MODULE H

ECO-MATERIALS

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1. BASIC INTRODUCTION OF ECO-MATERIALS

1.1 WHAT ARE ECO-MATERIALS

Eco-materials are defined as those materials that enhance the environmental improvement throughout the whole life cycle, while maintaining accountable performance (Halada and Yamamoto 2001). Eco-materials play a key role in material science and technology to minimize environmental impacts, enhance the recyclability of materials, and to increase energy and material efficiency.

In North America and Europe, eco-materials are often called "environmentally-friendly materials" or "environmentally preferable" materials.

1.2 HOW DO ECO-MATERIALS DIFFER FROM CONVENTIONAL MATERIALS?

One of the most comprehensive definitions for eco-materials was proposed by Professor Yagi in 2000 (Yagi 2002). From the view point of material science and engineering, an eco-material should pose at least one among ten superior properties compared to conventional materials. A more detailed explanation of each superior property of eco-material can be found in box 1. As a result, there is a very wide range of eco-materials developed in various industries such as iron and steel, electronics, chemicals, paper, construction, textile and polymers. Some examples of commercialized eco-materials are given in table 1 and in the examples section.

Eco-materials are those that can contribute to reduction of environmental burden through their life cycles" (Shinohara 2004). In other words, any material could be an eco-material as long as it could satisfy pre-requisites (I) and necessary conditions of eco-materials (II and/or III) (see figure 1). The pre-requisites of eco-materials include the optimization of physical and/or chemical properties and best technical performance (I). The necessary conditions are as follows:

> Significant environmental improvements compared to conventional materials (II),

> No tradeoff of environmental load through the whole life cycles, and

> If there is a tradeoff, whole life cycle environmental data must be available to verify the improvement of environmental performance (III).

It should be noted that the whole life cycle impacts of eco-materials must be considered and be improved. The conditions (II) include six vectors: as 1) green resource profile; 2) minimal environmental impact during the material manufacturing process; 3) high productivity in use; 4) minimal hazardous substance; 5) high recyclability; and 6) high environmental purification efficiency. More details of these six vectors are described in the eco-materials guideline section. An eco-material is not necessary to meet all these six vectors, but at least one must be satisfied, while the others should be similar to the reference material

TEXTBOX 1> DEFINITION OF SUPERIOR PROPERTIES OF ECO-MATERIALS

1> Energy saving ability to reduce total life cycle energy consumption of a system or device.
2> Resource saving ability to reduce the total life cycle material consumption of a system or device.
3> Reusability to allow the reuse of collected product as similar functions.
4> Recyclability I to allow the use of collected product of material as a raw material.
5> Structural reliability to be used on the basic of its reliable mechanical properties.
6> Chemical stability to be used over long term without chemical degradation.
7> Biological safety ability to be used without causing negative effects to the ecological system.
8> Substitutability to be used as an alternative of "bad" materials.
9> Amenity to ensure the comfort of working environment
10> Cleanability to separate, fix, remove and detoxify a pollutant for environmental treatment process.

2. MORE BACKGROUND INFORMATION

2.1 THE DEVELOPMENT OF ECO-MATERIALS

A study by Nguyen reported a list of eco-materials based on the environmental reports or responsible care reports in 2002 of more than 40 Japanese companies in several industrial sectors including metals, cement, chemicals, and others (Nguyen, Honda et al. 2003). A total of 359 different eco-materials were identified and further investigated for the eco-material classification.

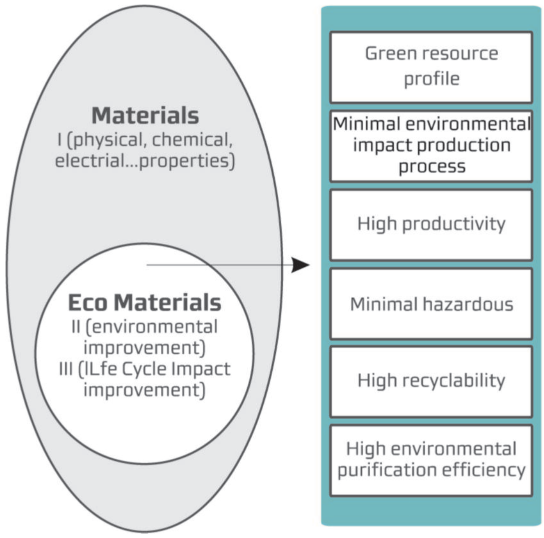


FIGURE 1 ___ CONCEPTUAL MODEL OF ECO-MATERIALS WITHIN THE CONTEXT OF MATERIAL SCIENCE

2.2 ECO-MATERIAL CLASSIFICATION

Some authors have been tried to classify eco-materials from the view point of life cycle concept. New development of materials or eco-materials should be viewed in the full context of sustainability. This classification method of eco-materials was based on the four sustainable principles: (i) "cyclic" materials; (ii) materials for ecology and environmental protection; (iii) materials for society and human health; and (iv) materials for energy based on the two main criteria as their sources and functions. These four main categories were then classified further to ten sub-categories (see table 1).

GREEN RESOURCES PROFILE

This aspect is related to both the new resource and recycling stages. The main question is if "*materials are from resources of green resource profile*" (Shinohara 2004). Four major issues for this aspect are including:
> Reducing use of non-renewable resources;
> Substituting non-renewable by well-managed renewable natural resources;
> Reducing use of renewable natural resources, and
> Increasing use of recycled resources.

Sub-categories	Examples
I A: Recycled Materials	Eco-cement. Coal ash concrete, glass ceramics from wastes, recycled plastics, silica fertilizer, marine block.
I B: Renewable materials	Wood ceramics, wood based materials, soil ceramics, biodegradable plastic made of vegetable base.
I C: Material for efficiency	Wasre reduction materials, wear resistant metals and alloys, pre-paint steel and alloy.
II A: Materials for waste treatment	Membranes for exhausted gas separation, ion-exchange resins, microbial enzymes, absorbement materials for oil and grease removal.
II B: Materials for reduction of environment load	Catalysts and biological membrane materials for fuel cells, carbon-fiber composites, photo-catalyst coating materials for construction.
II C: Materials for easy disposal or recicle	Biodegradable plastics, functionally graded material, colorbetos which replace asbestos, TSOP.
III A: Hazardous free materials	Lead-free solder, halogen flame retardant-free plastics, chromium-free steel, VOCs-free adhesive, heavy metals free polyesters.
III B: Materials for reducing human health impacts	Vibration damping steel sheet, sound proof panels, anti-bacteria coating materials, bone-cream for orthopedic surgery and brain surgery.
IV A: Materials for energy efficiency	Ultra-ligh steel, Al-Mg lightweight alloys, heat resistant alooy for turbines, high magnetic induction steel sheets, highly endothermic steel, chromo phobic fibers, heat mirror film for household energy saving.
IV B: Materials for green energy	High grade silicon for solar cells, thermoelectric conversion materials, selective transparent glass, highly durable sealing sheets for solar batteries.

TABLE 1 ___ SOME EXAMPLES OF ECO-MATERIALS WHICH ARE CURRENTLY COMMERCIALIZED IN JAPAN

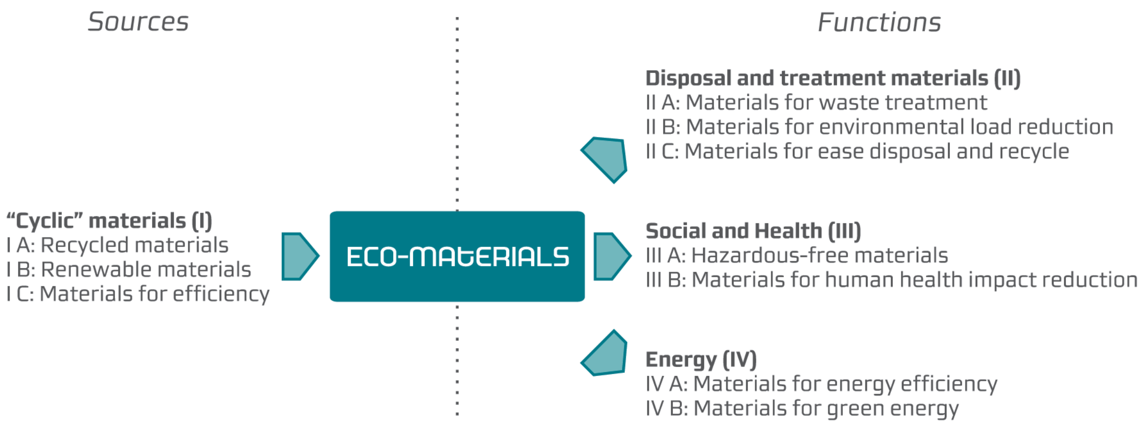


FIGURE 2 ___ CLASSIFICATION MODEL FOR ECO-MATERIALS

Several quantitative indicators could be used including total material requirement (TMR), material intensity (MI), ecological footprint (EF), and ratio of recycled materials used.

PRODUCTION PROCESS OF MINIMAL ENVIRONMENTAL IMPACTS

This aspect is related to four life cycle stages including material manufacturing, product manufacturing, recycling, and waste disposal. The main question is if "*materials are fabricated, disposed of and recycled through the process of low environmental impact*" (Shinohara, 2004). Seven major issues for this aspect are:

> Reducing CO_2 emission at material manufacturing process;

> Reducing emissions of pollutants at material manufacturing process;

> Increasing production yield;

> Reducing energy and input materials at product manufacturing process;

> Reducing energy and input materials at recycling process;

> Reducing energy and input materials at waste disposal stage, and

> Saving the landfill area.

Quantitative indicators for this aspect could include the CO_2, SO_x, NO_x emission, energy consumption, and material productivity.

HIGH PRODUCTIVITY

This aspect is related to the consumption stage of the whole life cycle of materials. The main question is if "*materials can exhibit high productivity in the applied product*" (Shinohara 2004). Major issues in this aspect are:

> Reducing energy and input material at consumption stage, and

> Enhancing reuse and longevity of materials and products.

Quantitative indicators in this aspect could be energy and material efficiency during the consumption stage.

MINIMAL HAZARDOUS SUBSTANCES

This aspect is related to the material manufacturing, collection and recycling stages. The main question is if "*material could reduce emission of hazardous chemical substances from the product and waste*" (Shinohara 2004). Major issues are:

> Reducing use of hazardous or potentially hazardous substances, and

> Establishing a collection system for hazardous chemical substances from used products.

Quantitative indicators of this aspect could be total amount of hazardous substances used and released in these life cycle stages. Information of hazardous substances could be obtained using a pollutant release and transfer register (PRTR) approach.

HIGH RECYCLABILITY

This aspect is related to the material manufacturing and recycling stages. The main question is if "*material could contribute to efficiency recycling*" (Shinohara 2004). Major issues in this aspect are:

> Increasing ratio of recycled resources,

> Enhancing separation and recovery ability of other products,

> Establishing a closed-loop recycling system, and

> Enhancing a open-loop recycling system.

Quantitative indicators for this aspect could be the ratio of recycled over virgin material.

HIGH ENVIRONMENTAL TREATMENT EFFICIENCY

This aspect is related to the consumption stage. The main question is if "*material can increase efficiency of environmental treatment or purification process*" (Shinohara, 2004). Major issues of this aspect are:

> Purifying volatile organic compounds (VOCs) or sick-house syndrome organic compounds in the living environment,

> Removing hazardous substances in contaminated environment (air, water, and soil), and

> Removing hazardous substances from exhaust gas.

2.3 ECO-MATERIALS EXAMPLES

ECO-CEMENT (I.A)

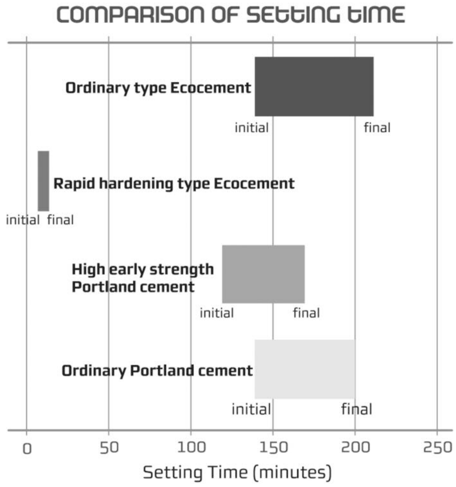
Eco-cement is a product of Taiheiyo Cement Corporation. This eco-cement is manufactured using municipal wastes as its substitute for raw materials. The municipal waste can be used as raw materials for eco-cement in two different ways, in the form of incinerated ash, and in the form of municipal sludge. In the eco-cement, approximatetly 50% of municipal wastes has replaced the cement raw materials (table 2). Quality of

Raw material	Ordinary Portland cement	Eco--cement
Lime stone	78%	52%
Incenerated ash	-	38%
Sewage sludge	-	9%
Clay	16%	-
Silica sand	4%	-
Iron resource	2%	-
Sodium carbonate	-	1%

TABLE 2 ___ RAW MATERIALS IN ECO-CEMENT AND PORTLAND CEMENT

eco-cement is similar to ordinary Portland cement.

Use of eco-cement has two benefits, reducing non renewable raw material extraction and reducing the waste released to the environment. A life cycle assessment result of eco-cement indicated that CO_2 emissions are reduced up to 50%, energy consumption is reduced up to 89%, and prolongation of landfill could save up to 30000 yen per square meter (Taiheiyo, 2003).



Cement type	Density g/cm3	Specific surface cm3/g	Setting (hr,min)		Compressed strength (N/mm2)			
			Start	Finish	Day 1	Day 3	Day 7	Day 28
Regular Eco-cement	3.16	4.30	2:20	3:30	10.0	27.0	40.0	55.0
Quick hardening Eco-cement	3.13	5.30	0:09	0:13	25.0	38.0	52.5	58.0
Fast hardening cement	3.13	4.34	2:03	2:50	27.0	43.0	57.0	65.0
Normal cement	3.15	3.22	2:2	3:20	14.5	27.5	43.0	59.0

Source_ Taiheiyo Cement

TABLE3 ___

M-WOOD2 (I.B)

M-Wood2 is a synthetic wood blend product combining various types of plastics (polyvinyl chloride or polypropylene) with wood chips. The wood composition in this material is about 51-55% or less (by weight). The other components consist of about 25-30% of plastic wastes such as polypropylene trays, automobile bumpers, agricultural PVC, and less than 20% of pigments and additives which are normally used in olefin resins. The production of this M-Wood2 will not produce any VOCs. In addition, 100% recycled materials are used for the production of M-Wood2. Furthermore, the testing phase reported that M-Wood2 could be recycled 10 times

M-Wood 2			The lumber
PP (extrusion)	PP (pouring into a mould)	PVC (extrusion)	American cedar
0.6	0.3	3.2	20.6

TABLE 4 ___ WATER RESISTANCE PROPERTY OF M-WOOD 2

without losing its characteristics.

M-Wood2 has superior characteristics compared to normal wood, such as ease to process, light, natural color and pattern. The material which is used PP resin can be incinerated without any formation of dioxin. Some material characteristics of M-Wood2 are explained below.

Water resistance: Water absorption coefficient (%) (The weight change rate is due to water absorption. The greater the value is, the easier to absorb water).

Weather resistance: The time span of outdoor home products of general wood is normally about 10 years. The deterioration of wood material is due to rain and ultraviolet radiation. However, M-Wood2 is proved to be more weather resistant than normal wood.

Heat resistance: polyvinyl chloride has self-extinguishing properties. When M-Wood2 is produced by mixing wood chip with PVC, the material will also has this characteristic. PP M-Wood2 will have the same heat resistance property with natural wood.

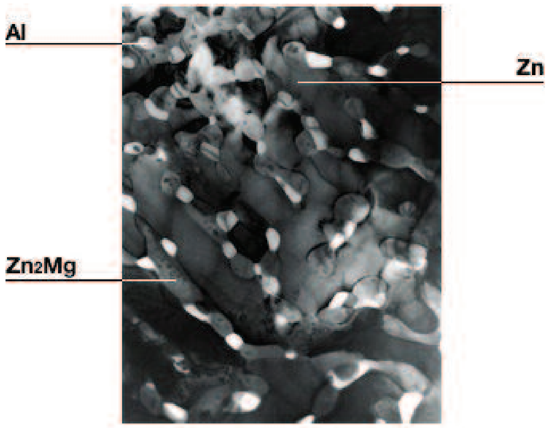
Abrasive resistance: M-Wood2 is proven to be more abrasive resistance than natural wood as shown in table 5.

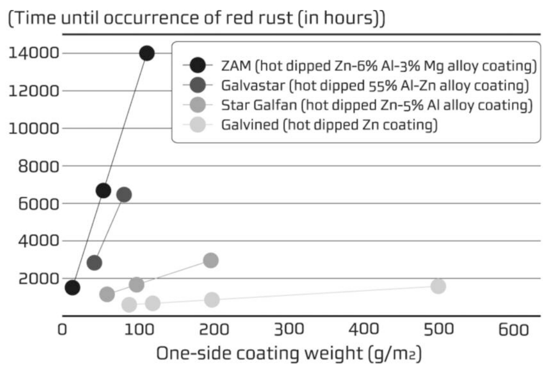
M-Wood 2 flooring	General flooring
0.415g / 500 times	0.750g / 500 times

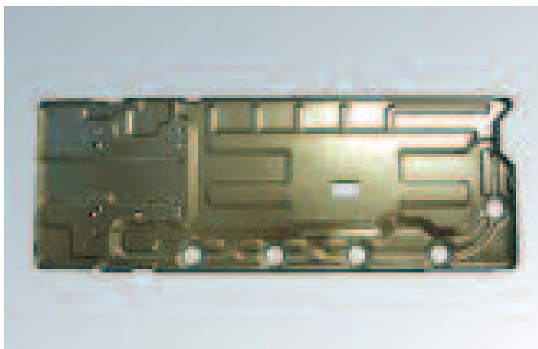
TABLE 5 ___ FLOORING ABRASION PROOF TEST (AS FOR METHOD OF EXAM IN JIS FLOORING CONFORMITY)

ZAM (I.C)

ZAM is a zinc-aluminum-magnesium high-corrosion-resistance hot-dip coated steel sheet. It is a three-layer coated steel sheet. The first two corrosion protective layers are magnesium-zinc and a zinc-aluminum with magnesium. Its flat section is 10 to 20 times more corrosion-resistant than conventional Zn steel and 5 to 8



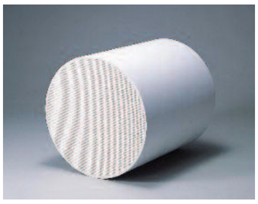




times more corrosion resistant than Zn-5% Al steel, and its cut end has greater corrosion resistance than previous coated steel sheets.

Its high corrosion resistance and hence longer life contributes to waste reduction, resource conservation, and energy saving. It eliminates coating process after forming, and contributes to environmental protection. (ZAM won the 2000 Nikkei prize for superior product and service (Nihon Keizai Shimbun award).

CERACAT™ (II.A)



This material is a ceramic honeycomb catalyst carrier use for exhaust gas purification and energy-saving heat reservoirs. This ceramic honeycomb resembles a bee's nest with its many chambers separated by thin walls and is capable of a variety of functions depending on the materials used and the cell structure. Materials that can be used in high-temperature environments include alumina (Al_2O_3), mullite ($3Al_2O_3 \cdot 2SiO_2$) and cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$).

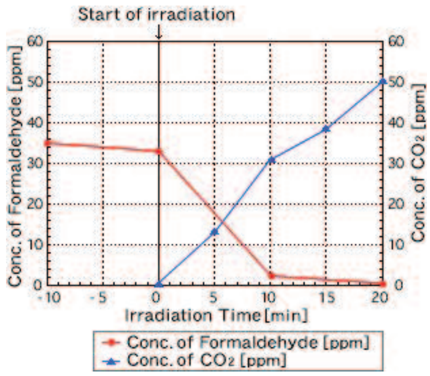
Recently, more and more strict regulation on the exhaust gas emission from diesel engines has been introduced worldwide. Installation of exhaust gas controlling systems has two constraints, removal of particulate matters (PM) and NOx while maintaining the engine system. Normally, exhaust gas control system will reduce the performance of engine. The ceracat material produced with world class technology enables more than 95% removal of PM while minimizing pressure loss in the control system. Some of characteristics of Ceracat are shown in table 6.

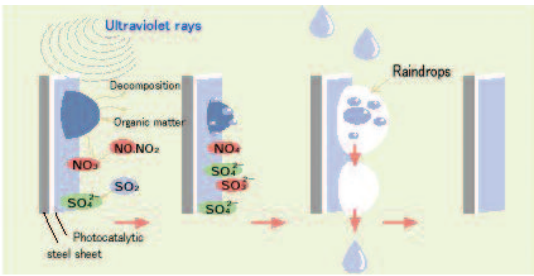
Material		Cordierite
Cell Struture		12mil/260cpsi
Diameter		266.7 mm
Lenght		304.8 mm
Porosity (reference)		65%
Filtration efficiency		Over 95% at weight ratio
Reduction of pressure drop	Initial After soot loading	20 ~30% (*) 50% (*)

TABLE 6 ___ PROPERTIES OF CERACAT™ FOR EXHAUST GAS FILTER

FOLIUM® - PHOTOCATALYST COATING AGENT (II.B)

Folium is a titanium dioxide photocatalyst coating agent which is used in building (external and internal wall, transparent glass), and transportation (car body, roads). The Folium will help to protect environment byreducing the concentration of formaldehyde and CO_2 in the atmosphere under the exposure of UV radiation. Immediately after exposure to ultraviolet light irradiation, formaldehyde concentration is decreased sharply to almost zero in about 20 minutes.





In addition, the use of titanium oxide as anti-bacteria could dramatically reduce the contamination of bacteria such as colon bacillus (*Escherichia col*) and *Staphylococcus*. An anti-bacteria effect test reported that after 24 hours, the *Coliform* and *Staphylococcus* count have fallen to less than 10 while the untreated samples shown about millions counts from *coliform* and thousand counts for *Staphylococcus*.

Another function of Folium is to protect the coated surface from dirt: A folium-coated surface will be able to remain clean, while a non coated surface will become dirty and deteriorate. The mechanism of this function is shown in the figure.

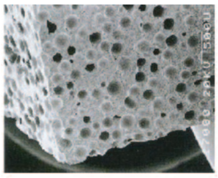
TOYOTA SUPER OLEFIN POLYMER (II.C)

One method to reduce the total weight of a vehicle is to replace steel by other materials such as aluminum or plastics as much as possible without reducing the safety. Car bumpers and interiors are now made of plastic. Recently, Toyota Company introduced their TSOP (Toyota Super Olefin Polymer) which had excellent recyclability in their car bumper. The TSOP is a polypropylene based blend material. The bumper could reduce plastic use by 18-30% compared to the traditional plastic bumper with similar safety properties. At the moment, TSOP is used in a wide range of interior and exterior parts in Toyota cars such as the new model of Corolla.

VOLATILE ORGANIC COMPOUNDS-FREE ADHESIVES (III.A)

These adhesives are free from all VOC (volatile organic compounds) including formaldehyde, toluene and xylene as sick-building syndrome gases. Two types are available: one for film installation and the other for wood and paper. These have outstanding adhesiveness and durability equivalent to the best conventional products.

BONE-CERAM (III.B)

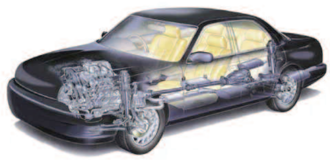


Spherical pores of 50~300μm in diameter are observed.(SEM)

Boneceram is a highly processable apatite hydroxide bone substitute material which plays an active role in medical fields. This material has an excellently biocompatible property to human tissue. The material is so highly processable that it could be made into complicated shape to fit to specific part. Boneceram is now essential for orthopedic surgery and brain surgery.

ULTRA-LIGHT STEEL FOR AUTOMOBILE (IV.A)

In Japan the automobile industry is greatly involved in the development of eco-materials including steel, non-ferrous and bioplastics for their "eco-car". For energy efficiency, some studies indicated that a 10% decrease in automobile weight would improve fuel efficiency by 10-12% . Whole life cycle energy consumption of a passenger car was mainly due to driving (75-80%) and material production, (15-20%) (Marukawa and Edwards 2001). In addition, about 75% (by weight) of a car was made of steel. It was obvious that if the weight of steel was reduced, energy efficiency of the car would increase. This could be achieved by selecting a high tensile strength steel without any reduction in safety of vehicle. According to Ultra-Light Steel Auto Body (ULSAB) project, a car body could reduce by 23% its weight contributing to a 5% weight reduction of a passenger car (Kawai 2001). High strength steel specifications range from 210 to 800 MPa yield strengths with thickness range from 0.65 mm to 2.0 mm. Further more, the use of materials which enable high-efficiency power generation would also improve the whole life cycle energy consumption.



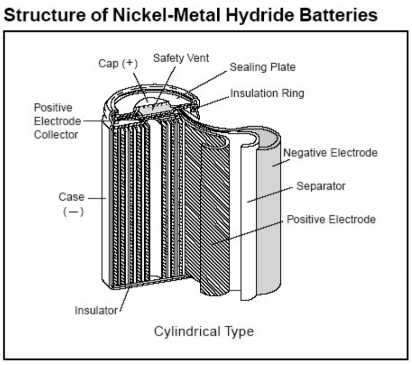
Product name	Boneceram P	Boneceram K
Generic name	Hydroxyapatite	
Molecular formula	$Ca_{10}(PO_4)_6(OH)_2$	
Molecular weight	1004.63	
Form	White porus body	White dense sintered body
	Can dissolve rather easily in 1N hydrochloric acid solution. Hardly dissolvel in any other solutions	
Sintering temperature	1150°C	
Weight per volume	1.66 ~ 2.02 g/cm^3	2.83 ~ 3.14 g/cm^3
Bending strength	Over 8.33 MPa	Over 58.8 MPa
Percentage of pores	35 ~48%	Dense body
Diameter of pores	50 ~300 µm	-

TABLE 7

HIGH HYDROGEN ABSORBING ALLOY (IV.B)

Hydrogen-absorbing alloys have a comparatively short history which dates back about 20 years to the discovery of NiFe, MgNi and LaNi5 alloys. They are capable of absorbing hydrogen equivalent to about a thousand times of their own volume (or about 3% by mass), generating metal hydrides and also releasing the hydrogen that they absorbed. More than 65% of hydrogen absorbed could be utilized. These hydrogen-absorbing alloys combine metal (A) whose hydrides generate heat exothermically with metal (B) whose hydrides generate heat endothermically to produce the suitable binding energy so that hydrogen can be absorbed and released at or around normal temperature and pressure levels. Depending on how metals A and B are combined, the alloys are classified into the following types: AB (TiFe, etc.), AB2 (ZnMn2, etc.), AB5 (LaNi5, etc.) and A2B (Mg2Ni, etc.). From the perspective of charge and discharge efficiency and durability, the field of candidate metals suited for use as electrodes in storage batteries is now being narrowed down to AB5 type alloys in which rare-earth metals, especially metals in the lanthanum group, and nickel serve as the host metals; and to AB2 type alloys in which the titanium and nickel serve as the host metals.

This hydrogen absorbing alloy has several potential applications such as heat utilization systems, hydrogen storage systems, actuators, hydrogen purification equipments, nickel-metal hydride secondary batteries, and catalysts. Recently, Sanyo electric has developed nickel-metal hydride secondary batteries, a portable fuel cell for notebook computers and a refrigeration system using this alloy. Toyota has also developed a new fuel cell system which combines with hydrogen-absorbing alloy to make a hydrogen storage device. This promises to be a more efficient, faster charging and farther travelling fuel cell.



3. FOUR STEP APPROACH FOR ECO-MATERIAL SELECTION FOR ECO-REDESIGN AND ECO--INNOVATION

A conceptual model of eco-material selection guidelines is illustrated in figure 3. 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 TNS (Robert 2002).

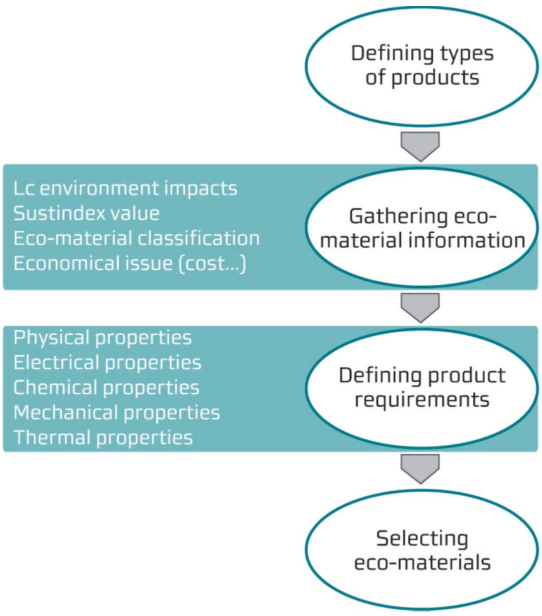


FIGURE 3 ___ FOUR STEP MODEL OF ECO-MATERIAL SELECTION PROCESS

3.1 DEFINING TYPE OF PRODUCTS (A)

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

Figure 4 illustrates the four general product types with a full consideration of life cycle concepts (Young 2002). A type I product normally has a very short lifespan and material intensiveness. A single use of package is a typical example of a type I product. In comparison to a type I product, a type II product has relatively longer lifespan, but has more manufacturing-intensiveness. Notebook computers and digital cameras are typical examples of type II products. In contrast, a type III product has a comparatively long lifespan. Energy and/or resource consumption during the use phase are the main concerns of type III products. Automobiles and washing machines are some typical examples of type III products. The last type of product is that with special end-of-life or disposal characteristics. Typical examples of this type of product are disposal diapers and Ni-Cd battery.

Defining the right product type is crucial in D4S 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

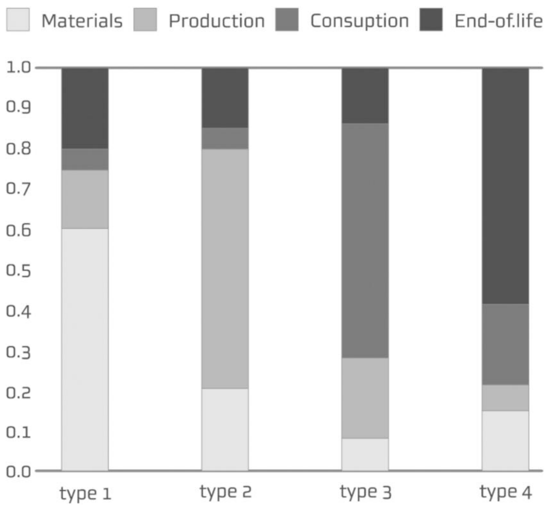


FIGURE 4 ___ FOUR GENERAL PRODUCT TYPES WITH LIFE CYCLE CONCEPT appropriate for type II product like digital cameras, as the lifespan of this product is relatively short (about 2-5 years). Another example is that the use of readily biodegradable polymers as a construction material is not appropriate. Renewable material is appropriate for type I products, while material that is most efficient to process is appropriate for type II products. Lightweight or high tensile strength steel should be used for type III products, while biodegradable or recyclable materials should be used for type IV products.

3.2 GATHERING ECO-MATERIAL INFORMATION (B)

The second step in eco-material selection guidelines is to obtain as much eco-material information 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.

The classification and database of eco-materials in previous sections are among the crucial information needed. By studying the information, product designers would have a better understanding on the state-of-the-art of eco-material development. From then, product designers should be able to direct themselves towards sustainability.

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 obtain, while some others like qualitative assessment are relatively easier to conduct.

Besides environmental and social information, economic information is also vital information. One of the 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 fluctuates in the market. Thus collecting cost of materials should be carefully carried out.

3.3 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 need to be defined. Information of these properties could be found in various sources such as IDEMAT, MATWEB, literature, handbooks, or company 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 and strength while having a high density. Polymers are lower in density with relatively low strength and stiffness. Thus defining appropriate product requirements will ease eco-material selection.

3.4 SELECTING ECO-MATERIALS (D)

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

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