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Cement Based Materials for Sustainable Development

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ABSTRACT

The human sensibility concerning environment has grown greatly since the environmental problems have shown to the world their devastating impact on human life. Thus the sustainable development of human activities has become one of the most important target of the human race. In this context the cement and concrete industry plays an important role because it leads to a production of CO_2 and it consumes raw materials and energy. This paper discusses how the cement based materials can contribute toward sustainable development. A stating point for the construction industry should be to think their activities in four keys concepts: energy efficiency, recycling materials, low emissions and durability. This could lead to some benefits in environmental terms but also can improve profits and investments in order to ensure a sustainable and durable future for the construction industry.

INTRODUCTION

The most accepted definition of sustainable development is from the Brundtland Report: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The basic concept is that the world is a system connected in space but also in time. The equilibrium between the resources and needs has to be controlled in the present time and for the future time. It means that in qualitative terms the needs of today will be the needs of tomorrow but in quantitative terms the needs will increase with population growing. This is not a new concept; Egyptian, Greek, American Indian but also the modern societies of European cities of the Renaissance understood, not without problems, the limits not to overcome in order to preserve the equilibrium (Huppert 1998). The reasons of their success were both in the possibility of travel and discover new resources when something threatened the equilibrium and in the relative ease to manage small independent systems (villages, towns, cities). Nowadays, because of many factors (economic interests, fast technical development, globalization), we have to follow new regulations in order to restore a sustainable development. The construction industry shares an important role for the worldwide economy. However, it sustains a thick slice of the world employers such as engineers, architects, plant operators and technicians. Therefore it has a duty to support the sustainable development in order to maintain the well-being that the human society has achieved. A great environmental impact is attributed to construction industry. Indeed a lot of construction materials, i.e. cement based materials, derive from processes which are pollutant and/or consume a significant quantity of raw materials and energy. One of the most important threat to the environment is due to the CO_2 emission coming from the production of cement. It was calculated that the quantity of the released CO_2 into the atmosphere is more or less equal to the quantity of Portland cement produced. It is no wonder that, taking into account the aforesaid information, the sustainability of the concrete and cement industries has to be improved. Furthermore it is worth of notice that the construction industry, especially the concrete manufacturing, has the possibility to contribute largely to the sustainability development. In the last years a lot of studies have been carried out in order to improve the sustainability of construction materials. In this contest the main targets of cement and concrete industry are:

- limitation of greenhouse gases emission;
- developing resources-saving solutions for infrastructure and building based on concrete;
- utilizing the ability of concrete to reduce the need for energy to heat and cool buildings;
- promoting construction materials recycling.

LIFE CYCLE ASSESMENT

The contribution of the cement based materials to the sustainable development can be related to a fundamental concept: every construction material has to have a minimal environmental impact thinking about all its life starting from the extraction of raw material up to the disposal. In other words it has to be taken into account the material life cycle. A life cycle analysis is the most common approach of identifying and assessing the environmental effects of construction products during their life; it is based on the vision that every element of the productive processes is taken into account all together (meanwhile the traditional engineering has studied them disconnected). The living process of a construction material can be divided in five steps (exploitation of raw materials, construction material production, construction phase, service life and demolition). After the demolition, part of the waste materials has to be recycled in order to produce new construction materials. The recycled amount of demolition materials is a very important parameter of a life cycle analysis.

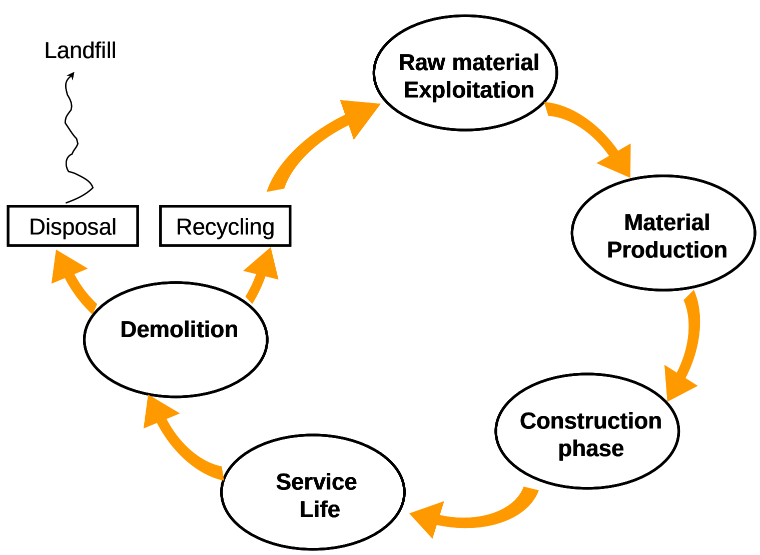

Fig. 1. Construction material life cycle analysis.

Energy

One of the most important aspect which has to be considered in a life cycle analysis is the energy saving. For instance, the cement manufacturing takes an appreciable quantity of energy because of the clinker production. Normally the energy requirements are satisfied with thermal energy arising from traditional fuels such as coal, pet coke and oil. While total electrical consumption per unit of production has remained fixed over the last decade in all types of kilns, total energy consumption has varied considerably. The switch to the relative new dry kilns resulted in greater production and so it favoured over natural gas, fuel oils and alternative fuels. Thus alternative fuels such as car tyres, waste oil/plastic/paper, sewage sludge and bone meal appear to have increased significantly in recent years (Fig. **2** Heagermann 2008). If in 1970, cement plants burned over 1500 million litres of fuel oils and about 6000 million cubic meters of natural gas, now only 124 million litres of fuel oils and a little more than a thousand million cubic meters of natural gas is burned.

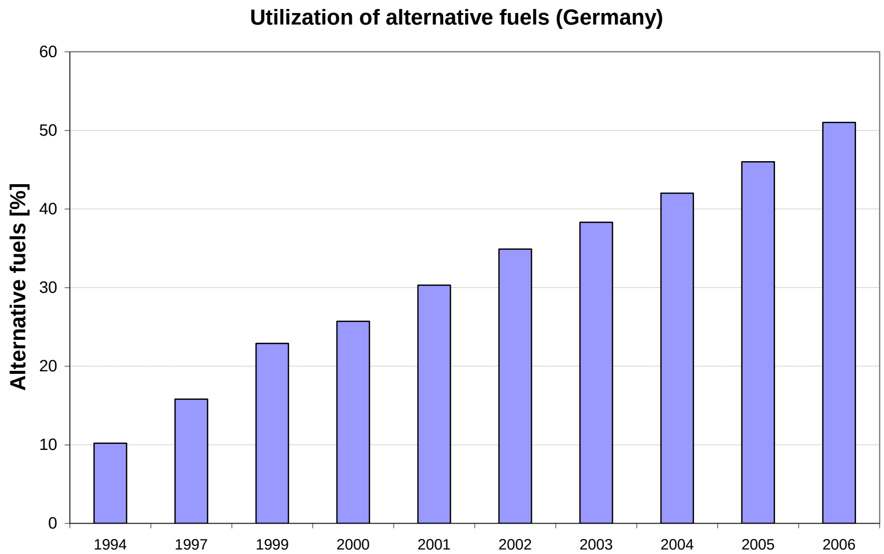

Fig. 2. Utilization of alternative fuels in cement manufacturing.

Emissions

In a life cycle analysis the role of each life phase of the construction material concerning pollutant emissions is studied. As example in Fig. **3** the general flowchart for ordinary concrete life cycle is shown (the compression strength of the ordinary concrete is about 30 MPa, w/c=0.65 and the density is 2330 kg/m^3). Each phase causes CO_2 emission.

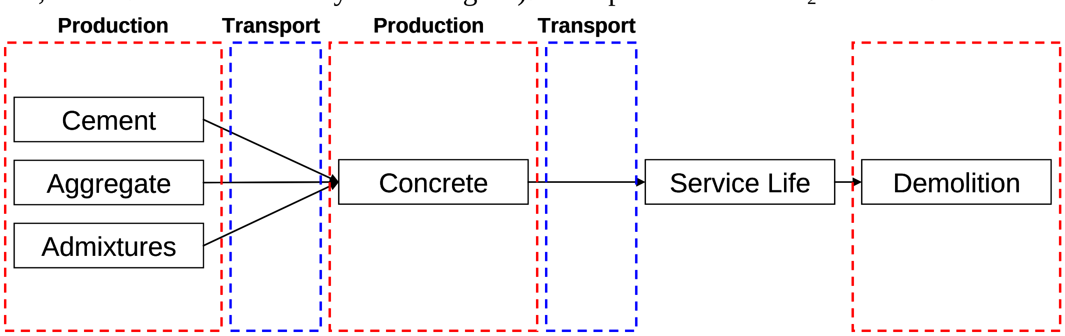

Fig. 3. General flowchart for the concrete life cycle.

The diagram of
Fig. **4** shows that the raw material production and the transportation operations are the major contributors to the environmental impact of concrete in terms of CO_2 emissions (Sjunnesson 2005). The transport operations include the transport of the concrete and the transport of the cement to the depot. Obviously the environmental load of the transport depends on distances, especially for cement, aggregates and admixtures. Transportation by ship has the smallest impact per tonne kilometre and covers the longest distance. Within the production of the concrete components, the Portland cement manufacturing has the largest environmental impact. Cement manufacturing leads to large-scale emissions of pollutant agents. The most dangerous are greenhouse gases like carbon dioxide, nitrogen oxides, carbon monoxide and volatile organic compounds and toxic chemicals. Greenhouse gas emissions from the cement manufacturing industry are the result of both the process of transforming limestone and other components into clinker and the burning of fuels in the rotary kilns, which also releases carbon dioxide. For each ton of Portland cement clinker produced, almost 1 ton of CO_2 and up to 10 kg of NOx are introduced into the atmosphere (Malhotra 2004).

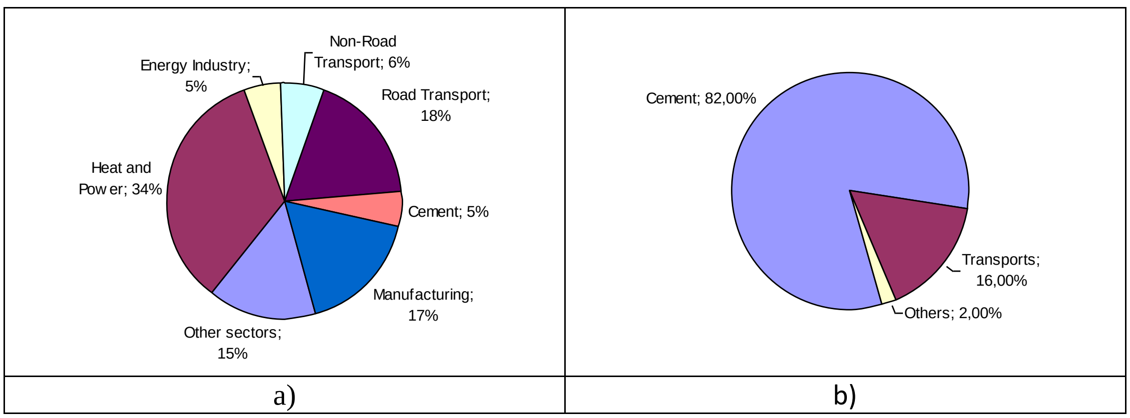

Fig. 4. CO_2 emissions of human activities (a) and difference in impact between the different stages in the concrete life cycle (b).

Cement production accounts for 5 % of the total CO_2 emissions. Approximately half of that stems from the calcinations of limestone; the rest comes from fuel combustion (40-50%) and the use of electric power (0-10%) (Malhotra 2004). However the environmental load in terms of CO_2 emission is decreased in the last ten years up to about 6%. The main reasons of this may be the development of better cleaning steps in the production, more effective incineration and the increased use of renewable fuels. In order to reduce the clinker production the Portland cement can be substituted by various by-products deriving from industrial process. The other factors such as demolition and admixture production have trivial roles. In the last years a lot of studies have been carried out about passive strategies for the reduction of CO_2 emissions. One of the most important of these, in cement and concrete field, is based on the capacity of cement matrix to uptake carbon dioxide by carbonation process. Carbonation of concrete is a well known process where the carbon dioxide reacts with calcium hydroxide (product of reactions coming from the cement hydration) leading to the calcium carbonate ($CaCO_3$) precipitate. The source in the carbonation process is the natural CO_2 in the atmosphere. Normally this process is dangerous for reinforced concrete durability because it accelerates the corrosion of steel reinforcement. Theoretically, hardened concrete can bind the same amount of CO_2 produced for the calcination process of limestone with carbonation process. This happens if all the calcium hydroxide reacts with carbon dioxide. The important parameter because it take place is concrete quality correlated with water/binder ratio and so porosity, the cement/binder types, the microclimate (wet, dry, sheltered etc.) and the surface (paint, wallboard etc.). The CO_2 amount up-taken by the concrete structure during their service life is not enough to allow the complete carbonation reaction. An essential part of the CO_2 binding take place after demolition of the structure. When concrete structures are demolished the produced recycled concrete aggregates (RCA) largely increase the specific surface area which can up-take carbon dioxide. The CO_2 uptake rate per unit mass of concrete and thus the total amount of CO_2 uptake is therefore increased in the secondary life (after demolishing stage).

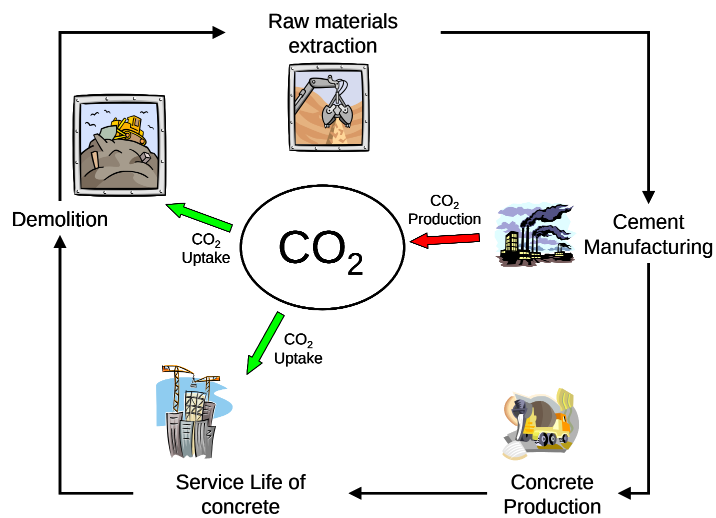

Fig. 5. CO_2 cycle concerning cement and concrete manufacturing.

Recycling and valorization

Some materials coming from wastes can be used for the production of new construction materials. They are usually used as substitution of cement in order to reduce the CO_2 emission related to the clinker production otherwise as secondary aggregate so as to preserve the primary aggregates (natural alluvial or crushed). The recycled materials are divided in two main categories: the pre-consumer and post-consumer. Pre-consumer materials normally are by-products deriving from industrial process. They include slag, fly ash, silica fume and rice-husk ash. Normally this type of materials are in powder state and so that they are largely used in the cement production as substitution of clinker. Beside the reduction of CO_2 emission these additions allow to reach improved concrete durability. Pre–consumer materials derive also from extractive operations such as ornamental stone waste, from boat manufacturing such as glass reinforced plastic or from. The most common post-consumer materials come from the recycling of common domestic materials such as glass and plastic or from demolition waste such as concrete, bricks and rubble. Construction and demolition wastes (C&D) are largely used as source of recycled material; it represents the 80% of all recycled materials used in construction. Of this approximately 10% of waste is used directly in the manufacture of new concrete. The rest is used in applications such as sub-base and fills, preserving primary aggregate for use in higher quality applications. A specific type of recycled aggregates is recycled concrete aggregates, where the masonry content is limited to not more than 5%. The performance characteristics of recycled concrete aggregates are better than for recycled aggregates generally and consequently there are fewer restrictions on the use of recycled concrete aggregates in concrete. A lot of studies have been carried out also for less common materials which include wooden ash, paper sludge ash and municipal solid incinerated wastes. The designer of concrete mixes who use these materials has to be careful about some harmful aspects that can limit the use of them (e.g. expansion, shrinkage, water adsorption, bad smell, etc.). In the last years are growing some technologies for the polluted soil valorization by producing aggregates from it. Normally the process is divided in a phase of soil solidification by encapsulating wastes into a solid cement matrix and a second phase of stabilization of inorganic contaminants. In some case the produced aggregates also have good mechanical properties.

Durability

During the service life phase the structure durability plays an important role on the construction sustainability. The main indicator of the building sustainability are the costs, comprising construction costs and maintenance costs. The repair actions are very expensive and they involve a lot of logistical and environmental problems such as traffic jam or new pollutant emissions. Thus the target of architects and engineers should be positioning the maintenance point as far as possible in time. The building durability could be enhanced by careful structural and architectural project and by using durable materials.

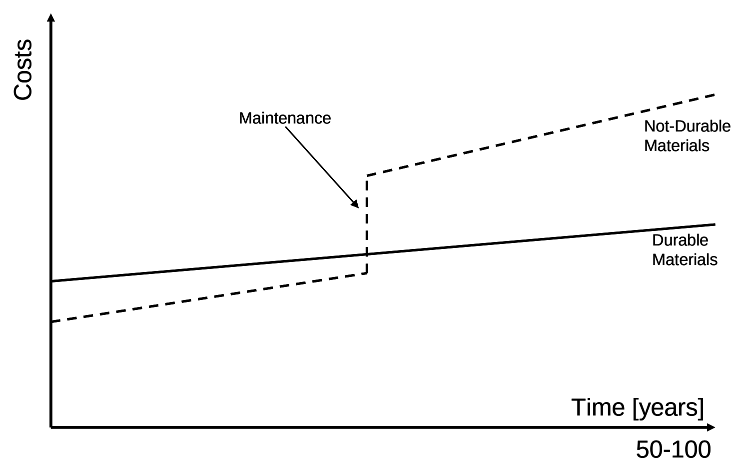

Fig. 6. Costs development during service life of buildings.

In the last decades many studies has been carried out in order to develop the mix design of concretes with enhanced durability properties with particular reference to the resistance to penetration of aggressive ions intended as an intrinsic material properties. However the problem of mass transport should be always coupled to the cracking susceptivity of the material owing for example to its shrinkage behaviour. The most common way to reach high durability in concrete is the using of blended cements composed by Portland cement and mineral addictions (slag, natural pozzolan, fly ash and silica fume are the most common). Studies suggest that the improvement of the strength and durability using mineral additions are governed by refinement of the pores in the cement paste. Both the physical and chemical properties of these materials and appropriate curing conditions affect the paste microstructure.

GREEN BUILDING

The concept of green building includes a variety of strategies during the design, construction and service life of buildings which are able to reduce energy consumption and improve occupant health. A green building has to be also easily recyclable during demolition phase. In this regard the system of certification for Green Building best-known and widespread in the world is the LEED protocol (*Leadership in Energy and Environmental Design*). It provides some criteria, developed in the United States since 1993 and now used in over 60 countries, for design and management of sustainable buildings. Certification is obtained through the allocation of credits by independent third-party entities for each of the required performance. The sum of these credits gives the level of certification (certification 40-49 credits, silver certification 50-59 credits, gold certification 60-79 credits and platinum certification 80 credits). The requirements are divide in 7 categories (Table 1). In Italy this protocol is promoted by the GBC Italy (no-profit association sponsored by the Consortium Technology Cluster).

Table 1. LEED requirements and credits (LEED 2009 NC&MR).

Category	Prerequisite	Credits
Sustainable Sites	1	26
Water Efficiency	1	10
Energy and Atmosphere	3	35
Materials and Resources	1	14
Indoor Environmental Quality	2	15
Innovation in Design	-	6
Regional Priority	-	4

In this context, sustainable building materials could be used for credits achievement in the following categories:

- Materials and Resources: this category includes a wide range of credits concerning waste recycling, waste management and renewable resources. Some requirements award the amount (based on cost) of recycled material content, such as aforesaid industrial by-products.
- Energy and Atmosphere: this category analyzes all the energy parameters of the building: mechanical systems, heating systems, cooling systems, energy production, energy consumption and also pollutant emissions. Energy use during the life of a structure take a huge amount of the total energy necessary for the building (much more than the energy spent in construction phase and in materials production phase). The main part of this energy is used for heating and cooling. Thus, the thermal efficiency of buildings is a key element in computing its environmental impact and is also a factor widely recognized for its importance. Both the design of external walls and the choice of insulating and structural materials are contributor to thermal insulation. In the last years the building thermal efficiency is becoming one of the most important parameter for the sustainability also for standards and laws.

NEW TARGETS IN CONSTRUCTION MATERIAL INNOVATION

Many efforts are spent at present time by the cement and construction industry in order to develop new products able to guarantee a sustainable development. This target is a challenge and an opportunity also for Italcementi Group. In fact it is deeply involved in new strategies aimed to realize the industrial growth compatible with environmental protection. Concerning the sustainable topics, R&D Department has produced in the last years several green materials thank to a close relationship with Universities and international boards. Especially new cements have been developed in order to run direct and positive actions on reduction of the main air pollutants. Moreover other cement based materials, able to significantly reduce the environmental impact in indirect way, have been developed.

Photocatalytic cements

These cements acts direcly on the reduction of air pollutants such as NOx and organic materials. They can have also a cleaning effect on the exposed surface. Their principle of action is based on photocatalysis which allows the oxidation reaction of NOx and organic matters. The photocatalysis is based on the presence of a special type of titanium dioxide which acts as catalyst when is exposed to sunlight. It has been demonstrated in real applications (road pavements and tunnel lining) that is able to reduce the pollutant concentration up to 25%. It does not get consume during the reaction, so that its effects are not limited in time. This cements are used for manufacturing a wide range of cementitious products such as pavements, structural elements, plasters and coating.

Sulfoaluminate cement

It is another example of a new sustainable product. Sulphoaluminate cement developed by ITC is a special binder that can be comprised in the sulfobelitic cement family. The main phases present are: $C_4A\$$, C_2S e anhydrite. Other minor phases as CFT (calcium iron titanate), sulfospurrite ($C_5S_2\$$) and mayenite ($C_{12}A_7$) could be present. Calcium sulfoaluminate cements in general have a much lower embodied RM-CO_2 content than Portland cement due to their significantly lower total CaO contents (30% lower than a modern OPC clinker). These type of clinker can be manufactured using existing high-efficiency cement kilns, leading additional CO_2 emission reduction due to the lower clinkering temperatures. The peculiar physical and mechanical properties of are:

- the ability to vary the setting time by changing blending ratios between sulfoaluminate clinker, Portland cement and calcium sulfate;
- fast development of mechanical properties;
- gradual increase of mechanical properties up to values higher than those of Portland cement.

Blended cements

Others studies on special cements have been carried out. Some subsidiaries materials (fly ash, slag, silica fume) were selected and blended together with Portland cement. The result is a series of blended cements with very high slag content (up to 90%) which can be used to achieve high performance concretes with higher mechanical properties, higher durability and lower heat development than HPC made with Portland cement.

Concretes

About thermal efficiency the European and Italian standards establish lower limits to thermal efficiency of building by imposing stringent upper limits to thermal transmittance. In addiction other requirements concerning vapour permeability and thermal inertia shall be considered. In the last years lightweight insulating concretes were studied in order to obtain high building thermal performances. The result is the development of a family of concretes with different density for different aims. The lightest concretes (500 kg/m^3) are characterized by low thermal conductivity and very high vapour permeability meanwhile the heaviest (1700 kg/m^3) presents structural mechanical properties. With this type of concretes it is possible to produce pre-casted panels, bricks and structural masonry. Furthermore waste lightweight aggregates and pre-consumer materials have been used so that the total amount of recycled material is about 90% (in volume). From studies on concrete it has been developed a particular mix design of a self compacting concrete which combine the already known advantages typical of SCC with the absence of fillers. It means a great precious material saving.

ITC-Lab

A lot of these products have been used for the construction of the ITC-Lab, the new R&D headquarter of Italcementi Group. The building, designed by American architect Richard Meier is located on the far East of the Bergamo science park called "Kilometro Rosso" and spread to 11,000 m^2, of which about 7500 reserved for research laboratories. It will be the first Italian construction awarded with the LEED Platinum Certification.

CONCLUSIONS

In the 2002 the document "United nations decade of education for sustainable development" recommended particular attention to resources and to environmental fragility. In the text was underlined the limits of economic growth and its impact on society. It invited the human society to make responsible choices on the basis of consequences of human actions on environment. The construction industry has the great opportunity to transform itself in order to reach environmental benefits and new profits and investments in order to ensure a sustainable and durable future. A careful life cycle analysis of construction materials may be the best way to improve both the relationship with nature and economic stability. The role of innovation is fundamental for the valorization of waste materials, design of "green" processes and integration of plants in the natural context.

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