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Functions of Eco-materials in the context of Eco-design

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Eco-materials concept has been well developed in Japan since 1991. A number of nearly 2000 of commercialized eco-materials were reported in 2003 by a numerous Japanese companies. Eco-materials have been ad-hoc used in several commercialized products. Problems raised during the product design phase are how to select the appropriate eco-materials, and how to ensure environmental enhancement of the selected eco-materials in eco-products. This research is attempted to analyze the real functions of eco-materials in the context of eco-design concepts which introduced by Delft University in the Netherlands and UNEP. Eco-materials could have two major functions in eco-redesign. First of all, the selection of material during product design phase of product development will ensure the production of eco-product at the earlier stage. The second function of eco-materials in eco-design is to improve eco-efficiency of products or services. In addition, a summary of eco-materials and eco-products development in Japan, and a proposed four step model of eco-materials selection are discussed to give a better view of eco-materials concept to product designers.

Key words: Eco-materials, Eco-design, Eco-products, Eco-efficiency, material selection.

1 INTRODUCTION

The term "eco-materials" was first introduced by Professor Yamamoto and his colleagues in Japan since 1991 as a pro-active measure to response to the movement of sustainable development. Eco-materials play a key concept of material science and technology to minimize environmental impacts, to enhance the recyclability of materials, and to increase energy and material efficiency. Eco-materials have been ad-hoc used in several commercialized products. A number of nearly 2000 of commercialized eco-materials were reported in 2003 by a numerous Japanese companies [1].

This research is attempted to analyze the real functions of eco-materials in the context of eco-design concepts which introduced by the Delft University in the Netherlands and the United Nation for Environmental Program [2]. In addition, a summary of eco-materials and eco-products development in Japan, and a proposed four step model of eco-materials selection are discussed to give a better view of eco-materials concept to product designers.

2 DEVELOPMENT OF ECO-MATERIALS

In the beginning, the eco-material concept focused on the development of materials that could contribute to environmental conservation and protection. Environmental issues and functional properties of materials were considered, including structural materials used in construction or automobile manufacture and special functional materials such as semiconductors or solar cells. Halada and Yamamoto stated that there are three dimensions to eco-materials: 1) expanding human frontiers or functional properties; 2) coexisting with the environment; and 3) optimizing amenities or socioeconomic performance [3].

Recently, the Eco-materials Forum in Japan has started an eco-materials guideline project to develop a standardized concept of and criteria for the evaluation of eco-materials. The conceptual definition of eco-materials in this project is: "Eco-materials are those that can contribute to reduction of environmental burden throughout their life cycles" [4]. In other words, any material can be an eco-material as long as it satisfies prerequisites (I) and the necessary conditions for eco-materials (II and/or III). The prerequisites (I) include the optimization of physical and/or chemical properties and superior technical performance. The necessary conditions (II) are: significant environmental improvement compared with conventional materials; and no tradeoff of the environmental load throughout the whole life cycle, and if there is a tradeoff, all life cycle environmental data must be available to verify the improvement of environmental performance (III).

3 FUNCTIONS OF ECO-MATERIALS IN ECO-DESIGN

3.1 Material selection for eco-products

Eco-materials could have two major functions in eco-redesign. First of all, the selection of material during product design phase of product development will ensure the production of eco-product at the earlier stage. Eco-redesign guideline already addressed several issues related to the selection of materials. The quick-start guide to eco-design in this book indicates four main steps of eco-design including the use of materials in your product, the use of resources for and by your product, the end of your product life, and innovation (Fig. 1). By carefully looking at the definition of eco-material, eco-materials could surely play an important role in all four steps.

At the component level (A), selection of green resource profile materials, minimal hazardous substance-contained materials, high recyclability materials would reduce the overall impacts of component and product. Use of recycled materials such as PET recycled fibers for new cloth, use of Toyota Super Olefin

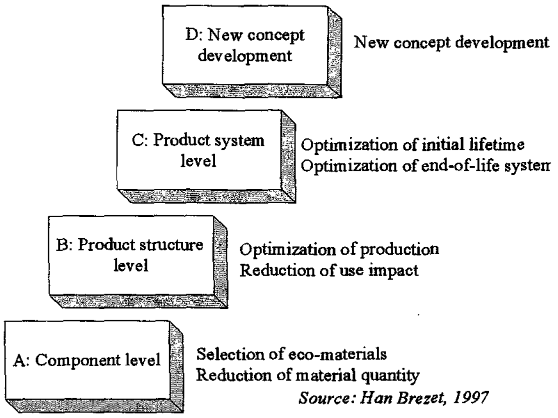

Fig. 1: Four levels of eco-design strategies

Polymer (high recyclability) in automobile, use of bio-mass plastics for CD-ROM, and use of lead-free lenses for camera are some examples of use of eco-materials in eco-products.

Similarly, at production structure level (B), use of eco-materials such as those with high productivity, high technical performance, and high environmental treatment materials would reduce the impacts of product at use phase. The most typical example is the use of ultra-light high tensile steel in automobile to reduce the overall weight of cars, thus to increase the energy efficiency during use phase. Other examples include the use of VOC (volatile organic compound)-free plastics, non-halogen flame retardant plastics, and use of high performance Nd-Fe-B magnets in motors.

In addition, at the production system level (C), use of high productivity materials, use of high recyclability material would optimize the life-span of product as well as minimize the environmental impacts at the end-of-life phase. Use of biodegradable plastics, non-halogen flame retardant plastics, weather-resistant steel, soil ceramics in building, M-wood in building, and recycled vegetable oil inks are only few examples to be addressed here.

At the highest level of eco-design (D), innovation eco-materials could also contribute to the eco-design innovation, especially the radical innovation. Recently, new eco-materials could be found in various forms such as nano composites, amorphous metals, shape-memory alloys, and titanium oxide coating materials for building. Display technology, for example, has been changed from cathode rays to liquid crystal display technology thank to the development of liquid crystal polymer. The invention of light-emitting polymer films will once again lead to the transformation of display technology to LED technology. Memory shape alloys (MSA) is another example of application of eco-material at the level D of eco-design. MSA could be used for the control to damage to building and infrastructure during earthquakes. In addition, MSA enables the development of endo-prostheses surgery with minimal post-surgery effects.

3.2 Eco-efficiency improvement

The second function of eco-materials in eco-design could be mathematically expressed in eco-efficiency of products or services. The eco-efficiency of products or services was defined in a report published by the World Business Council for Sustainable Development (WBCSD) as:

$$Eco-efficiency = \frac{\text{Product or Service value}}{\text{Environmental influence}} \qquad \{1\}$$

If the material efficiency (M) is defined as:

$$M = \frac{v}{m} = \frac{v}{p} \times \frac{p}{m} \qquad \{2\}$$

and resource productivity (R) is defined as:

$$R = M \times \frac{m}{r} \qquad \{3\}$$

Then: $$Eco-efficiency = \frac{v}{p} \times \frac{p}{m} \times \frac{m}{r} \times \frac{r}{e} \qquad \{4\}$$

Or $$Eco-efficiency = M \times \frac{m}{r} \times \frac{r}{e} \qquad \{5\}$$

or $$Eco-efficiency = R \times \frac{r}{e} \qquad \{6\}$$

Where v, p, m, r, e are value, product, material, resource, and environmental impact, respectively.

Equations {4}, {5}, and {6} indicate that in order to improve the overall eco-efficiency, either material efficiency (M) of a product or resource productivity (R) should be improved. The ratio p/m tells the efficiency of product manufacturing process, while the ratio m/r tells the efficiency of material production process.

Mathematically, in order to increase the eco-efficiency value of product or service, the material efficiency (M) and/or resource productivity (R) must be increased in the context of eco-materials functions in eco-design.

4 FOUR STEP APPROACH OF ECO-MATERIAL SELECTION

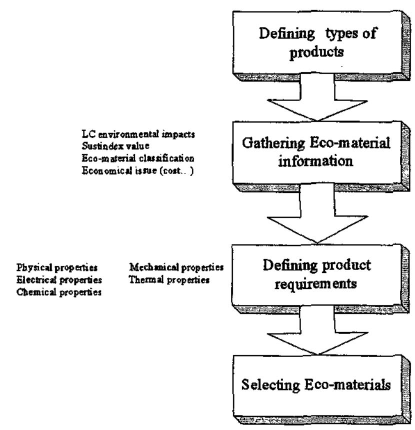

Fig. 2: Four step model of eco-material selection process

A recent study by Nguyen has introduced a four steps approach for eco-material selection used by product designer in eco-design [6]. This selection approach was developed to be used by product designers during their product development process, not by customers in selecting the materials.

In Japan, eco-product development has become one of the most important marketing tools. Selecting the appropriate eco-material would lead to a new eco-product. A conceptual model of eco-material selection guideline is illustrated in Fig. 2. The four steps are defining type of products, gathering eco-material information, defining product requirements, and selecting eco-material. This process is also considered as a back-casting approach or ABCD analysis of The Natural Step [7].

4.1 Defining type of products (A)

The first step of eco-material selection process is to define product type with a consideration of whole life cycle (LC) concept.

Fig. 3 illustrated the four general product types with a full consideration of life cycle concepts. Type I product normally has a very short lifespan and material intensiveness. A single use of package is a typical example of type I product. In comparison to type I product, type II product has relatively longer lifespan, but has more manufacturing-intensiveness. Notebook computers and digital cameras are typical examples of type II product. In the contrast, type III product has comparatively long lifespan. Energy and/or resource consumption during the use phase are the main concern of the type III product. Automobile and washing machine are some typical examples of the type III product. The last type of product is those with special end-of-life or disposal characteristics. Typical examples of this type IV product are disposal diapers and Ni-Cd battery.

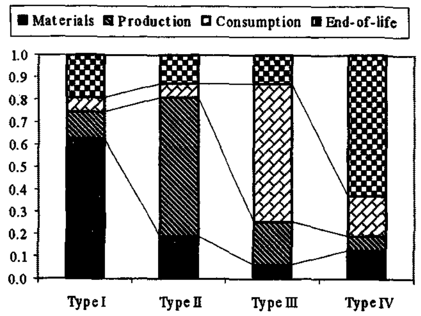

Fig. 3: Four general product types with LC concept[8]

Defining the right product type is crucial in eco-design and material selection. An eco-material appropriate for one application might not be suitable for another application. For instance, high tensile strength steel is not appropriate for type II product like digital cameras. The lifespan of this product is relatively short (about 2-5 years). Another example is that the use of readily biodegradable polymers as a construction material is not appropriate. Renewable material is appropriate for type I product, while material that is most efficient to process is appropriate for type II product. Lightweight or high tensile strength steel should be used for type III product, while biodegradable or recyclable materials should be used for type IV product.

4.2 Gathering eco-material information (B)

The second step in eco-material selection guideline is to obtain eco-material information as much as possible. In this step, all necessary information on eco-materials is collected and verified. Necessary information should cover all "triple bottom line" aspects, including social, economic and environmental aspects.

In addition to information on eco-material classification, life cycle impact assessment or eco-efficiency or other similar assessment results of the related materials should also be collected. Some assessment results like LCA are difficult to be obtained, while some others like qualitative assessment are relatively easier to be conducted.

Other important information is the legislations and regulations. In Japan, for instance, the law for material reduction such as Basic Law for establishing a recycling-based society, law for promotion of effective utilization of recyclable resources, Law for recycling of specified kinds of home appliances or Law concerning chemical substances like Pollutant Release and Transfer Register (PRTR) are some of related laws and regulations.

Beside environmental and social information, economic issue is also vital information. One of the concerned economic issues in material selection is the cost of material or the market price. The cost of eco-materials could be influenced by many factors and normally fluctuated in the market. Thus collecting cost of materials should be carefully carried out.

4.3 Defining product requirements (C)

The third step of eco-material selection process is defining product requirements. In this step, five main properties of a particular product including physical, mechanical, electrical, thermal, and chemical properties needed to be defined. A wide range in physical properties of material includes density, water absorption, melt flow, shrinkage and other similar mechanical properties. The mechanical properties include hardness, tensile strength, creep, elongation, elasticity, and other similar properties. The electrical properties consist of electrical resistivity, dielectric strength and others. Thermal properties of product requirement include the thermal conductivity, heat capacity, deflection temperature and similar properties. Finally, chemical properties consist of flammability, corrosive resistivity, toxicity, and others. Information of these properties could be found in various sources such as IDEMAT, MATWEB, literature, handbooks, or company's brochures.

Relative importance of each property will depend on the application. Different classes of material will have different specific properties. Metals, for instance, tend to have high stiffness, strength while having a high density. Polymers are lower in density with relatively low strength and stiffness. Thus defining appropriate product requirements will ease in eco-material selection.

4.4 Selecting eco-materials (D)

The final step in eco-material selection process is to select appropriate eco-material for eco-product. In this step, eco-material is strategically evaluated and selected. The objective of this step is to optimize number of product requirements during the product design phase. Several performance metrics will be involved in selecting eco-materials. This step is, therefore, required a multi-criteria optimization process for eco-material choice.

Recently, a multi-objective optimization in material design was introduced by Ashby to help product designers in mechanical design[9]. A performance metric (P) of component is a function of load (F), geometry (G) and material (M) as equation.

$$P_j = f_j(F, G, M) \qquad \{7\}$$

Normally, the load (F) variable is fixed for a particular component. Optimum design or optimum performance metric (P) is, therefore, the optimal selection of material (M) and geometry (G). The multi-objective optimization is to optimize several interdependent performance metrics (P). In the case of only two performance metrics, these performance metrics would be plotted against each other to form Ashby's material selection charts[9]. These material selection charts is in logarithm scale. The value function (V) as a diagonal line on the selection charts could be expressed as equations below.

$$V = \frac{P_1}{P_2^n} \qquad \{8\}$$

Or $$\log P_1 = n \log P_2 + \log V \qquad \{9\}$$

In the case of multi-objectives, the value function will be as equation.

$$V = \sum_i \alpha_i P_i \qquad \{10\}$$

The equation will exhibit a trade-off line or surface in the charts. Any material with plotted point closes to this trade-off line will be the optimal material for product.

4.5 Eco-materials selection chart for plastics

The author used result of proposed sustainable assessment methodology (SAM) [10] for eco-materials presented in IUMRS-2003 to illustrate an example of eco-material selection chart.

The single value index ($Sust_{index}$) is used to help development of eco-material selection guideline for eco-product. A guideline for eco-material includes several charts of $Sust_{index}$ value as one dimension and other values such as market price, mechanical properties as the other dimension. Fig. 4 showed the relationship of $Sust_{index}$ and market price of investigated thermoplastics and biodegradable thermoplastics. In the theory, the best plastic should be located on the top-left hand side corner of the chart. A relationship of these two dimensions could be expressed as equation{11}, where C is coefficient constant.

$$M_{eco} = C \times Sust_{index} + Cost \qquad \{11\}$$

When the value of C is changed, the option of selection will be changed.

In this figure, even though the biodegradable plastics (Bi-NF and Bi-PE) have higher value of $Sust_{index}$, their market prices are almost double that of some synthetic polymers such as polypropylene or polyethylene. If cost of material is more important than sustainability, the product designers might not prefer biodegradable plastics than PE or PP. However, some product designers might select biodegradable plastics for their eco-products due to a better image of eco-product. In the Fig. 4, an example on the selection of PET or PP or PS for car bumper is illustrated. When $C = 10$, PS is better material than PET, and PP and PET are equal choices, when $C = 0.1$, PET is better than PP.

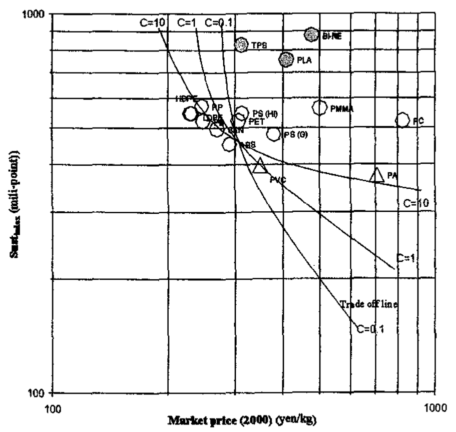

Fig. 4: Sustainability-economy selection chart for plastic.

It is assumed that before making any choice, product designers already have a set of mechanical property requirements of materials. In plastic selection, for instance, this set could consist of density, elastic modulus, elongation break, and shrinkages.

5 CONCLUSION

In conclusion, eco-materials pose two main functions in eco-design approach, material selection and eco-efficiency improvements. This research also proposed a four step model of eco-materials selection guideline for eco-design. Eco-product designers would be able to select an appropriate eco-material for their eco-product by using this guideline.

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