A METHODOLOGY FOR ENVIRONMENTALLY-AWARE MATERIALS SELECTION IN CONSTRUCTION

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The 20th century has witnessed the development of a huge range of materials for engineering and construction, during which time the Earth's population has increased by between 3 and 4 times. There has been a corresponding increase in economic activity, and the global construction industry is now very large, and is a massive consumer of materials and energy.

The environmental impact of all these activities has become a matter of major concern, and, as a consequence, we are exhorted to be more economical with materials and energy. Construction is no exception and it needs to be more efficient and environmentally aware, as well as more economical in its selection and use of materials. This is not a simple problem. Environmentalists and ecologists have proposed a number of criteria for assessing the impacts of materials use, and engineers have devised rational methods for materials selection on the basis of their physical and mechanical properties. This paper reviews one of these selection methods and some of the environmental criteria, and examines the problem of incorporating environmental parameters into the selection method. It is concluded that environmental criteria can be built into a rational selection method.

Keywords: construction, energy, environment, materials.

INTRODUCTION

The construction industry in the UK faces a number of challenges, one of the most important of which is the need to address the environmental agenda which becomes daily more urgent. World-wide, construction consumes larger amounts of materials than any other industry. These are not high-technology materials, in the main, but the scale of consumption has a major impact on our environment.

One of the major technological developments of the 20th century has been an explosion in the number of materials that have become available for meeting the many applications in construction and engineering. The Victorian builders and engineers had perhaps two dozen materials at their disposal, and these were used for all applications. These materials were not very sophisticated, but they were tolerant of abuse, and so would serve in situations even where they were less than ideal. At the close of the 20th century, we have between 40,000 and 80,000 materials available to us (Ashby 1992). Material selection is therefore important, but with such a large array of materials, it is not necessarily easy.

In the latter half of this century we have slowly begun to realize that our economic and industrial activities are having an impact upon the natural environment which could, if allowed to continue unchecked, ultimately threaten the future of our existence on Earth. Since the construction industry uses so much material and energy, it shares the

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Table 1: Material consumption and value

Industry	Consumption of materials (tonnes)	Total costs	Material value (£/tonne)
UK Construction	400,000,000	£16,000,000,000	£40
UK Car Market	2,000,000	£13,000,000,000	£6,500
US Boeing Corp.	250,000	$30,000,000,000	£100,000
Rolls Royce Aero-engine (UK)	3,000	£4,500,000,000	£1,500,000

need, along with the other industrial sectors to be responsible in its use of these resources.

CONSTRUCTION MATERIALS

Construction materials are, in the main, low-technology, low cost materials. A survey carried out over ten years ago into the use of construction materials in the UK showed that enough materials were wasted on site each year to construct around 13,000 extra houses (Institute of Materials 1987). The fact that building materials are cheap has led to a certain complacency and an under-valuation of these materials, and the impact of construction is well illustrated in a paper recently published by Kelly (1994). He published data showing global trends in the consumption of various classes of materials.

Two of the most widely used materials show interesting trends. Consumption of iron and steel runs at around 800 million tonnes per annum, and has done so since the Middle East War of 1973. It can also be seen that the production of this steel consumes around 350 to 400 million tonnes of scrap steel per year. Production of Portland cement runs in excess of 1.5 billion tonnes per annum, is rising, and shows no sign of levelling off. Whereas steel is used in many industries besides construction, all of the cement produced will go into construction, to make concrete. So the world production of concrete is of the order of 7 billion tonnes per year, and rising. Furthermore, the production of this concrete, together with road and highway construction, will involve the quarrying of aggregate materials to the extent of 6 or 7 billion tonnes per annum.

Comparing construction with one or two other familiar industries in the UK, the total consumption of materials in UK construction is of the order of 400 million tonnes per annum. The UK market has sales of approximately 2 million new cars per year (HMSO 1998) and around 2 million tonnes of materials will be consumed in their production. This is two orders of magnitude less than materials consumption in construction. The Boeing aircraft corporation probably uses no more than 200 to 250 thousand tonnes of materials each year, while Rolls Royce aero-engines requires 3500 tonnes of very high value materials each year (Coney 1999). As the scale of consumption goes down, the value of the materials increases quite dramatically. This is illustrated in Table 1.

We have, therefore, a picture of an industry with a voracious appetite for materials on a scale much greater than any other sector of industry. These materials are inexpensive and intrinsically of low-value, and so there has been little systematic recycling of many of them. However, construction has been able to benefit from the developments in new materials which have taken place during this century, so that architects and engineers have a much wider range of materials from which to choose when undertaking a project. Some of these new materials are finding their way into building construction.

THE ENVIRONMENTAL DIMENSION

Environmental concerns have become a matter of prime importance in the 1990s. The dangers of global warming and the threat to the ozone layer are now taken very seriously, as shown by the Rio summit meeting of 1992, and the following meeting in Kyoto in 1997. There is now an extensive literature on this subject, typified by the writings of Lowe (1997).

In the United States, it is estimated that the manufacturing and processing of materials accounted for 14%of that country's energy consumption in 1994. The production of cement gives rise to 5%of the world's emission of carbon (Gardner and Sampat 1999).

It must be emphasized that the construction industry does not face these environmental issues alone. Other industries, including the materials industry are operating with the same constraints. They also are addressing the environmental agenda, and are producing materials more efficiently, with lower energy consumption, lower emissions of dust and greenhouse gases, etc. (Vos *et al.* 1999). Therefore the construction industry can be assured that the materials that it purchases are becoming less damaging to the environment.

SELECTION METHODS

Simple selection methods are possible. Cost data are available in such publications as Spon's and Griffith's guides to construction material prices. The cost data comes in various forms, price per unit weight, unit length, area, volume, etc. However, using density values, the prices can be standardized to (say) unit weight. Material property data are also easily obtained from texts, such as that by Ashby and Jones (1980).

However, with so many materials from which to select, and a set of environmental concerns to meet, the business of materials selection is not as straightforward as it once was. Designers can adopt various strategies; they can use the same material as was used in a previous similar situation, they can consult data books, talk to colleagues, etc. but in doing so they may miss the optimal solution for their design. Recognizing this problem, engineers have devised rational selection methods for materials, such as those due to Dieter (1991) and Ashby (1992).

These methods begin by recognizing that the performance of a component, artefact or structure is limited by the properties of the materials from which it is made. It is rare for the performance of the item to depend solely on a single material property. In nearly all cases, it is a combination of properties which matter. So in lightweight design, strength to weight ratio (σ_f/ρ), and stiffness to weight ratio (E/ρ) will be important. Ashby (1992) has proposed the idea of plotting material properties against each other to produce material property maps. On these maps, each class of material occupies a field in material property space and sub-fields map the space occupied by individual materials. These maps are information-rich, but accessible, and they reveal correlations between material properties that can help in checking and estimating data, and they can be used as the basis of a performance optimizing technique, as shown below.

For each property of an engineering material there will be a characteristic range of values, and this range can be large. For example, values of elastic modulus thermal conductivity, etc. have ranges that span about five decades. These property values are set out on charts or maps, an example of which is shown in Figure 1.

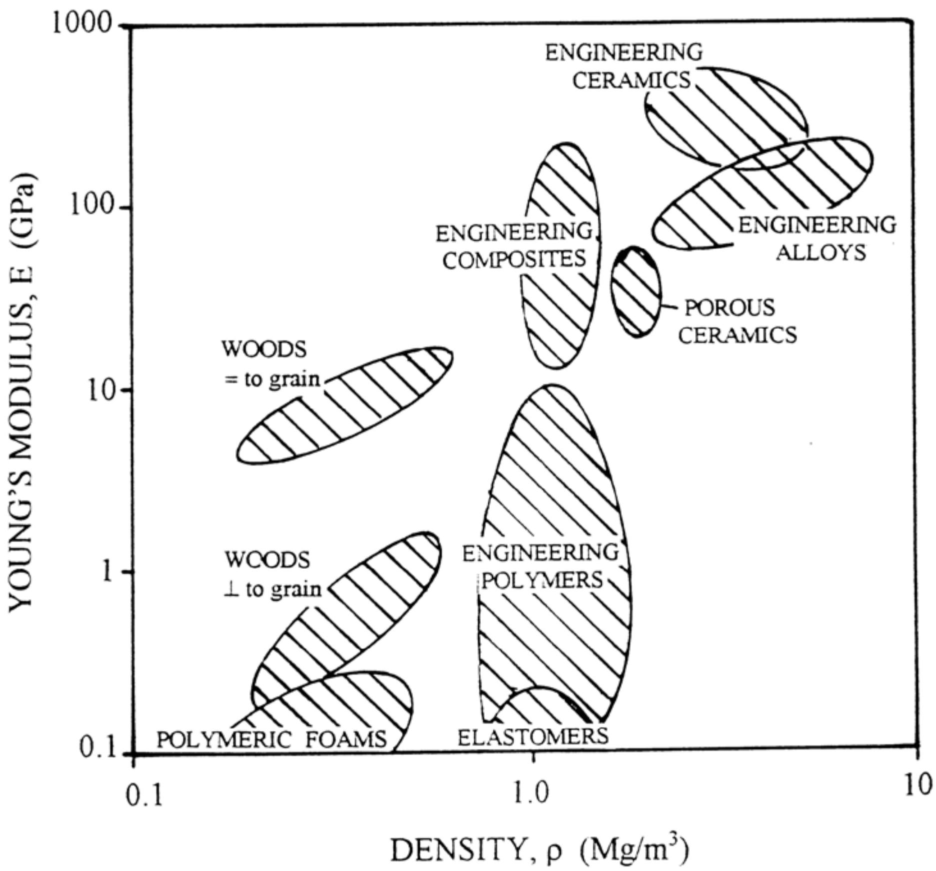


Figure 1: Materials Property Chart. Young's Modulus E, plotted against Density ρ, on log scales *(after Ashby 1992)*

In this case, one property, the Elastic Modulus E is plotted against another, the density ρ on logarithmic scales. The range of the axes is chosen to span the heaviest, stiffest metals down to the lightest, flimsiest foams. Ashby found that the data points for a given class of material cluster together in one region of the map. Figure 1 illustrates the data for the various classes of material grouped inside property envelopes.

The material properties commonly of interest to designers include strength, stiffness, density, cost, etc. The process of design involves identifying the required property profile and then making comparison with those of real engineering materials to determine the best match.

However, design also involves the choice of a shape or form as well as a material. Sometimes material and shape are linked, and in these cases the best choice of material will depend on the shapes in which it is available, or the shapes to which it can be made. It is important to begin with the full range of materials to hand; a missed opportunity may result from leaving out a class or classes of materials. The extremely wide search area is then narrowed down by applying the primary or main constraints dictated by the design, and then by looking for the sub-set of materials which will maximize the performance of the structural element or component.

When designing a structural element (Dieter 1991, Ashby 1992) we need to specify three things: the functional requirements, the geometry, and the properties of the material from which it is to be made. The performance of such an element can be described by an equation of the form:

$$p = f[F, G, M]$$

Where F denotes the functional requirements, G denotes the geometry, and M denotes the material properties.

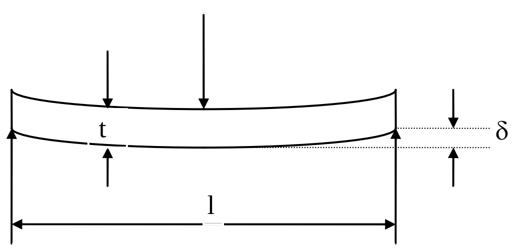
Where the three groups of parameters are separable, the equation can be re-written thus:

$P = f_1(F).f_2(G).f_3(M)$

Where f_1, f_2 and f_3 are functions.

When the parameters are separable, the optimum choice of material becomes independent of the details of the design, i.e. it is the same for all values of the functional requirements, F and for all geometries, G. To illustrate this, the design of a simple beam is considered below. Suppose we wish to design the lightest but stiffest beam, selecting from the full range of available materials. The beam has square section of side t, and is of length l.

Also: W = Load on beam (N)
l = Length of beam (m)
t = Depth of beam (m)
δ = Deflection of beam under load W



Now the deflection of the beam

$$\delta = \frac{Wl^3}{48.E.I.} \quad \text{...(1)}$$

where E = Young's Modulus of Elasticity
I = Second Moment of area about the axis of bending.

and, for square section beam $I = \frac{t^4}{12}$..(2)

Combining (1) and (2) we have:

$$\delta = \frac{W.l^3}{4\,E\,t^4} \quad \text{...(3)}$$

Mass M, of the beam is given by;

$$M = l.t^2.\rho$$

Therefore $t = \left(\frac{M}{l.\rho}\right)^{\frac{1}{2}}$

Substituting t in equation (3) we have:

$$\delta = \left(\frac{Wl^3}{4E}\right)\left(\frac{l^2\rho^2}{M^2}\right)$$

Transposing for the mass M:

$$M = \left(\frac{W}{4\delta}\right)^{\frac{1}{2}}\left(l^5\right)^{\frac{1}{2}}\left(\frac{\rho^2}{E}\right)^{\frac{1}{2}}$$

Function Material
Geometry

So we obtain an expression containing terms for the function, geometry and material properties. We obtain the lowest value of M (i.e. the lightest beam) by choosing the material with the lowest value of (ρ^2/E). This can be found by interrogating a materials property database. This design method has been devised with the aim of satisfying the normal design parameters, and achieving optimal solutions with minimum cost. Can such a methodology be used to optimize designs where minimum environmental damage is one of the important parameters?

DISCUSSION

The method developed by Ashby works with material properties such as stiffness, density, strength, cost, etc. In principle, any material specific property could be used, and the list of physical, mechanical and cost data could be extended to include things like embodied energy, embodied CO_2, and ecological rucksack (see below). These parameters, while not physical properties, have their basis in the physics and chemistry of the materials. For example, many metals are extracted from oxide ores by a reduction or smelting process. The process can involve pyrometallurgy or it may be electrolytic, but the end result is the same; an oxide is being reduced. Study of the thermodynamics of metal oxide reduction shows that there is a correlation between the free energies of metal oxides and the energies involved in their extraction. Therefore while embodied energy values are not absolute properties of materials they do represent a real intrinsic property of each material, and so can be used with confidence with this selection methodology. In fact, Ashby has produced one or two charts where embodied energy is one of the material parameters (Ashby 1992). Since there will be a link between the energy expended and the CO_2 emitted when a material is produced, embodied CO_2 values can also be fitted into this selection methodology.

Two powerful tools for evaluating environmental impact have been developed during the present decade; the environmental rucksack (Schmidt-Bleek 1994) and the ecological footprint (Wackernagel and Rees 1996). The author has attempted to assess these in terms of their suitability for incorporation into the selection method. It soon became apparent that the ecological rucksack concept was capable of being treated as a valid material property, whereas the ecological footprint was not. The ecological rucksack is a measure of how much material is discarded when unit quantity of a given material is produced. For example, 14 tonnes of waste material are used to produce 1 tonne of iron, and 350,000 tonnes of waste are produced when 1 tonne of gold is extracted. This is obviously a powerful index of environmental damage, and it reflects various characteristics of the material, including:

1. Relative abundance or concentration of the species being extracted,
2. Location depth in the Earth's crust,

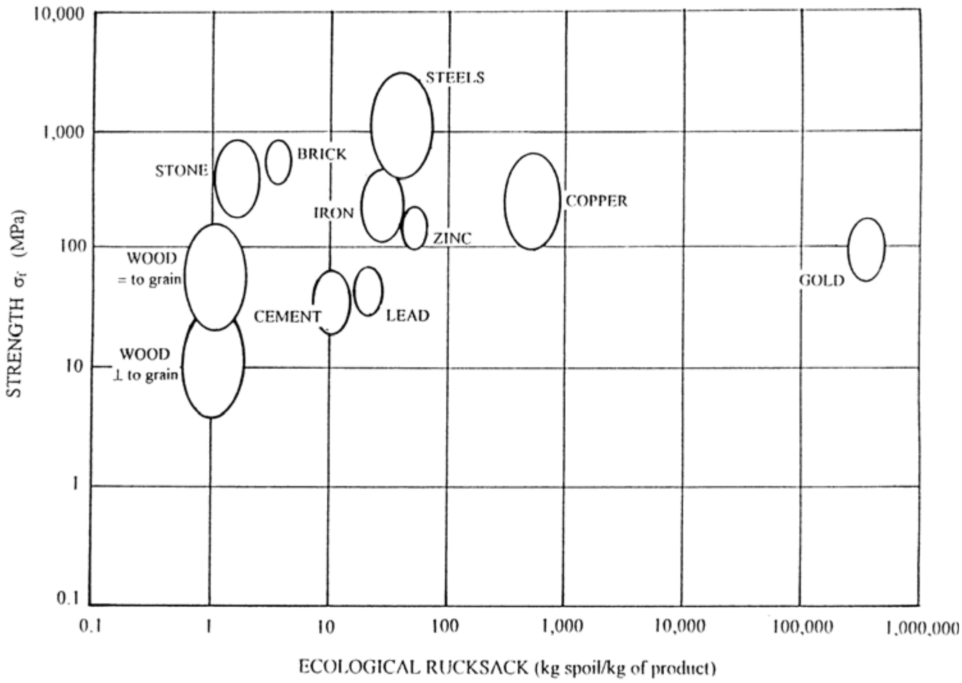


Figure 2: Materials property chart. Strength σ_f plotted against the ecological rucksack

3. Chemistry or thermodynamics of the species being extracted.

Therefore we have justification for regarding the rucksack as a material property, and we can incorporate it into the rational selection method. Figure 2 shows a first attempt at producing a materials property chart for strength v. ecological rucksack.

The ecological footprint attempts to evaluate the land area involved in the production of a material or resource. It is an excellent way of assessing environmental impact, but it does not represent a meaningful material property, and so cannot be used in the selection method.

RECYCLING AND RE-USE

If the construction industry is going to move towards a sustainable future then it will have to consider its materials at the end of their service lives as well as their initial selection. There needs to be a large increase in the proportion of materials that are re-used or recycled. If this is to happen, then the industry needs to address three main areas; firstly, where possible, buildings must be designed and constructed so that they can accommodate future changes of use or internal configuration. Secondly, buildings will need to be designed for ease of dismantling when they do eventually reach the end of their lives. Finally, each building will need a proper and complete record of exactly what materials have been used in its construction. All of these will help the demolition waste stream become better integrated into the recycling industry. This has to happen because there is so much low-value material in demolition waste, and re-use and recycling incur their own costs.

CONCLUSIONS

Rational selection methodologies, such as that developed by Ashby (1992), can incorporate ecological/sustainability parameters. At the detail design level, rational selections could be made in which environmental impact is minimized/optimized.

Properties such as embodied energy, embodied CO_2, and the ecological rucksack could easily be incorporated into the selection method. The information needs to be made available in a readily-accessible form for architects, engineers, builders, etc. The manufacturers of materials are also working to the environmental agenda, and so the embodied energy values of construction materials are reducing; and at the same time, the recycled content of materials is on the increase.

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