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Sustainable cements for green buildings construction

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Abstract

The large amount of waste yearly disposed to landfill, the global impoverishing of natural resources and environment, the emergency of carbon dioxide emissions, are some of the motivations driving research institutes and industrial world to move towards sustainable solutions for civil engineering field. Accordingly, the use of sustainable materials for green buildings construction is an important goal that must be reached in short times.

Sustainable cements can be designed by partially replacing clinker content with non hazardous waste. Indeed, recycling process can transform waste in secondary raw materials that work as new cement constituents usually leading to sustainable binders with peculiar environmental resistances. Details of cement manufacturing process and its effect on the environmental pollution as well as the route that can be carried out to tailor sustainable cements are reported and discussed.

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Keywords: sustainable materials; waste management; recycling; cement; building materials;

1. Introduction

Materials are the fundamental elements of buildings construction. Chemical, physical and mechanical properties of materials as well as a proper design are responsible of the building mechanical strength. Moreover, materials have the aim to ensure structures durability. The Italian Ministerial Decree 14/01/2008 "Regulations for constructions" [1] lists materials and products allowed for structural use, their characteristics and the main performances that must be fulfilled. CE (Conformité Européenne or European Conformity) marking is compulsory for the most important building materials, such as cement, aggregates for concrete and mortar, steel, etc., according to the 89/106/EEC "Construction products

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directive, CPD" [2]. The directive states "in Europe, construction products on the market must satisfy, for a reasonable working life, the essential requirements with regard to mechanical strength and stability, safety in the event of fire, hygiene, health and the environment, safety in use, protection against noise and energy economy and heat retention" [3]. The use of certified materials, their selection on the basis of environmental exposure during their working life and a proper design should guarantee building durability, including ordinary maintenance, over a period of at least 50 years (100 years for large and/or strategic public works) [1].

The design of green buildings should thus start with the choice and use of sustainable materials with similar or better features than traditional building materials. However, some questions arise: Can a frequently used building material such cement be sustainable and available on the market? Do sustainable cements follow all the requirements fixed for traditional ones? Do they have performances comparable to those of traditional materials?

Sustainable building materials are usually based on recycling of proper waste that, thank to its own characteristics, can partially and/or entirely replace natural materials deriving from no-renewable resources. Quarries exploitation to obtain natural raw materials, treatments such as grinding, washing, selection that are usually carried on natural resources, technological process (e.g. the sintering at high temperature for bricks and tiles, the clinkerization process for cement production, etc.) are all energy consuming procedures. Accordingly, in Europe building industry requires almost the 40% of the total energy consumed and is one of the main producer of CO_2 emissions.

Indeed, moving towards green buildings means modifying the usual building materials introducing between their components what today it is still called waste, but tomorrow it shall be called secondary materials. This strategy will lead to a strong decrease of landfill disposal, to safeguard non-renewable natural resources, to preserve the environment, to save energy and reduce costs. However, to be sure of the effectiveness and success of this change, it is extremely important that all the requirements provided by technical standards for traditional materials are completely fulfilled for the unconventional ones. Therefore, European Directive CPD has introduced a tool, the European technical approval (ETA), that need to be issued when no harmonized standards exist for the product, no mandate for such a standard has been given by the European Commission, no standard is going to be developed (yet) or a product deviates significantly from the relevant harmonized standards [4]. ETA is thus a European certification that can help the introduction of unconventional building materials based on waste, guaranteeing performances and characteristics of new building products and allowing their use even if a CE marking is still not available. When an ETA has been issued, it is valid in all EEA countries, for a period of five years, renewable thereafter.

The aim of this contribute is to highlight how cement, probably the most popular building material in Europe, can become sustainable thank to waste introduction in its productive process. Although reviews about waste recycling for building materials are available [5-7], not all the parameters necessary to validate and allow the use of waste based cement are usually taken into consideration and reported.

2. Cement Production

Italy is one of the main cement manufacturers with 32 Mton in 2009. In the European Union countries and in the world, cement production in 2009 was 191 Mton and 789 Mton, respectively [8]. The European standard EN 197-1 [9] disciplines which are the cements available on the market, their compositions, the chemical-physical-mechanical requirements that they have to fulfill and conformity criteria. Five main cement typologies are recognized, even if each category can have further division. Ordinary Portland cement (OPC) is defined as CEM I, composite Portland cement is CEM II, blast furnace and pozzolan cements are respectively CEM III and CEM IV, and composite cement is defined as CEM V.

Cement production is highly energy consuming and has a severe impact on the environment [10-11]. Clinker is the main constituent of most used cements: its production causes a large consume of natural raw materials (calcium carbonate (75-80 wt%) and clays (20-25 wt%)), very high temperature process (≈1500°C), a huge consume of natural solid fuels and a massive production of CO_2 emissions in atmosphere. In Fig. 1 a schematic representation of cement manufacturing process is reported. Besides clinkerization process (firing) occurring in a horizontal kiln, several grinding operations are necessary to obtain a final product with an average size of about 50 μm. In Fig. 2 cement, clinker and CO_2 emissions yearly produced in 2007 and 2009 are reported [8]. From 2007 to 2009 it can be observed a general decrease in cement production due to the recent economical crisis, however the weight ratio between CO_2/Clinker is constant and equal to 0.87. Thus, every year, for each ton of clinker produced, a little bit less of a ton of CO_2 is released in the environment with the well-known consequences on global warming and climate changes. In 2009 European cement production represented about 25% of the total production in the world.

The five main typologies of cement are generally produced in different amounts. European data are reported in Fig. 3 [12]. The most common cement produced is Portland-composites cement (CEM II) with almost 57%, followed by ordinary Portland cement (OPC, CEM I) with 27%. The clinker content in CEM II and CEM I is quite different, being at least 65 and 95 %, respectively. Of course, according to great environmental impact due to clinker manufacturing, the less clinker is produced and contained in the cement, the more the cement is sustainable.

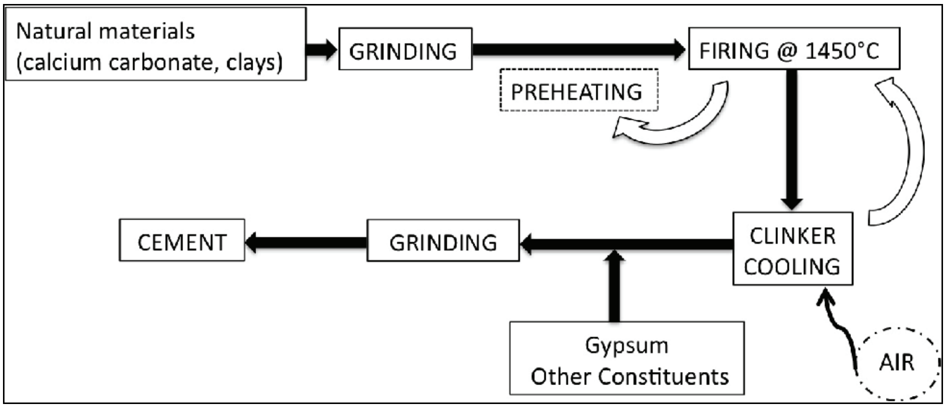

Fig. 1. Cement manufacturing process

However, one third of cement production in Europe is still addressed to CEM I as clinker is the fundamental constituent for cement mechanical strength development and fast setting time. Besides clinker, CEM II cements are composed by different constituents that can be natural materials such as calcium carbonate and natural pozzolan, or artificial ones (e.g. fly-ash, silica fume, blast furnace slag, etc.). The latter are very important because they have an active role in cement hydration process and are classified as secondary materials, being waste coming from different industrial processes (thermo-electric energy production, semi-conductors industry and iron production, respectively).

Indeed, Portland-composite cements constituted by fly-ash or silica fume or blast furnace slag can be considered the first examples of sustainable cements, although their diffusion is still rather limited (about 20-25%, fig. 3b).

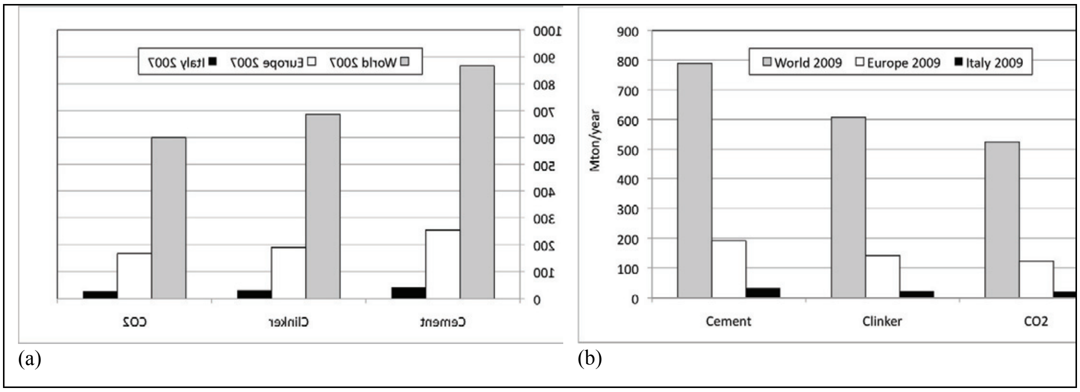

Fig. 2. Cement and clinker production, CO_2 emissions yearly produced in (a) 2007; (b) 2009 [8]

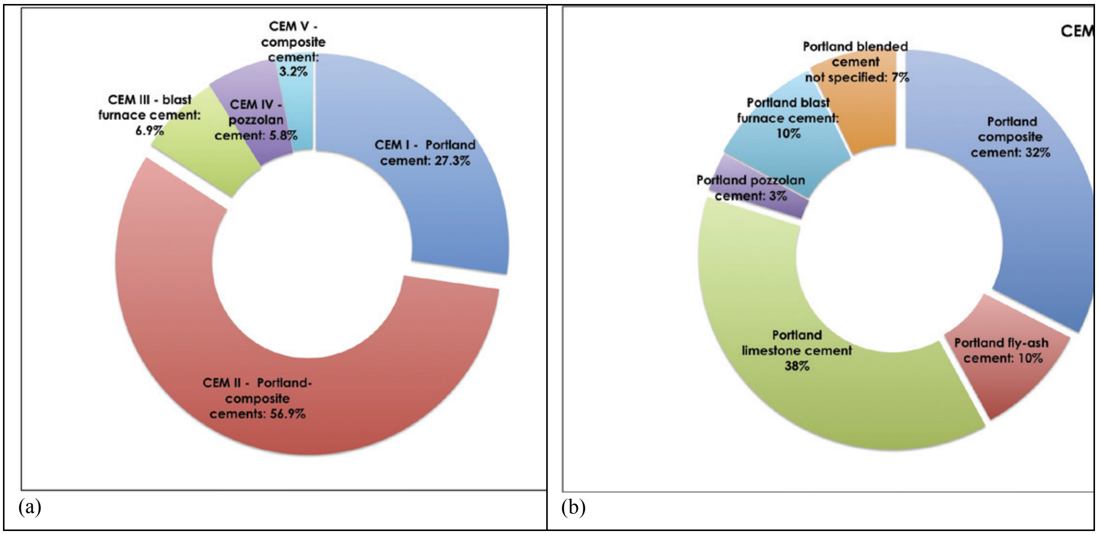

Fig. 3. Cement types production in Europe (a) and CEM II further subdivision (b) (year 2007 [12])

3. Sustainable Cements

Clinker content reduction and its substitution is the goal to follow to obtain sustainable cements according to the numerous researches carried out so far [13-19]). A very large interest has been recently addressed to investigate new cement constituents (also defined supplementary cementing materials (SCM)) based on waste. Pulverized soda lime glass [13], matt waste from glass separated collection [14,15], treated bottom ash [16], activated slag [17] and even ceramic residues [18,19] have been tested as SCM. But what are the fundamental requirements that sustainable cement has to fulfil to become part of the European Cement classification reported in EN 197-1?

Chemical, physical and mechanical parameters have been set for traditional cements by international standards and the limits fixed for each property (Tables 1 and 2). Thus new sustainable cements, constituted by SCM replacing clinker for amount usually ranging between 20-35%, must be classified for their mechanical strength class, setting time, soundness and the content of chemical substances potentially dangerous for the hydration process (e.g. chloride and sulphate ions, etc.). Unfortunately, not all these tests are usually carried out on the new binders thus leading to a partial characterization usually limited to mechanical features. However this cannot be sufficient to ensure a proper and safe use of new sustainable cements in constructions (Fig. 4).

Table 1 Physical and mechanical properties of cements according to EN 197-1.

Strength Class	Compressive Strength (MPa) (a) 2 day	7 day	28 day	Initial setting time (b) (min)	Soundness (b) (mm)
32.5 N		≥ 16.0	≥ 32.5	≥ 75	≤ 10
32.5 R	≥ 10.0	-	≥ 32.5		
42.5 N	≥ 10.0	-	≥ 42.5	≥ 60	
42.5 R	≥ 20.0	-	≥ 42.5		
52.5 N	≥ 20.0	-	≥ 52.5	≥ 45	
52.5 R	≥ 30.0	-	≥ 52.5		

(a) according to EN 196-1 [20];

(b) according to EN 196-3 [21]

Table 2 Chemical properties of cement according to EN 197-1.

	Cement Type	Class Strength	
Loss on ignition (a)	CEM I, III	All	≤ 5%
Insoluble residue (a)	CEM I, III	All	≤ 5%
Sulfate content as SO_3 (a)	CEM I, II, III, IV, V	All	≤ 3.5-4%
Chloride content (b)	CEM I, II, III, IV, V	All	≤ 0.10%
Pozzolanicity (c)	CEM IV	All	Test passed

(a) according to EN 196-2 [22]

(b) according to EN 196-21 [23]

(c) according to EN 196-5 [24]

Non observing physical and chemical limits can cause severe problems on concrete such as delay in setting, expansion products formation (e.g. ettringite), steel bar reinforcement corrosion, etc..

Concrete durability is a very important issue in civil engineering and cement plays an important role to make concrete compact enough to resist to environmental attacks. Acid rains, pollution, marine aerosol, seawater and chemical aggressions by industrial products are some of the environments that can damage cement and concrete consequently. During concrete hardening process, the exothermic hydration of the two main clinker constituents, tricalcium silicate ($3\ CaO \cdot SiO_2$ or C_3S) and bicalcium silicate ($2\ CaO \cdot SiO_2$ or C_2S), leads to the formation of a water soluble product ($Ca(OH)_2$, calcium hydroxide) and insoluble tobermorite or cementitious gel (C-S-H). Therefore, clinker hydration products are responsible at the same time of cement mechanical performances (C-S-H) and water solubility behaviour ($Ca(OH)_2$). Decreasing clinker content usually leads to an improvement of cement durability when pozzolan constituents and/or blast-furnace slag are added. The presence of unconventional constituents can thus work in the same manner: waste with suitable nature and chemical composition can behave as active and/or pozzolan constituents creating sustainable cements with improved durability properties.

Matt waste, coming from treatment of glass separated collection [14-15], and polishing residues, deriving from porcelain stoneware tiles production [17], have been successfully used as new constituents for the preparation of new sustainable cements. Thanks to their chemical compositions (both containing $SiO_2 \geq 60\%$) and the presence of amorphous phases show pozzolan activity, thus leading to binders able to resist to water and/or chemical aggression.

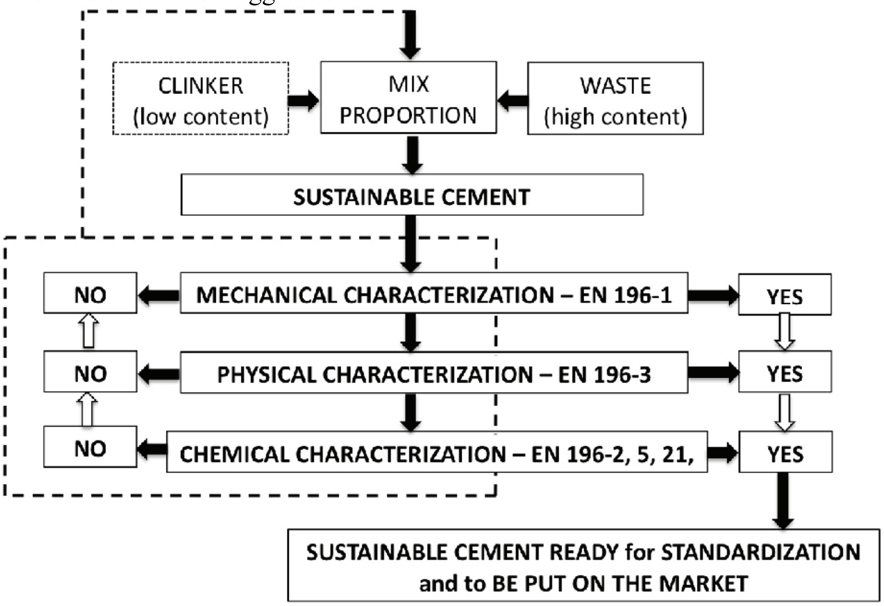

Fig. 4. Scheme for the standardization of sustainable cements

4. Final Remarks

Clinker replacement with unconventional constituents deriving from waste is an attractive route to produce sustainable cements. However, it is very important that the selected waste has an almost constant composition and be available in large amount, possibly well spread on the territory. Limits to the development of innovative blended cements are the necessity to start a complete standardization process of all the properties and to ensure the total absence of undesired chemical reaction (such as expansive products formations). Moreover, the national and/or European legislation must approve the use of the new binder for structural constructions to avoid risks of sudden damages.

Other routes to make cement production sustainable involve different approaches. For example, the alternative fuels use (e.g.: discarded tires) is becoming popular in cement kilns. Regional and national legislation shall strictly control what is burnt in cement kilns, the amount and relevant emissions. Although waste can be used in this way, disadvantages as low calorific value, high moisture content, presence of chlorine compounds or other potentially dangerous elements, can occur thus limiting this procedure.

Thermal and electrical efficiency of cement plant can be improved through equipments retrofitting with the aim to avoid energy loss and large consume of fossil fuels, however this solution is rarely adopted as usually very expensive.

Finally, a number of low CO_2 emissions cements are under studying. Between them, alkaline activated cements also called with name of geopolymers are receiving particular attention in these recent years, although they have been developed in 1905s. Strong alkaline solutions are required to activate raw materials mainly constituted by aluminosilicate. Geopolymers precursors can be obtained by firing process usually carried out about 600°C (e.g.: caolin calcination) and/or by aluminosilicate rich waste. Up to know, in Europe geopolymers are only commercialized in small-scale plants for special applications.

References

[1] Decreteo Ministeriale 14/01/2008 "Norme Tecniche per le costruzioni".

[2] Council Directive 89/106/EEC "Construction Product Directive".

[3] http://ec.europa.eu/enterprise/sectors/construction/documents/legislation/cpd/index_en.htm.

[4] www.eota.be/.

[5] Shi C, Fernández Jiménez A, Palomo A. New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and Concrete Research* 2011; **41**: 750-763.

[6] Shi C, Zheng K. A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling* 2007; **52**: 234-247.

[7] Gartner EM, Macphee DE. A physico-chemical basis for novel cementitious binders. *Cement and Concrete Research*, 2011; **41**: 736-749.

[8] http://www.wbcsdcement.org/.

[9] European standard EN 197-1 Composition, specifications and conformity criteria for common cements. Brussels:CEN; 2007

[10] Madlool NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews* 2011; **15**: 2042-2060.

[11] Rehan R, Nehdi M. Carbon dioxide emissions and climate change: policy implications for the cement industry. *Environmental Science & Policy*, 2005; **8**: 105-114.

[12] http://www.cembureau.be/.

[13] Shi C, Wu Y, Riefler C, Wang H. Characteristics and pozzolanic reactivity of glass powders *Cement and Concrete Research* 2005 ; **35** : 987–993.

[14] Bignozzi MC, Saccani A, Sandrolini F. Matt waste from glass separated collection: An eco-sustainable addition for new building materials. *Waste Management* 2009; **29**: 329-334.

[15] Bignozzi MC, Saccani A., Sandrolini F. Chemical- Physical behavior of matt waste in cement mixture. *Construction and Building Materials* 2010; **24**: 2194-2199.

[16] Saccani A, Sandrolini F, Andreola F, Barbieri L, Corradi A, Lancellotti I. Influence of the pozzolanic fraction obtained from vitrified bottom-ashes from MSWI on the properties of cementitious composites. *Materials and Structures 2005;* **38**: 367-371.

[17] Bignozzi MC, Sandrolini F, Andreola F, Barbieri L, Lancellotti I. Recycling Electric Arc Furnace Slag as Unconventional Component for Building Materials. Proceeding of 2nd International Conference on Sustainable Construction Materials and Technologies, 28-30 June 2010, Ancona (Italy), 2010; **1**: 557-567.

[18] Andreola F, Barbieri L, Lancellotti I., Bignozzi MC, Sandrolini F. New Blended Cement from Polishing and Glazing Ceramic Sludge. *International Journal of Applied Ceramic Technology* 2010; **7**, 546–555.

[19] Pacheco-Torgal F, Jalali S. Reusing ceramic wastes in concrete. *Construction and Building Materials* 2010; **24**: 832-838.

[20] European standard EN 196-1. *Methods of testing cement - Part 1: Determination of strength.* Brussels:CEN; 2005.

[21] European standard EN 196-3. Methods of testing cement - Part 3: Determination of setting times and soundness. Brussels:CEN; 2009.

[22] European standard EN 196-2. Methods of testing cement - Part 2: Chemical analysis of cement. Brussels:CEN; 2005.

[23] European standard UNI 196-21. Methods of testing cement. Determination of the chloride, carbon dioxide and alkali content of cement. Brussels:CEN; 1991.

[24] European standard EN 196-5. Methods of testing cement - Part 5: Pozzolanicity test for pozzolanic cement. Brussels:CEN; 2011.