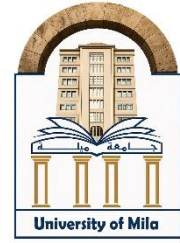




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Innovative materials and sustainability

COURSE: Master 01 / Civil Engineering

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CHAPTER 1: ECO-MATERIALS

1. Introduction

The construction sector is one of the major consumers of natural resources and energy worldwide. The production of conventional construction materials, particularly cement, concrete, fired clay bricks, steel, and aggregates, requires significant quantities of raw materials and energy and generates considerable environmental impacts.

These impacts include:

- depletion of natural resources;
- high energy consumption;
- greenhouse gas emissions;
- generation of industrial and agricultural waste;
- extraction and transportation of raw materials;
- excessive consumption of non-renewable mineral resources;
- land occupation associated with waste disposal.

In this context, eco-materials have emerged as an important component of sustainable construction.

An eco-material is a construction material designed, produced, or used in a way that reduces its environmental impact while maintaining the required technical, mechanical, durability, and functional performance.

Eco-materials are therefore not simply "natural materials." They may also include:

- recycled materials;
- industrial by-products;
- agricultural residues;
- activated mineral materials;
- recycled aggregates;
- waste-derived construction products.

The development of eco-materials is closely related to the principles of sustainable development, resource efficiency, waste valorization, and the circular economy.

2. Objectives of Eco-Materials

The development and use of eco-materials in construction aim to achieve several objectives.

2.1 Reduction of natural resource consumption

The use of recycled materials and industrial or agricultural by-products reduces the demand for virgin raw materials.

2.2 Reduction of environmental impacts

Eco-materials can reduce:

- embodied energy;
- carbon dioxide emissions;
- waste generation;
- extraction of raw materials;
- transportation requirements.

2.3 Waste valorization

A major objective is to transform materials traditionally considered as waste into useful resources. This principle can be expressed as:

Waste → Processing → Secondary raw material → Construction product

This approach is called waste valorization or material recovery.

2.4 Development of a circular economy

In a conventional linear economy, materials generally follow the sequence:

Extraction → Production → Consumption → Disposal

A circular economy attempts to establish a different system:

Extraction → Production → Use → Recovery → Reuse/Recycling → New product

Eco-materials are therefore strongly associated with the transition from a linear to a circular construction sector.

3. Valorization of Materials

The term valorization refers to the process of recovering the economic, technical, or environmental value of a material that would otherwise be discarded.

In construction engineering, material valorization may involve:

- reuse;
- recycling;
- recovery;
- mechanical processing;
- thermal treatment;
- chemical activation;
- incorporation into cementitious materials;
- incorporation into bricks, mortars, concrete, or geopolymers.

The objective is not simply to eliminate waste but to convert it into a useful secondary resource.

4. Classification of Materials for Valorization

Materials used in eco-material production can be classified into three major categories:

Category 1 – Natural materials

- natural stone;
- clay;
- natural pozzolans.

Category 2 – Activated materials

- calcined clays;
- metakaolin;
- rice husk ash.

Category 3 – Industrial by-products and waste

- rubber aggregates;
- blast furnace slag;
- LD steel slag;
- sediments;
- biomass ashes;
- sewage sludge ash;
- animal meal;
- recycled glass.

Each category has specific characteristics, processing requirements, advantages, and limitations.

4.1 Natural Materials

a) Natural Stone

Natural stone is one of the oldest construction materials used by humans. It is obtained from geological formations and can be used directly or after limited processing. Common examples include: limestone; sandstone; granite; basalt and marble.

Engineering properties

The properties of natural stone depend on its mineralogical composition, geological origin, porosity, and microstructure. The important properties include: compressive and tensile strengths; density; water absorption; porosity; abrasion resistance; frost resistance; thermal conductivity and durability.

Natural stone can be considered an eco-material when it is locally sourced and requires limited processing. However, its environmental performance depends strongly on:

- quarrying operations;
- extraction techniques;
- transportation distance;
- energy consumption during processing;
- waste generation.

Therefore, the environmental assessment must consider the entire life cycle of the material.

b) Clay

Clay is a naturally occurring fine-grained material composed mainly of clay minerals and other mineral constituents.

Traditional earth construction uses soil or clay-rich earth to manufacture adobe blocks; compressed earth blocks; stabilized earth blocks and rammed earth structures. One important eco-material is the stabilized compressed earth brick.

Stabilized Compressed Earth Blocks

A stabilized compressed earth block is produced by compacting a controlled soil mixture under pressure, generally with the addition of a stabilizing agent for instance; cement; lime; pozzolanic materials and combinations of mineral binders.

Typical constituents may include: clay soil; sand; water and cement or lime as a stabilizer. The general production process can be represented as:

Soil selection → Preparation → Mixing → Stabilization → Compression → Curing → Use

The stabilization process improves the mechanical and durability characteristics of the earth material. (increasing compressive strength; reducing water sensitivity; reducing shrinkage; improving durability; increasing dimensional stability).

c) Pozzolans

A pozzolan is a siliceous or silico-aluminous material which, although not necessarily cementitious by itself, can react with calcium hydroxide in the presence of water to form cementitious compounds.

The fundamental reaction can be simplified as:

Pozzolan + $\text{Ca}(\text{OH})_2$ + H_2O → C-S-H / C-A-S-H phases

where: **C** = CaO ; **S** = SiO_2 ; **A** = Al_2O_3 ; **H** = H_2O .

The reaction products contribute to strength and durability.

Natural pozzolans are geological materials exhibiting pozzolanic activity. Examples include: volcanic ash and natural pozzolanic earths. In concrete technology, natural pozzolans can be used as supplementary cementitious materials (SCMs).

Pozzolanic Activity

The pozzolanic activity represents the ability of a material to react with calcium hydroxide and generate secondary cementitious phases. A high pozzolanic activity generally contributes to:

- improved later-age strength;
- reduced calcium hydroxide content;
- refined pore structure;
- reduced permeability;
- improved durability.

The reaction is often slower than the hydration of Portland cement. Consequently, pozzolanic materials may influence early-age and later-age properties differently.

4.2. Activated Materials

Activated materials are materials whose physical or chemical reactivity has been increased through a treatment process. One of the most important activation processes is thermal activation. The general concept is:

Raw Material → Calcination → Structural modification → Reactive aluminosilicate

The resulting material can exhibit significant pozzolanic activity.

a) Calcined Clays

Calcined clay is clay that has been subjected to controlled heating at elevated temperature in order to modify its mineralogical structure and increase its reactivity.

During calcination, clay minerals undergo dehydroxylation. The key effects of dehydroxylation and calcination:

- remove structural hydroxyl groups;
- destroy the ordered crystalline structure of certain clay minerals;
- increase the amorphous fraction;
- increase pozzolanic reactivity.

b) Metakaolin

Metakaolin is a highly reactive aluminosilicate material obtained through the controlled calcination of kaolinite-rich clay. It is widely studied as a supplementary cementitious material.

In Portland cement systems, cement hydration produces calcium hydroxide. Metakaolin reacts with part of this calcium hydroxide and contributes to the formation of additional cementitious phases which may produce:

- increased compressive strength;
- reduced permeability;
- pore refinement;
- improved resistance to some aggressive environments;
- reduction of calcium hydroxide;

However, metakaolin may also increase:

- water demand;
- rheological sensitivity;
- the need for chemical admixtures.

Consequently, mix design is essential.

c) Rice Husk Ash

Rice husk is an agricultural residue generated during rice processing. When rice husk is subjected to controlled combustion, the resulting material is called rice husk ash (RHA) which may contain a high proportion of silica. Its properties depend strongly on:

- combustion temperature;
- combustion duration;
- oxygen availability;
- cooling conditions;
- grinding;
- original rice husk composition.

The form of silica is particularly important. Amorphous silica is generally much more reactive than highly crystalline silica. Therefore, controlled combustion is required to produce a highly reactive ash. An inappropriate thermal treatment can result in excessive crystallization and reduced pozzolanic activity. As engineering product Rice husk ash can be incorporated into:

- cement-based mortars;
- concrete;
- blended cement;

- geopolymeric systems;
- other alkali-activated materials.

Its use contributes to agricultural waste valorization and can reduce the consumption of conventional clinker.

4.3. Industrial By-Products and Waste

Industrial activities generate large quantities of mineral and organic residues. Instead of treating these materials exclusively as waste, some can be incorporated into construction materials after appropriate characterization and treatment.

a) Rubber Aggregates

Waste tires represent an important source of polymeric material. After mechanical processing, tires can be transformed into rubber granules; rubber chips; rubber fibers and rubber aggregates. Recycled rubber can be incorporated into concrete; cementitious composites; asphalt mixtures; impact-absorbing materials and lightweight construction materials.

Effect on Concrete

Rubber aggregates have a low density and relatively high deformability compared with mineral aggregates.

Their incorporation can lead to:

- reduced density;
- increased deformability;
- improved impact resistance;
- increased energy absorption;
- improved damping characteristics.

However, increasing rubber content generally tends to reduce:

- compressive strength;
- stiffness;
- sometimes bond quality between rubber and cement paste.

Therefore, surface treatment, particle size optimization, and mix design can be important.

b) Blast Furnace Slag – HF

Blast furnace slag is a by-product generated during the production of pig iron in a blast furnace. It is formed when the non-metallic constituents of the iron ore and fluxes combine and separate

from the molten iron. When rapidly cooled, molten slag can form a glassy material with hydraulic or latent hydraulic properties. A major valorization route consists of producing Ground Granulated Blast Furnace Slag (GGBFS) which can be used as a supplementary cementitious material aiming to:

- reducing clinker consumption;
- lowering embodied carbon;
- improving later-age strength;
- reducing permeability;
- improving durability in appropriate environments.

c) LD Steel Slag

LD slag refers to slag produced during the Linz–Donawitz (LD) basic oxygen steelmaking process. It is generated during the conversion of molten iron into steel. LD slag contains significant amounts of calcium oxides; iron oxides; silicon oxides and magnesium oxides.

After appropriate processing and characterization, steel slag can be used in:

- road construction;
- aggregates;
- hydraulic engineering applications;
- cementitious systems;
- other construction materials.

d) Sediments

Disposal of accumulate Sediments in rivers; reservoirs; ports; canals and dams can become an environmental and economic problem. Depending on their composition and contamination level, sediments may potentially be used in:

- bricks;
- mortars;
- concrete;
- embankment materials;
- road materials;
- ceramic products.

Before valorization, sediments must be characterized in terms of:

- particle-size distribution;
- mineralogy;
- organic matter;
- moisture content;

- heavy metals;
- soluble salts;
- contaminants.

e) Biomass Ashes

Biomass ash is produced during the combustion of biomass for energy production. Possible biomass sources include: wood; agricultural residues; crop residues and plant wastes.

The resulting ash may contain significant quantities of silica; calcium; potassium; magnesium and alumina. Depending on its composition and reactivity, biomass ash may be used in:

- cementitious materials;
- mortar;
- concrete;
- stabilized soils;
- bricks;
- geopolymeric materials.

The chemical composition of biomass ash varies significantly according to the biomass source and combustion process. Consequently, characterization is essential before use.

f) Sewage Sludge Ash – STEP

Wastewater Treatment Plant (WWTP) generates sewage sludge. After appropriate thermal treatment, the resulting ash is referred to as sewage sludge ash (SSA). It contains significant mineral phases and may be investigated for incorporation into cementitious materials; mortars; concrete; ceramics and construction blocks. However, its use requires careful assessment of heavy metals; phosphates; soluble compounds; mineralogy; chemical stability. Therefore, environmental characterization is particularly important.

g) Animal Meal

Animal by-products can be processed into animal meal. These materials may contain:

- organic matter;
- calcium;
- phosphorus;
- mineral constituents.

After suitable thermal treatment, the mineral fraction may potentially be recovered and incorporated into selected construction applications.

h) Recycled Glass

Waste glass can be collected, sorted, cleaned, crushed, and processed into different particle sizes. The resulting material may be used as: recycled glass aggregate; glass powder; fine filler and pozzolanic material.

Finely ground glass contains a significant amount of amorphous silica. When the particle size is sufficiently small, this silica can participate in pozzolanic reactions.

A simplified reaction is:



This can contribute to:

- strength development;
- pore refinement;
- reduction of calcium hydroxide.

Alkali–Silica Reaction

One of the major concerns associated with the use of glass aggregates in concrete is the Alkali–Silica Reaction (ASR). It can occur when:

- reactive silica is present;
- sufficient alkalis are available;
- sufficient moisture is present.

The reaction may generate an expansive alkali–silica gel, which results in internal expansion and cracking and consequently loss of durability.

Interestingly, finely ground glass can behave differently from coarse glass aggregate. Fine glass powder may exhibit pozzolanic behavior and can reduce some ASR-related risks when appropriately formulated.

5. Characterization of Eco-Materials

Before using a waste or by-product in construction, its characteristics must be carefully evaluated.

Type of Characterization	Main Parameters / Tests	Purpose
Chemical	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , CaO, MgO, Na ₂ O, K ₂ O, SO ₃ , LOI	Determines the chemical composition and helps assess the material's potential reactivity and compatibility with construction applications.
Mineralogical	XRD, thermal analysis, infrared spectroscopy	Identifies crystalline and amorphous phases and helps understand the mineralogical structure of the material.
Physical	Particle size, specific surface area, density, porosity, water absorption, morphology; SEM	Determines the physical characteristics and microstructure, which influence processing and material performance.
Mechanical	Compressive strength, tensile strength, flexural strength, elastic modulus, abrasion and fracture resistance	Evaluates the material's mechanical performance and suitability for structural or non-structural applications.
Durability	Water absorption, permeability, chloride penetration, carbonation, sulfate attack, freeze–thaw, chemical resistance, alkali–silica reaction	Assesses the material's long-term performance and resistance to environmental degradation.
Environmental	Leaching, heavy metals, toxicity, pollutant release, environmental compatibility	Verifies that the waste-derived material is safe and environmentally acceptable for use in construction.

6. Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic methodology for evaluating environmental impacts associated with a product or process during their entire life cycle. For instance:

Raw material extraction → Production → Transportation → Construction → Use → Maintenance → End of life

Important environmental indicators may include: Global Warming Potential (GWP); energy consumption; water consumption; resource depletion and waste generation. Therefore, a recycled material is not automatically sustainable in every application. The complete life cycle must be considered.

7. Eco-Materials and sustainable construction

In sustainable construction, the general objective is to keep materials and resources in use for as long as possible while minimizing waste and environmental impacts, this can involve:

Term	Definition	Example in Construction
Reduce	To decrease the consumption of raw materials, energy, water, and other resources, and to minimize waste generation from the beginning.	Using less cement in concrete by optimizing the mix design.
Reuse	To use a material or product again for the same or another purpose without significantly transforming it.	Reusing bricks recovered from a demolished building in a new construction project.
Repair	To restore a damaged or deteriorated product or component so that it can continue to be used instead of being discarded.	Repairing cracks in a concrete element instead of replacing the entire element.
Recycle	To process waste materials so that they can be transformed into new materials or products.	Crushing demolition concrete to produce recycled aggregates for new concrete.
Recover	To extract useful materials, energy, or other resources from waste that cannot be directly reused or recycled.	Recovering energy from combustible construction or industrial waste.

8. Advantages and Limitations of Eco-Materials

Advantages

Eco-materials can provide:

- reduction in natural resource consumption;
- reduction in waste disposal;
- reduction in clinker consumption;
- potential reduction in CO₂ emissions;
- resource recovery;
- development of local materials;
- economic benefits;
- contribution to circular economy;
- improved sustainability of construction.

Limitations

However, several challenges remain:

- variability of waste composition;
- contamination;
- quality control;
- durability concerns;
- processing requirements;

- transportation;
- regulatory constraints;
- lack of standardization;
- uncertain long-term performance.

Consequently, technical performance and environmental performance must be considered simultaneously.

9. General Valorization Methodology

A systematic approach for developing an eco-material can be summarized as follows:

Step 1 – Identification of the resource

Determine the origin and availability of the material.

Step 2 – Characterization

Determine:

- chemical composition;
- mineralogy;
- physical properties;
- environmental characteristics.

Step 3 – Treatment

Possible treatments include:

- grinding;
- sieving;
- washing;
- drying;
- calcination;
- stabilization;
- chemical activation.

Step 4 – Formulation

Determine the optimum proportion of the valorized material.

Step 5 – Manufacturing

Produce the construction material.

Step 6 – Performance evaluation

Evaluate:

- mechanical performance;
- durability;
- physical properties;
- environmental safety.

Step 7 – Life Cycle Assessment

Evaluate the environmental performance over the complete life cycle.

Step 8 – Optimization

Optimize the material considering:

Performance + Cost + Environmental impact + Durability

Conclusion

Eco-materials represent an important approach toward sustainable construction. Their development is based on the efficient use of natural resources, the recovery of industrial and agricultural residues, and the integration of secondary materials into construction products.

The central principle is that A waste material should not be considered only as a disposal problem; after appropriate characterization and treatment, it can become a valuable secondary raw material. However, the use of an eco-material must always satisfy three fundamental requirements: Technical performance + Environmental safety + Economic feasibility

Therefore, the development of eco-materials requires an interdisciplinary approach combining materials science, civil engineering, chemistry, environmental engineering, durability science, and life-cycle assessment.