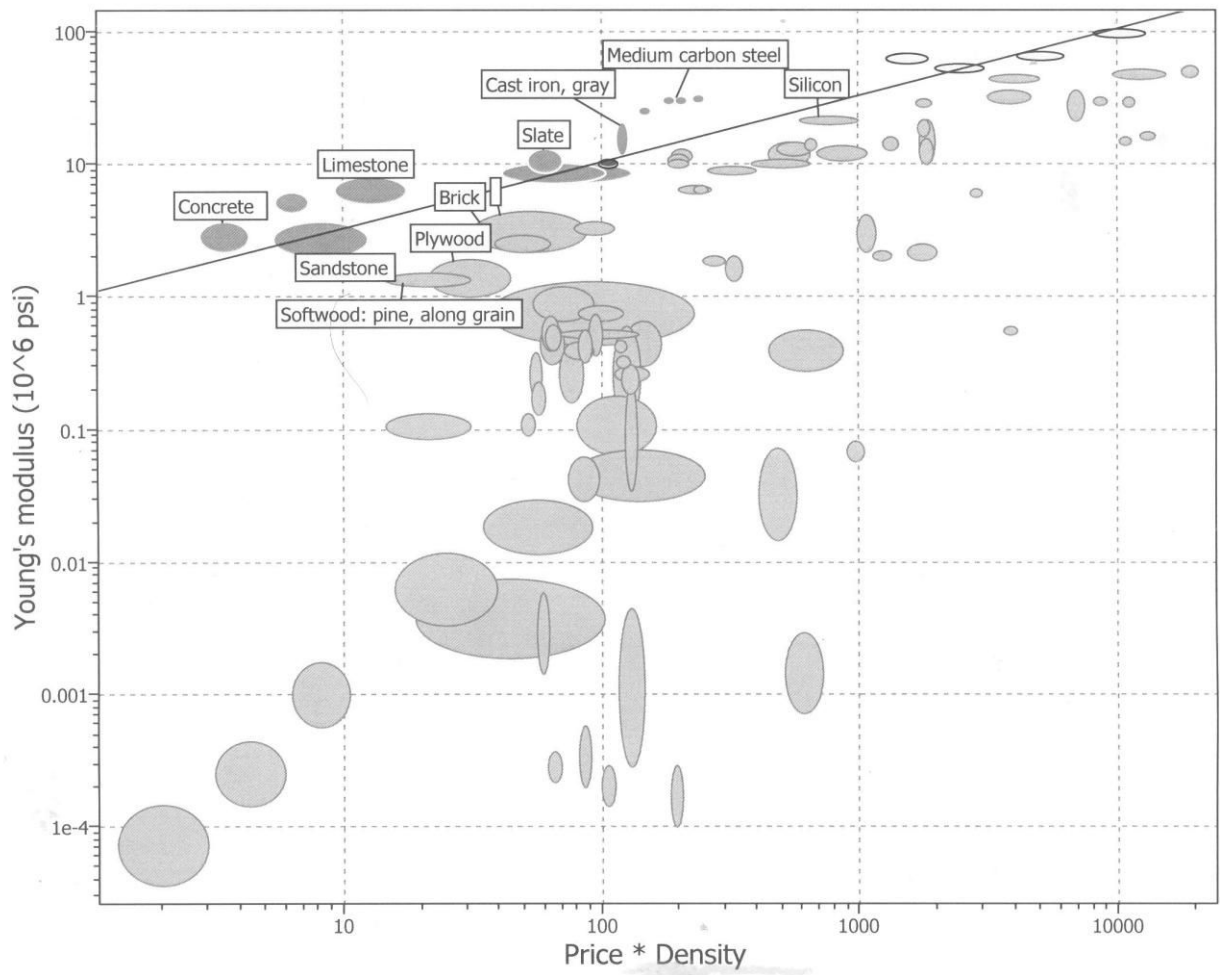
## MATERIAL SELECTION PROCESS

From the standpoint of stiffness, strength, and cost the material selection should be based on maximizing the parameters  $M_1$  and  $M_2$  obtained from equations (14) and (17) respectively.

The material selection software CES Edupack 2008 was used. The level 2 version was used and the following plots were obtained.

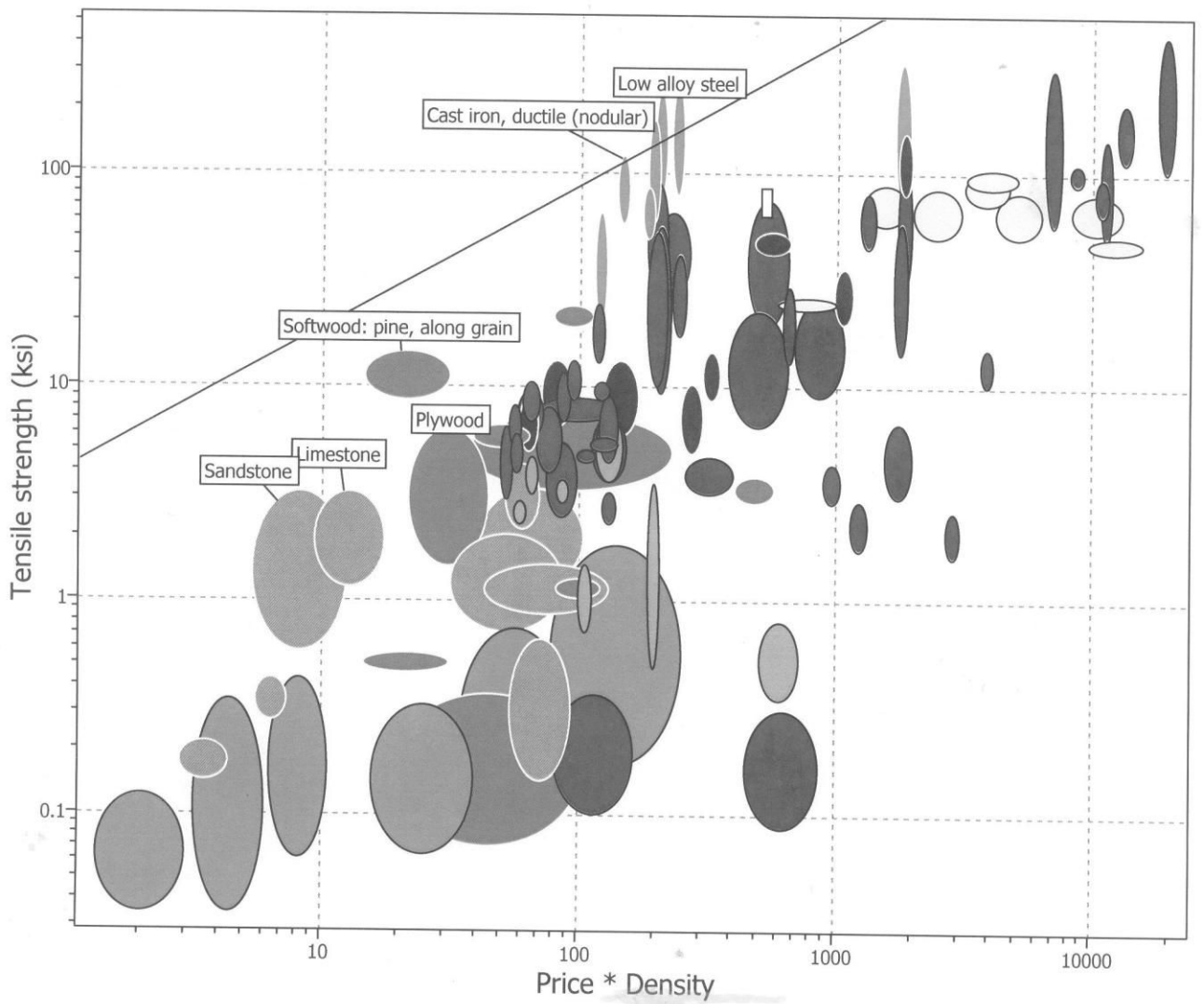
- (a) Young's modulus versus the product of density and unit material cost,
- (b) Tensile strength versus the product of density times and unit material cost.

In order to characterize materials for optimum stiffness and cost, the parameter  $M_1$  needs to be maximized. Accordingly a line with a slope of  $1/2$  was used in Figure 1 and the maximum y-intercept was used (in the log-log scale). The typical materials that fit the category were concrete, iron and steel, and wood.



**Figure 1 Material Selection based on structural stiffness and cost**





**Figure 2 Material Selection based on material strength and cost**

In order to characterize materials for optimum strength and cost, the parameter  $M_2$  needs to be maximized. Accordingly a line with a slope of 2/3 was used in Figure 2 and the maximum y-intercept was used (in the log-log scale). The typical materials that fit the category were steel and wood. It is interesting to discover that the selected materials are the ones with which the buildings are constructed now and have been constructed in the past.

## **OTHER MATERIALS**

To explore optimum materials for other functions of the building system the software was further explored, and the results are shown in Figures 3 and 4.

Figure 3 shows properties Thermal Resistivity (inverse of thermal conductivity) and density. Good insulators such as low-density foams lie at the top and good conductors such as copper and aluminum lie at the lower right.

Figure 4 shows a more informative chart, giving insight into the energy-related aspect of the material choice. The embodied energy is plotted on the x-axis – it allows a measure of the material-related energy commitment in construction. The thermal conductivity is plotted on the y-axis. High resistance implies the ability to insulate, one way of conserving energy during the use of the structure.

## **CONCLUSIONS**

The activity outlined in this paper has been implemented in a sophomore level strength of materials course, to emphasize the importance of cost in engineering design. The processing aspect was not covered, although it is typically addressed in the production design course, also using the CES EduPack software. One significant outcome of this activity relevant to the teaching of the strength of materials course is to develop an appreciation of the importance of material performance parameters (similar to  $M_1$ ,  $M_2$ ) in engineering design.

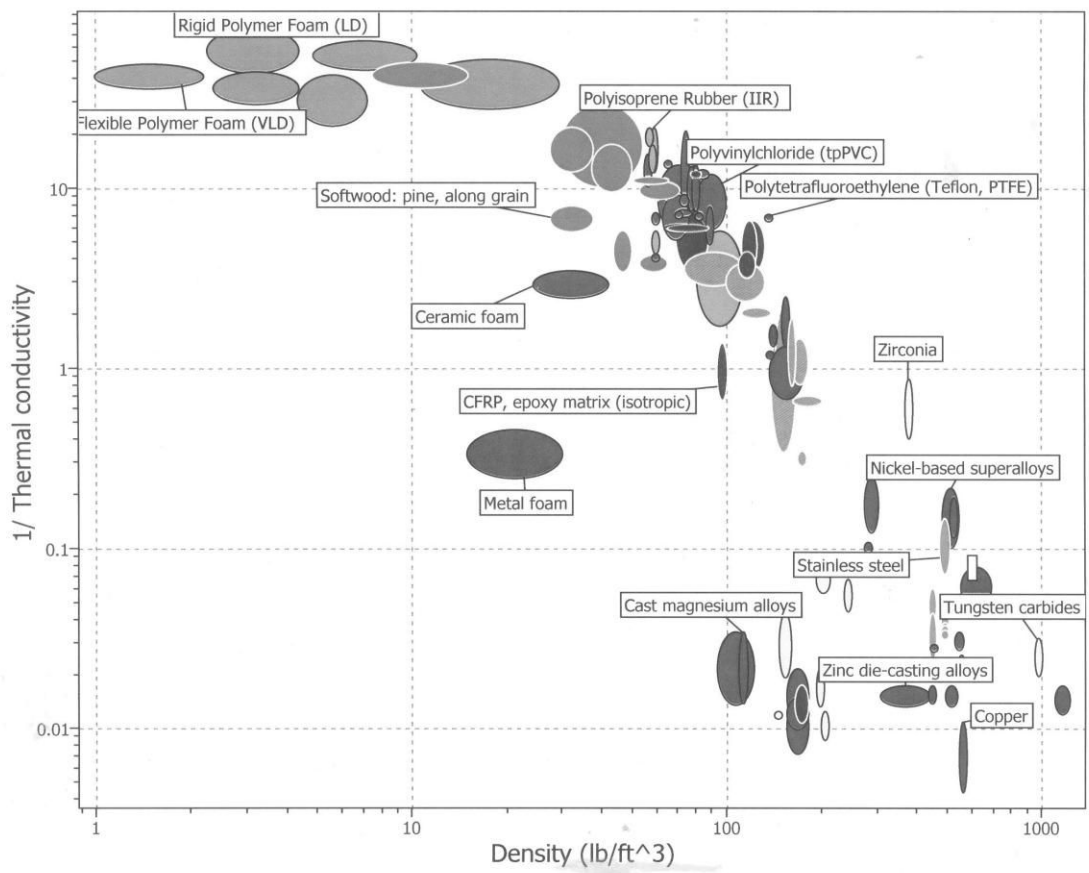
## **REFERENCES**

Ashby, M. F. (2005), *Material Selection in Mechanical Design*, 3<sup>rd</sup> Edition, Elsevier Butterworth Heinemann, Burlington, MA

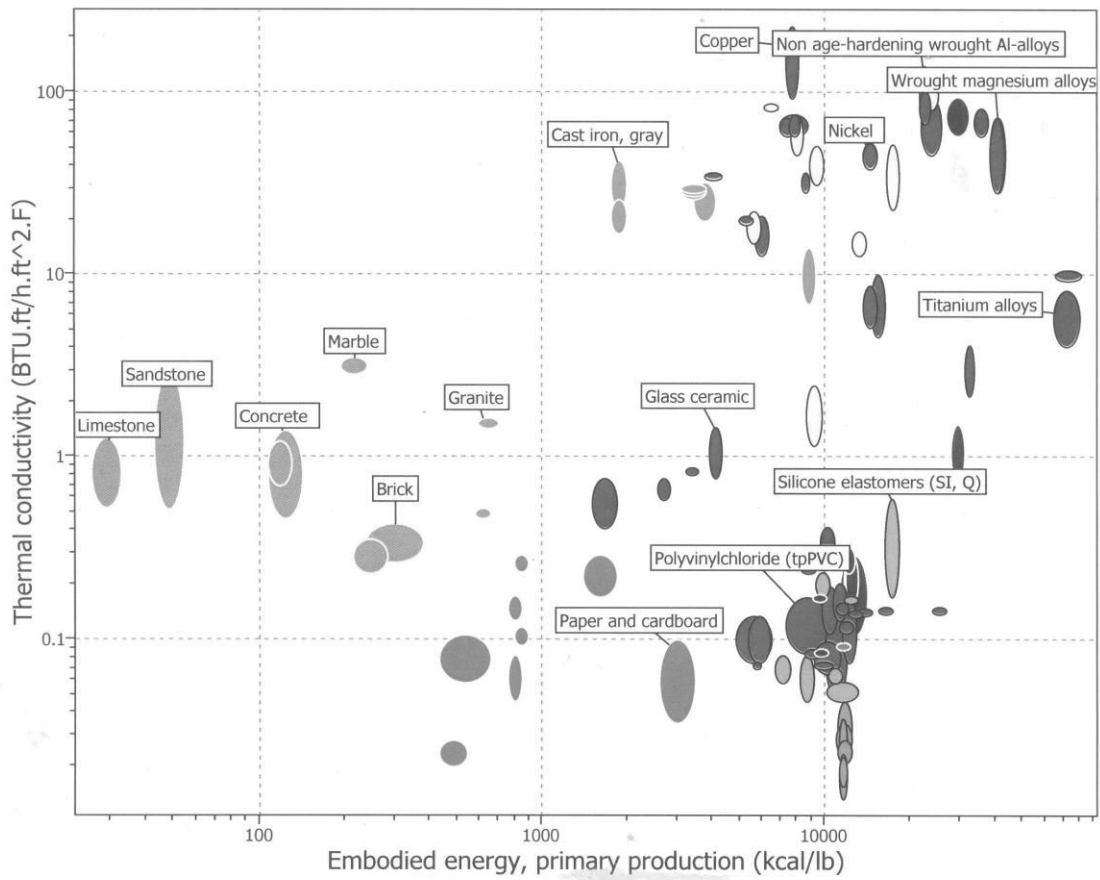
Ashby, M. F., J. Fernandez, and A. Gray (2007), *The CES Database for Architecture and Built Environment*, 2<sup>nd</sup> Edition, Granta Design, Cambridge, UK.

Granta Design (2008) *CES EduPack*, Cambridge, UK.

Frag, M. M. (2008), *Materials and Process Selection in Engineering Design*, 2<sup>nd</sup> Edition, Boca Raton, FL, CRC Press.



**Figure 3 A bubble chart of thermal resistivity and density**



**Figure 4 The thermal conductivities and embodied energies of materials**