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Life Cycle Assessment of Sustainable Concrete Made With Recycled Aggregates

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ABSTRACT

The results of an environmental study on concrete manufacture that follows the standard protocol of life cycle assessment are shown in this document. The study has been done for seven types of concrete: one conventional and six containing cement kiln dust (10%), marble sludge (10%) and demolition waste (10%, 80% and 100%) respectively, in partial or total substitution of natural aggregate. Six end of life scenarios have been proposed for the application of the life cycle assessment methodology. One of these is referred to the complete disposal of the waste obtained from demolition of studied concrete while in the others the treatment and recycling of demolition waste are analysed. In the latter cases the treatment plant location has been considered at different distances from the demolition site. The results show that, the life cycle of the considered concrete mainly impacts on greenhouse, summer pollution and winter pollution effects.

INTRODUCTION

The construction industry is a highly active sector in both developed and developing countries. A recent report shows that about 10% of the Gross Domestic Product and about 50% of the Gross Fixed Capital Formation of the European Union has been invested in this field [European Commission 2006]. As a consequence of this, environmental damage, resource depletion, high-energy consumption, solid waste generation and global greenhouse gas emissions are the main problems related the above industrial sector [CICA 2002; Melchert L. 2005; Zimmermann M. et al 2005]. Furthermore, the demand for energy and natural resources during the built phase and the life of buildings has to be kept in mind.
Building materials that prove to be more environmentally friendly, namely materials that better meet the two fold objective of reducing both consumptions of non-renewable resources and general pollution throughout their entire life cycle, are able to resolve the above problems.

In the past few years the European Commission has given great importance to the improvement of environmental impact of building products and components in view of the obtainment of an Environmental Product Declaration (EPD-ISO TC 14025 Technical Regulation). At the moment this represents a voluntary strategy for final users in order to obtain an environmental certification useful for possible economical incentives.

In the case of concrete components, data referred to raw materials employed, energy consumption, presence of mineral and/or chemical admixtures and production of waste materials and pollutants are needed in view of the obtainment of the EPD.

In the last decade, Life Cycle Assessment (LCA) methodology has been frequently used in the building sector to evaluate the environmental burdens of the various processes and products during their life cycle, including demolition and final disposal or recycling of final waste. A "*from cradle to grave*" approach has been applied for building components, such as masonry, concrete blocks, tiles and bricks. The results of the application of LCA to the construction industry is reported in a recent document where different ways of LCA employment for building materials and components have been explored [Ortiz, O. et al. 2009].

Definition of the scopes, creation of the inventory, impact assessment and the interpretation of the results represent the steps of the LCA methodology that is based on International Standard Series ISO 14040. The objectives, the system boundaries, the data sources and the functional units are defined into the scope definition phase.

The Life Cycle Inventory (LCI) consists of a detailed compilation of all the environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the life cycle.

The Life Cycle Impact Assessment (LCIA) phase aims at quantifying the relative importance of all environmental burdens evidenced in the LCI by the analysis of their influence on the selected environmental effects.

In this paper the results of LCA study for the manufacture of sustainable concrete containing Marble Sludge (MS), Cement Kiln Dust (CKD) and Building Demolition Waste (BDW) are presented. MS, CKD and the fine fraction of BDW have been introduced in the mix-design of concrete as substitution of 10% of natural aggregate. The coarse fraction of BDW has been employed in the manufacture of concrete, replacing 40%, 80% and 100% of the total amount of aggregate, respectively. The concrete quality has been determined by means of the evaluation of the specimens technological properties.

Several end of life scenarios for each concrete component have been considered. Specifically, the final destination of waste obtained by the demolition of the above concrete components have been: a) 100% landfill disposal and b) 15% disposal and 85% recycling as artificial aggregate. Finally, different distances from building and concrete waste treatment plant have also been studied in terms of environmental impacts evaluation.

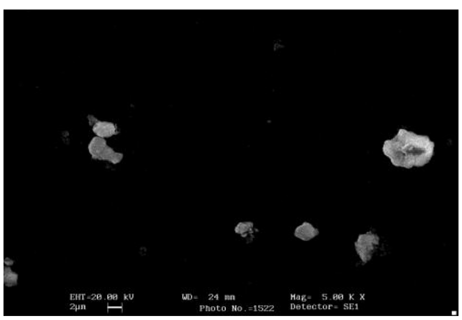
MATERIALS AND METHODS

Materials. All the materials considered have been characterized in order to prepare and study concrete mixtures with acceptable physical and mechanical properties. The cement used was a CEM II/A-L 32.5R. This met the requirements of the UNI-EN 197/1 standard.
The MS was a waste coming from marble block finishing operation made in presence of water. This waste, even if classified as an inert material, because of its extremely high fineness it could be dispersed in the environment causing very high damages in terms of soil reducing permeability. The CKD were waste powders collected from electrostatic precipitators in a cement clinker manufacturing kiln (Cementi della Lucania Factory, Potenza, Italy).

In order to evaluate the optimum substitution ratio of these wastes, their chemical and physical properties have been measured.

In Fig. 1(a) a Scanning Electron Microscopy (SEM) picture of MS particles is shown while the results of laser scattering particle size distribution analysis are reported in Fig. 2. These figures show that the particles are very well separated one from each other and the 90% of the powder has a diameter less than 10 µm. The chemical analysis of MS, reported in Table 1, shows a composition mainly containing $CaCO_3$ (CaO = 53.62%; L.O.I. = 42.94%, due to CO_2). The results of leaching test show that the total amount of heavy metals released is lower than 0.001 mg/l. The latter test is made according to Italian regulation (Environment Ministry Decree n.186/2006). As shown in Fig. 1(b) CKD is mainly composed of micron-sized particles. These particles are often agglomerated and very heterogeneous because their chemical composition and particle size distribution depend on raw materials and fuels employed, and on the kiln type present in the cement factory.

The results of laser scattering particle size distribution analysis of the CKD sample considered are reported in Fig. 3. They show that 90% of the powder has a diameter less than 8 µm. The CKD chemical composition, reported in Table 1 is suitable to propose its utilization in concrete manufacturing. In fact, the results of leaching test show that the amounts of heavy metals released are less than the limits imposed by Italian regulation (Environment Ministry Decree n. 186/2006).



(a)

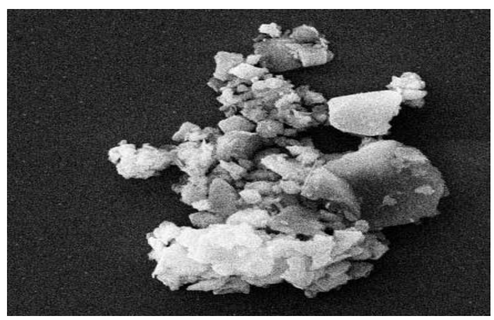

(b)

Fig. 1. SEM images of the particles of MS (a) and of the particles of CKD (b).

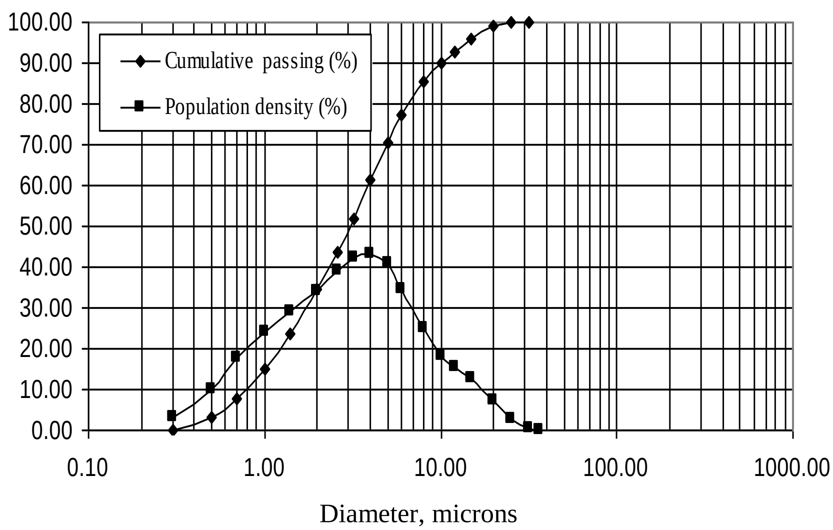


Fig. 2. Particle size distribution of the particles of MS.

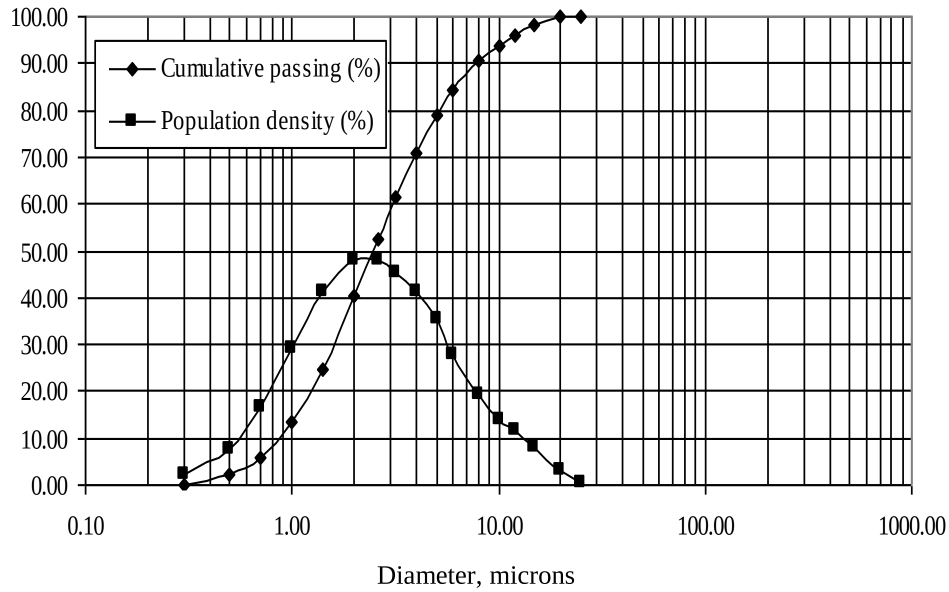


Fig. 3. Particle size distribution of the particles of CKD.

Table 1. Chemical composition of Cement Kiln Dust and Marble Sludge.

Waste	Oxides, wt.%							
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	L.O.I.
CKD	14.65	2.13	4.75	41.72	1.12	0.90	0.60	32.30
MS	1.12	0.11	0.37	53.62	0.87	0.14	0.10	42.94

Natural sand and crushed quartzite stone were used as sand (0÷5 mm) and coarse aggregate (5÷15 mm), respectively. The bulk density, specific gravity, water absorption, and void content were 1610 kg/m^3, 2.76, 0.40%, and 39% and 1760 kg/m^3, 2.49, 1.35%, and 31% for sand and coarse aggregate, respectively. An acrylic superplasticizer has bee selected and employed.

Mix-design and testing. The behaviour of natural aggregates and waste materials has been compared in concrete mixtures which have been designed according to previous studies [Colangelo et al. 2004]. The technological effectiveness of proposed mixtures has been evaluated by casting, curing and testing of concrete cubes (10x10x10 cm^3). Specifically, properties, such as slump and compressive strength, of fresh and hardened concrete specimens have been measured. The tests have been performed according to UNI EN 12390-3 and UNI EN 12350-2:2001 standards. At the end of these experimentations, the life cycle environmental burdens were calculated for the conventional and alternative concrete listed in Table 2.

Table 2. Mixtures proportions.

Materials, kg	Functional unit*: 1 cubic meter						
	Concrete types						
	CC	10MSC	10CKDC	10BDWC	40BDWC	80BDWC	100BDWC
Cement	320	320	320	320	320	320	320
Natural aggregate (0÷5 mm)	1020	839	839	839	612	204	-
Natural aggregate (5÷15 mm)	809	790	790	790	474	158	-
Artificial aggregate (0÷5 mm)	-	181	174	171	372	712	915
Artificial aggregate (5÷15 mm)	-	-	-	-	284	561	671
Water	170	170	170	170	170	170	170
Superplasticizer	3.0	3.5	3.5	3.4	4.5	6.1	6.4

CC=Conventional concrete; 10MSC=Concrete with 10% of marble sludge; 10CKDC= Concrete with 10% of cement kiln dust; 10BDWC, 40BDWC, 80BDWC and 100BDWC=Concrete with 10%, 40%, 80% and 100% of demolition waste.

*Functional unit means the concrete quantity considered during the environmental impact evaluation.

LCA procedure. The environmental assessment has been done following the protocols reported by ISO 14040-14043 standards and employing the SimaPro 7.1 software [Goedkoop, M., Oele M. 2008].

The studied phases of the life cycle of concrete are as follows:

- ✓ **Production of aggregates;**
- ✓ **Transport of materials;**
- ✓ **Concrete manufacture;**
- ✓ **Transport of concrete;**
- ✓ **Demolition;**
- ✓ **Disposal and/or recycling.**

As shown, the phases related to the production of cement and the use of building have not been considered. In fact, more often, the impacts due to the cement production are so high that they cover the effects of different artificial aggregates and different end of life scenarios.

In the application of LCA methodology the following parameters have been considered.

Functional unit. One cubic meter of concrete has been studied as a Functional Unit (FU).

In other kinds of analysis, when one single type of concrete is considered, a FU of 1 km of road, or 1 m of pipe, or one single part of building can be used. Another possibility is to include a time dimension, for example, 1 km of road during 100 years.

System boundarie. The end of life destination of the seven concrete studied have been included within the limits of the system that was the Basilicata Region (Southern Italy).

The impact from the manufacture of machines and other equipment used in the different processes is not included in the study.

The casting is excluded because of difficulties in gathering data, since the energy demand differs depending on the kind of concrete construction. It is estimated, however, that the energy input and emissions from this phase are limited. The use of water as a raw material is also excluded since water is not regarded as a limited resource.

Inventory data. Data were collected from existing environmental reports and communication with key actors on the concrete preparation and transportation. Demolition data are collected by personal communication with territorial operators.
In all cases, energy sources demand (coal, oil, natural gas, electricity) and emission to air production (CO, CO_2, SO_x, NO_x, hydrocarbons) are considered.
All Data are taken from 1995 to 2004, which is an accepted time span for this type of study.

End of life scenarios. The LCA analysis is made considering that, at the end of life, 100% of crushed concrete will be disposed off in a landfill or, alternatively, 15% will be disposed and 85% will be recycled. In case of recycling, the concrete waste will be treated in a plant located at different distances from the building demolition site. Specifically, distances of 30km, 40km, 50km, 60km and 150km have been take in to account.

RESULTS AND DISCUSSION

Technological properties. The results of the concrete specimens characterization are reported in Table 3. Here we can see that all the mixtures show the same workability and they are classified as a S4 consistency class. To obtain these results different amounts of super plasticizer have been employed. Specifically, as reported in Table 2, very similar super plasticizer amounts have been needed when MSC, CKDC and 10BDWC have been prepared. In the cases of mixtures 40BDWC, 80BDWC and 100BDWC the super plasticizer amount increases from 4.5 kg up to 6.4 kg. This effect is due to the higher porosity of BDW.
The superplasticizer amounts together with the types and amounts of aggregate have been considered in following phases of this work.

Table 3. Properties of fresh and hardened concrete

Properties	Concrete types						
	CC	10MSC	10CKDC	10BDWC	40BDWC	80BDWC	100BDWC
Compressive strength, MPa	36	38	35	34	31	25	23
Slump, class	S4	S4	S4	S4	S4	S4	S4

Global environmental impact
Greenhouse effect. The evaluation of concrete life cycle impacts must consider that generally the production of the materials is responsible of about 85% of the global warming potential. Specifically, cement production causes the largest greenhouse-gas emissions. In fact, almost the total of the CO_2 emissions comes from calcinations process and fossil fuel in the cement factory. Regarding this, it is known that CO_2 emissions decrease when replacing a part of cement with other mineral additions and a part of fossil fuel with renewable fuels.
The scope of this work is related to a life cycle study in which the quality and quantity of the cement employed are the same in all the analyzed systems. This way it is possible to evaluate

the environmental contribute of each artificial aggregate added. In fact, huge amount of slag, sludge, debris and powders coming from industrial processes could find useful employing in concrete manufacturing. This is more important if we consider that: a) the aggregate represent the main component of concrete; b) many industrial wastes are not reusable in cement production and c) disposal of such wastes will in the future always more difficult and expensive.
Figures 4, 5, 6 and 7 show the environmental impacts of the manufacturing of the seven concrete mixtures studied when four different end of life scenarios were considered.
In these figures it is possible to see that the Greenhouse Effect (GE) remains almost the same when the quantity of different artificial aggregates is equal to 10% for the systems containing MS, CKD and BDW, respectively. When replacing 40%, 80% and 100% of natural aggregate, this is the case of a coarser one, the effect of such substitution is more evident.
In the case of total substitution of natural aggregate, the GE arrives up to 50% of that calculated for concrete containing 10% of artificial aggregate.

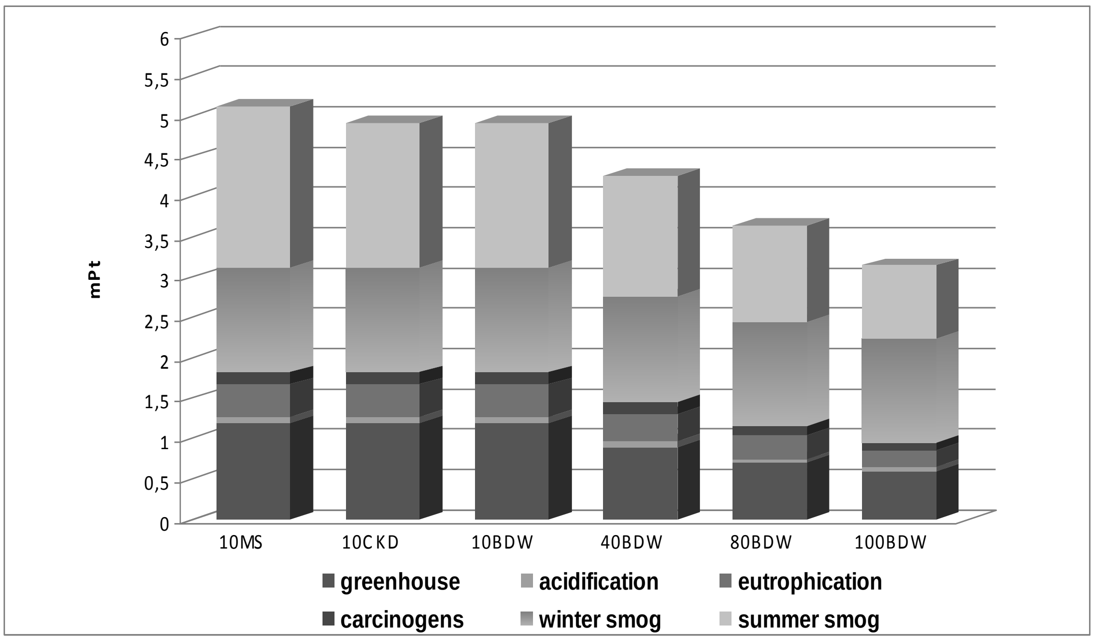


Fig. 4. Environmental impacts for concrete waste treated in a plant at 30 km from building demolition site.

When the distance of concrete waste treatment plant become longer the GE values remain almost the same, confirming that transportation phase has little influence on this effect.

Regional environmental impacts
Acidification Potential. Generally, 70% of the total acidification potential (AP) is mainly affected by transportation. The transport of concrete has the highest impact, closely followed by the transport of cement from factory to concrete manufacture. The production of raw materials also contributes to the AP, mainly in the production of cement.
In our study, as expected, the impacts due to AP is very low if compared to the others.

Eutrophication Potential. Usually, the main contributor to the eutrophication potential (EP) is the transportation phase. Very often it approximately represents 60-70 % of the total EP.

Concrete transportation, followed by cement transportation from factory to concrete manufacturing site, have the most significant effect on EP. Materials production has also a significant impact on the EP, mostly because of cement production, which causes high emissions of NOx.

In our study EP show the same behaviour for all the end of life scenarios with the exception of landfill disposed off (see Fig. 7). In fact, in all the recycling scenarios the values are the same for all systems containing 10% of waste, they decrease up to 100% of aggregate substitution. In the case of landfill disposal the EP values are generally 50% higher (see Fig. 7). This is due to the fixed distance between the landfill and the demolition site.

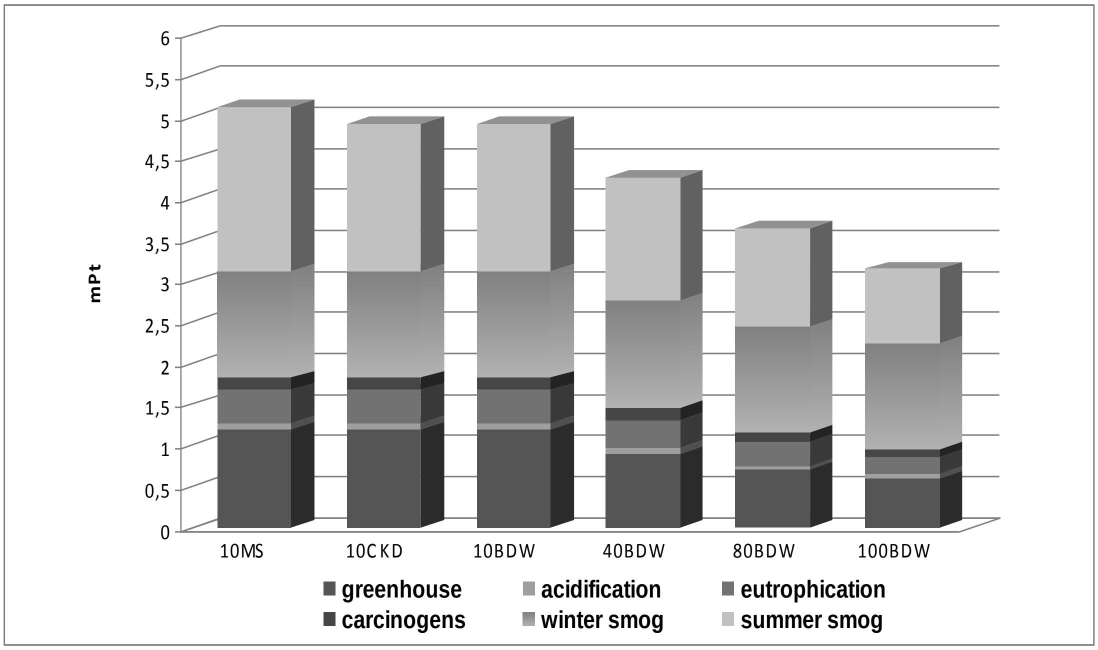


Fig. 5. Environmental impacts for concrete waste treated in a plant at 60 km from building demolition site.

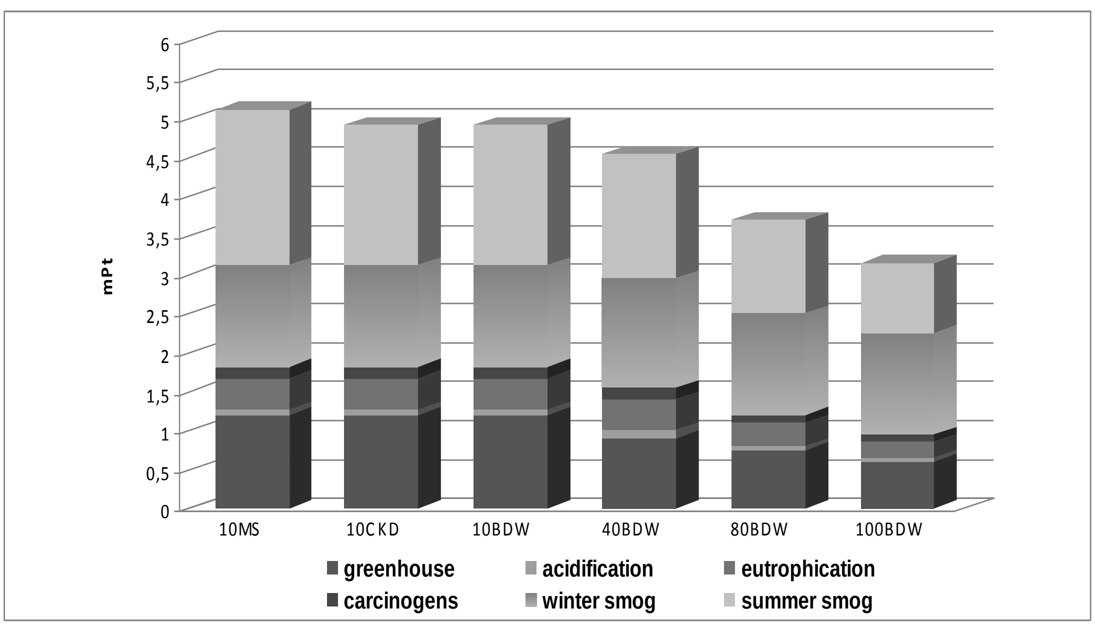


Fig. 6. Environmental impacts for concrete waste treated in a plant at 150 km from building demolition site.

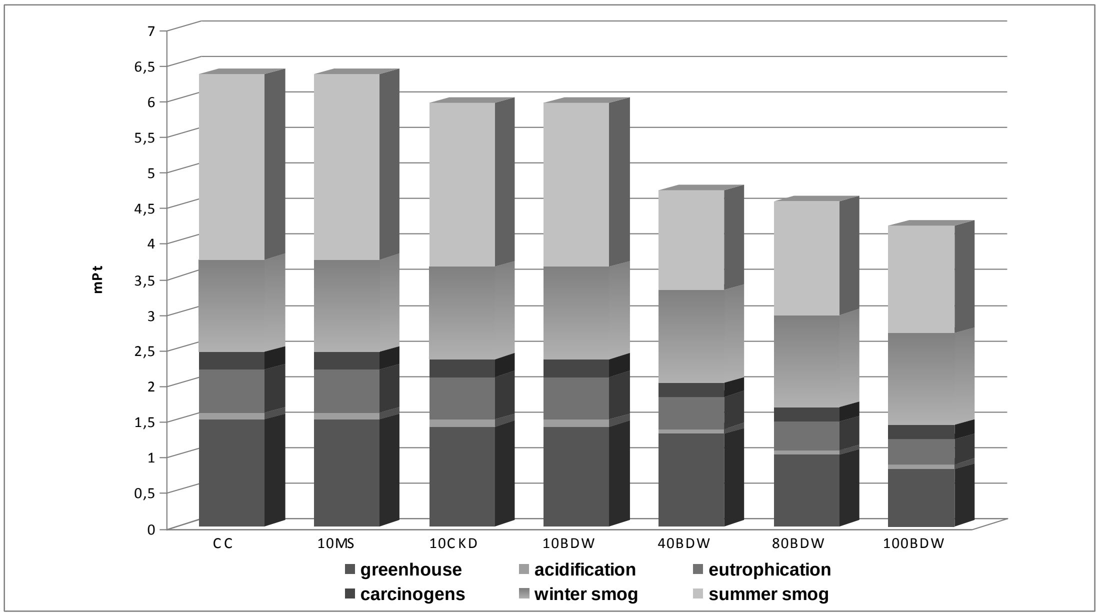


Fig. 7. Environmental impacts for concrete waste landfill disposed off.

Local impacts

Winter smog. The impact category as winter smog potential (WP) is associated to the air pollution due to the combustion by-products, such as dust and SO_2. In the case of concrete life cycle this impact is mainly correlated to the cement kiln emissions. In our study we can see very similar impact levels in Figs. 5-7. Furthermore, the absolute values of WP are very similar to the GE and the summer smog potential (SP).

Other environmental impact

*Carcinogens.*The carcinogens potential (CP) is related to adverse effects on health that pollutants, such as heavy metals, could determine. The harmful effect of different heavy metals is not always similar.

The raw material employed in our process contain small quantities of heavy metals and they can be found in oil, rock and coal. In Figs. 4-7, CP becomes lower when more than 40% of BDW is added. A 10% addition of CKD and MS does not determine a significant effect on CP.

Summer pollution. As showed in the case of WP the magnitude of summer smog potential (SP) calculated for our systems is very high. It depends on photochemical ozone formation. The contemporaneous presence of oxidizing photochemical substances (volatile organic compounds and carbon monoxide), nitrogen oxides and hydroxyl radicals are mainly due to the combustion associated with thermal processes. SP becomes lower when the amount of BDW increases. The observed trend is different in comparison with what is present in the case of WP. This means that the natural aggregate production gives an higher impacts in terms of the above pollutant emission.

CONCLUSIONS

The following general conclusions can be drawn from this study:
The transportation operations are the main phase that contributes to the environmental impact of sustainable concrete.
In our case, the maximum employable amounts of very fine wastes are equal to 10% by weight of the natural aggregate.
The workability and the resistance of the selected mixtures are comparable to the ones for medium grade structural concrete.
The addition of 10% of artificial aggregates doesn't significantly influence the environmental impacts.
The addition of coarse building demolition waste up to 100% of the aggregate produces significant positive effects on greenhouse and summer pollution environmental impacts.
The impacts evaluated for all the mixtures are almost the same when different end of life scenarios are considered with the exception of the total landfill disposals.

REFERENCES

Blengini, G. A. (2009) "Life cycle of buildings, demolition and recycling potential: A case study in Turin Italy" *Building and Environment*, 44(2), February, 319-330

Colangelo, F., Marroccoli, M., Cioffi, R. (2004) "Properties of self-levelling concrete made with industrial wastes" In :*The Use of Recycled Materials in Buildings and Structures* Edited by E. Vázquez, Ch. F. Hendriks and G.M.T. Janssen, RILEM, Barcelona, 1-11, ISBN: 2-912143-52-7 e-ISBN: 2912143756

Confederation of International Contractors' Associations (2002). "Industry as a partner for sustainable development" CICA. ISBN 92-807-2181-X.

European Commission. Construction unit of the European Commission: overview. <http://ec.europa.eu/enterprise/construction/index_en.htm> ; 2006 [accessed 18.07.06].

Goedkoop, M., Oele M., (2008), "SimaPro 7.1 - Database Manual - General introduction-Methods library"

Josa, A., Aguado, A., Heino, A., Byars, E., Cardim, A. (2004) "Comparative analysis of the life cycle impact assessment of available cement inventories in the EU." *Cement and Concrete Research*, 34, 1313-1320

Kellenberge, D., Althaus, H. J. (2009) "Relevance of simplifications in LCA of building components" *Building and Environment*, 44(4), 818-825

Melchert L. (2005). "The Dutch sustainable building policy: a model for developing countries?", *Build Environ*, 10, 7-17.

Mrouehm U. M., Eskola, P. (2001) "Life-cycle impacts of the use of industrial by-products in road and earth construction" *Waste Management*, 21(3), 271-277

Ortiz, O., Castells, F., Sonnemann, G. (2009). " Sustainability in the construction industry: A review of recent developments based on LCA." *Construction and Building Materials*, 23(1), 28-39

Zimmermann M., Althaus H.J., Haas A. (2005). " Benchmarks for sustainable construction – a contribution to develop a standard", *Energy Build*, 37(11), 1147-1157