Cement and Clean Aggregates from CDW: The C2CA Project

Francesco Di Maio   Peter Rem   Somi Lofti
Faculty of Civil Engineering and Geosciences
Delft University of Technology
2628 CN, Delft, the Netherlands
f.dimaio@tudelft.nl   P.C.Rem@tudelft.nl   S.Lotfi@tudelft.nl

Silvia Serranti   Giuseppe Bonifazi
Dipartimento di Ingegneria Chimica Materiali Ambiente
Sapienza - Università di Roma
Via Eudossiana 18, 00184 Roma, Italia
silvia.serranti@uniroma1.it   giuseppe.bonifazi@uniroma1.it

Mingming Hu
CML - Institute of Environmental Sciences
Leiden University
2300 RA Leiden, the Netherlands
hu@cml.leidenuniv.nl
Faculty of Construction Management and Real Estate
Chongqing University

Vasilis N. Burganos Eugene Skouras
Foundation for Research and Technology Hellas
Patras, Greece
vbur@iceht.forth.gr   eugene@iceht.forth.gr

Fernando Cucchietti Mariano Vázquez
Barcelona Supercomputing Centre
Barcelona, Spain
fernando.cucchietti@bsc.es   mariano.vazquez@bsc.es

Abstract: The recycling of end-of-life concrete into new concrete is one of the most interesting options for reducing worldwide natural resources use and emissions associated with the building materials sector. The production of the cement used in concrete, for example, is responsible for at least 5% of worldwide CO_2 emissions. Onsite reuse of clean silica aggregate from old concrete saves natural resources and reduces transport and dust, while the re-use of the calcium-rich cement paste has the potential to cut carbon dioxide emissions in the production of new cement by a factor of two. In order to achieve this goal, a new system approach is studied in which quality control assesses and maintains high standards of concrete demolition waste from the earliest stage of recycling, and novel breaker/sorting technology concentrates silica and calcium effectively into separate fractions at low cost. Finally, the smaller

calcium-rich fraction, which is typically also rich in fine organic residues, is converted into new binding agents by thermal processing, and mixed with the aggregate into new mortar. The project aims to develop three innovative technologies for recycling end-of-life concrete, integrate them with state-of-the-art demolition and building processes and procedures, and test the new system approach on two Dutch concrete towers involving 40,000 tons of concrete. The results of the project will be used to determine which kinds of strategies and policies are most effective to facilitate an efficient transition towards optimal value recovery from Construction and Demolition Waste and sustainable building.

Keywords: Recycling, **C***onstruction and* **D***emolition* **W***aste* (C&DW), **E***nd* **o***f* **L***ife* (EOL) concrete, green cement, hyperspectral, advanced sensors.

Introduction

The efficient high-grade recycling of **C***onstruction and* **D***emolition* **W***aste* (C&DW) is of increasing interest from an ecological and economic point of view, yet it is beyond what can presently be achieved by the recycling industry. The C2CA project aims at a new system approach for the production of cement and prime-grade aggregates from high-volume C&DW streams. It also aims to demonstrate the economic and ecological viability of this technology on a special case study in which the recycling of old buildings and the building of new ones are integrated into a single project. The final aim of the project is to define governmental policies that facilitate an efficient transition towards a combination of optimal value recovery from C&DW and sustainable building.

From the environmental point of view, the urgency of saving resources and reducing humanity's impact on the environment is evident. The millennium assessment report (WRI, 2005) as well as several other studies (WWF Living Planet Report, 2006) provide a clear indication that we have exceeded the Earth's ability to support our lifestyles. A major cause is the increasing consumption of primary raw materials.

The Fourth Assessment Report (WG III, 2007) of the IPCC identifies the building sector as the largest potential for cost-effective mitigation policies. Analyses by the European Community (SEC 1069, 2006) indicate that besides their ecological importance, raw materials and energy are also the most important competitiveness factor for EU industries, hence crucial to the success of the Lisbon Partnership for growth and jobs (COM-2008 699, 2008). At present the potential contribution of EOL concrete recycling to consumption is unknown (EEA Report No 8/201). The new C2CA system approach may clarify to what extent EOL concrete can supply resources for production of new concrete because it will clarify which fraction of EOL concrete is suitable to be used as secondary raw material. Therefore the need of increasing recycling and improving the quality and homogeneity of recycled materials to minimize environmental pollution and usage of primary resources is a topical subject for the European Community (Enterprise and Industry reports of the EC, 2008).

The consumption of cement in Western Europe has reached 239.6 Mton in 2007. Meanwhile the production of concrete has increased to 395.6 x 10^6 m^3 (European ready mixed concrete organization). These large numbers show that there is a strong drive to recycle concrete from C&DW into new concrete and to avoid its ending up in land fills. The electrical energy requirement to produce one tonne of cement is about 1584 MJ (Samarin, 1996). Calcination of one tonne of $CaCO_3$ releases 440 kg of CO_2, according to the stoichiometry of this reaction. Energy demand for the calcination of one tonne of clinker is 1750 MJ. Therefore for every tonne of Portland cement produced, cement plants generate about one tonne of CO_2 – one of the main greenhouse gases. About half of the emissions from cement production relates to the CO_2 that was chemically bound in the limestone ($CaCO_3$) feed. It is a major goal of this project to avoid the release of this chemically bound CO_2 by reusing the cement paste from old concrete as a low-CO_2 feedstock replacing primary limestone or as component of the Portland mixture. A second important socio-ecological impact of the building industry is road transport: in particular traffic congestion and the emissions of dust and CO_2. The transport of concrete from and to building sites amounts to an estimated 75 billion ton-km per year in Europe, or about 10-20 l of fuel per m^3 of concrete. The C2CA route allows a local reuse of up to 80% of EOL concrete, and therefore a significant reduction in road transport.

The proposed C2CA project is mainly addressed to produce a fundamental change of the use of the concrete component of C&DW: from material that is largely land filled or reused in low-grade applications to resources for high-grade recycle concrete (Figure 1). This aim is pursued through the definition of three routes, that is:

1. Innovation. Breakthrough technologies will be developed and set up for the liberation and production of cement and clean aggregates and fines (to be utilized as fillers) of high and consistent quality from C&DW streams, including: i) the novel **A***dvanced* **D***ry* **R***ecovery* (ADR) technology (de Vries et al.), ii) an ecological and economic effective thermal process technology that converts the cement paste fraction of C&DW into a cement product, and iii) developing process control and quality control technology based on powerful emerging sensor technologies;

2. Demonstration. Demonstrating the economic and ecological viability of this technology on special case studies in which the recycling of old buildings and the building of new ones are integrated into a single project;

3. Dissemination. Defining governmental policies facilitating an efficient transition towards a combination of optimal value recovery from C&DW and sustainable building. Part of this work may lead to the development of a management framework, based on a materials data bank, to make a quick inventory of local/regional availability of potential concrete volumes that can be used for new building activities.

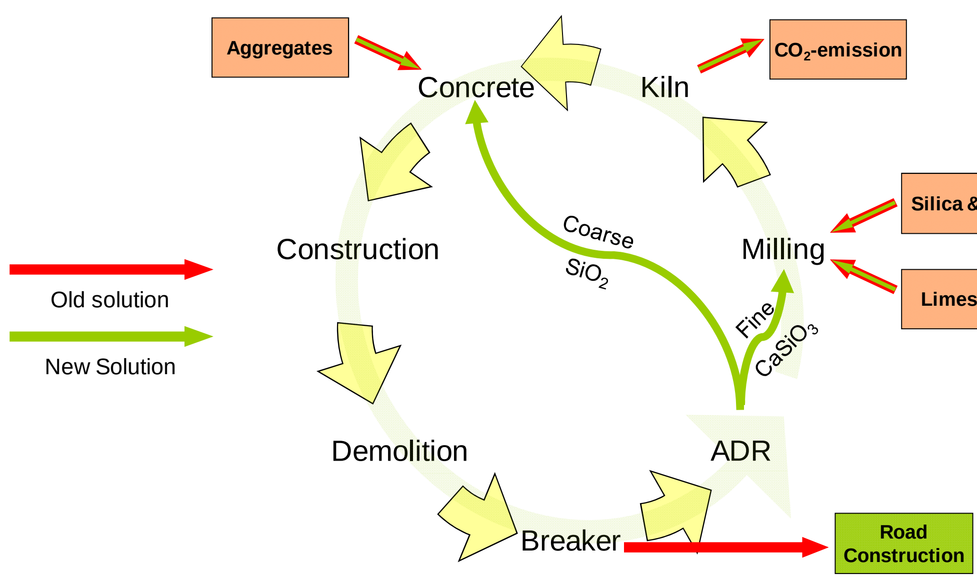


Figure 1. The old route and proposed novel closed cycle for C&DW.

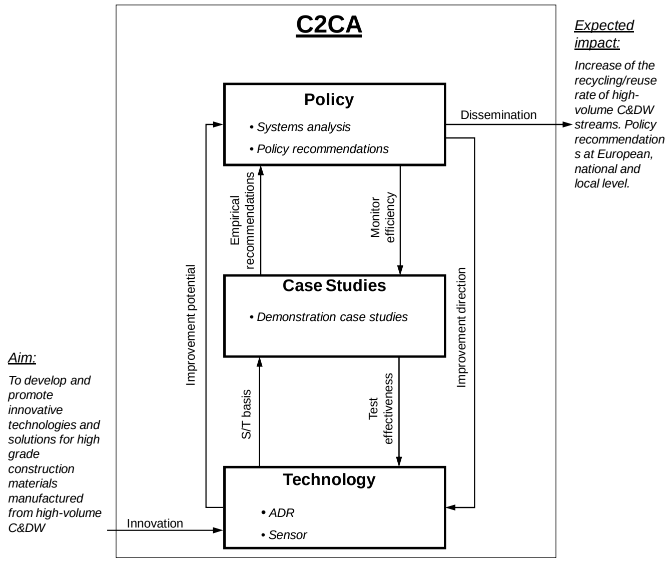


Figure 2. Logic framework of C2CA

Following the previous mentioned routes the C2CA project will create a significant step forward in the state-of-the-art of C&DW recycling in Europe and in the world. The project is carried out in a close cooperation between Universities, SMEs and industry in Eastern, Southern and Northern Europe, in order to implement the novel technologies in different markets and bring it into operation with the C&DW recycling stakeholders. Hence C2CA will contribute to creating a sound material-cycle in which there is a simultaneous pursuit of environmental preservation and economic development in the form of new business opportunities and improved competitiveness of European SMEs and industries.

Project description

In order to fulfill the goals of the project, the scientific and technological objective of the C2CA project (Figure 2) are defined according to the following main steps:

Step 1. Identification of all important factors and materials constituents related to the economic value and ecological impact of C&DW concrete streams, to quantify limits and set standards for dismantling operations and relate the relevant properties of actual wastes to the acceptance strategies, logistics and process technology of recycling facilities;

Step 2. Development and set up of innovative, easy to implement, low cost and reliable sensing technologies (laser and hyperspectral imaging based) and related data interpretation models to characterize feed and product streams in terms of the relevant composition parameters and performance in applications of the aggregates and cement in manufactured products;

Step 3. Optimization of comminution and separation processes by means of models, theory and experiment, in conjunction with the ADR technology for the removal of contaminants from broken concrete and to separate the fine cement paste fraction from coarse aggregate fraction by European recycling industries;

Step 4. Creation of models, by means of theory and experiment, of the chemical reactions, flow and mass transport, heat balance, and material properties that are necessary to develop the thermal technology for the conversion of the fine cement fraction into a new cementitious binder;

Step 5. Understanding of the economy, ecology and social impact of C&DW recycling

to such an extent that policies can be developed that facilitate an efficient transition towards a combination of optimal value recovery from C&DW and sustainable building.
The objectives will be attained in a progressive strategy: simulations and experiments, laboratory tests & performance assessment, small scale demonstrations, application to a case study in collaboration with industry and development of industrial processes and formulation of policy recommendations. This approach allows for a continuous evaluation of the progress and represents a safe investment since the developing of all products will be decided on objective performance criteria achieved in the previous stages. The sustainability of the technology development will be analysed through environmental Life Cycle Assessment (LCA) conforming to the ISO 14040 series of standards, L*ife* C*ycle* C*osting* (LCC) as well as S*ocial* L*ife* C*ycle* A*ssessment* (S-LCA).

Scientific and technology developments

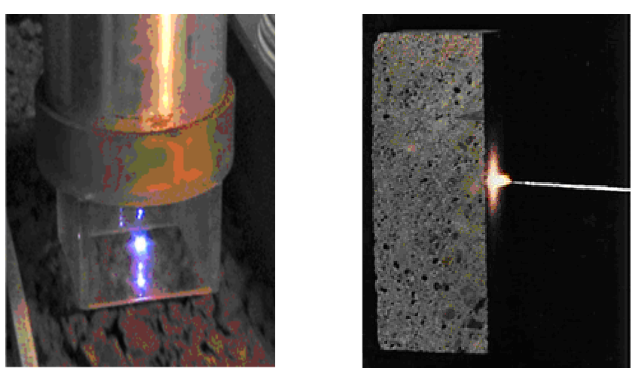
The technology proposed in this project is based on the notion that a wide, efficient and quick replacement of primary raw materials by recycled materials from EOL concrete is only possible if the resulting new concrete mixes have the same guaranteed quality as concrete produced from primary raw materials. The reason is that concrete is the most largely used structural material in the world. Its applications are subject to extensive regulations resulting from generations of experience. Creating a recycle concrete with the same quality as primary concrete is therefore a safe route that can be implemented quickly and at a large scale.
Particularly challenging is the integrated use of innovative sensors, sensing techniques and *quality-control-related* technologies inside a recycling plant for EOL concrete. Actually one of the great limits in solid waste recycling, and specifically in the EOL concrete recycling sector, is the lack of *on-line* quality control of dismantled materials and recovered products flow streams, both in terms of feed and concentrates.
Sensors and logics able to play the products characterization directly on the handled materials during the demolition phase could improve, not only the overall quality of the process, but also could represent a big step forward in respect of the final certification of the resulting materials as well as in respect of safety and durability issues and acceptance by users. Those aspects are of great importance for a stronger optimal reuse of the recovered products and for a consequent major utilization of demolition waste derived (secondary) raw materials. We therefore propose to develop and demonstrate a technology that breaks down EOL concrete into pure silicate (gravel and sand) fractions and a calcium-silicate (cement paste) concentrate. *On-line* sensor technologies will be developed that check the type of cement and guarantee the concentrations of potential pollutants in the input and output streams. Continuous inspection is required to guarantee the quality of a C&DW stream that is naturally prone to substantial variations in composition. This inspection capability may be realized by adapting and developing emerging sensor technologies to include *on-line* capability, i.e. make it operate around a conveyor that transports the waste materials from one processing step to the next.
Modeling of the kiln operation will be realized to understand and describe the complex phenomena that take place in the interior of the kiln when using the new feed.
The pre-processing of input minerals and the recipes for cement production need to be adapted to include the recycled cement paste into the input for the cement kiln, and the operation of the cement kiln needs to be optimized for the new feed.

ADR technology

To enable high-grade recycling of EOL concrete, strict classification according to particle size is necessary. However, size classification of the fine fractions (0-12mm) is problematic at the typical moisture contents of C&DW. Drying the material to lower moisture content consumes too much energy and wet methods produce sludge with a high negative value. Also both thermal and wet technologies involve relatively complex processing equipment which are difficult to operate *on-site*. Therefore technologies that involve thermal or wet steps cannot meet the environmental goals of minimizing transportation. Therefore a direct dry classification method is needed. The problematic moisture in the fine fraction of C&DW is primarily associated with the 0-1mm grains. This fraction contains the most moisture and makes the mixture sticky. Therefore, the removal of this fraction is essential to make the remainder processable by wind sifters. Moreover clean aggregates can be produced provided that the contaminations are removed. However, to remove contaminations like wood the material is processed wet, forming costly sludge. If fines and contaminations are removed from the C&DW, the product can be processed into aggregates without forming sludge. By closely examining the physics in classification, a new dry method called **A***dvanced* **D***ry* **R***ecovery* (ADR) was developed. This method allows classification down to 1 mm without the addition of water, and therefore reducing the high costs typical of water based treatment and linked to sludge removal. Experiments with ADR pilots plants at different throughput (40-120 t/h), show that in this way 80% of the EOL concrete is recovered as high-quality gravel, sand and aggregate. This large and clean gravel/sand fraction can be used without restrictions to make high-grade recycle concrete. When on-line quality control is used to rigorously guarantee its quality, the resulting recycled concrete can replace primary concrete in a wide range of applications without essential changes in regulation. One of the most interesting features of the ADR technology is that it is insensitive to the moisture content of the input. In *on-site* breaker operations, all materials must be kept moist to avoid dust. Since the ADR technology can deal with moist materials, it can produce gravel and sand from EOL concrete on-site, and with proper logistics, significant savings in road transport of building materials can therefore be achieved.

Laser based sensor techniques

Laser based sensor systems (Figure 3) are emerging as robust measurement platforms capable of determining the elemental composition of a wide range of waste materials



3a 3b

Figure 3. Examples of **L***aser* **I***nduced* **B***reakdown* **S***pectroscopy* (LIBS),utilized to determine the composition of stony materials on a conveyor (Honeybee Robotics, New York) (3a) and on a concrete sample (BAM, Berlin) (3b).

From metals to concrete (Weritz *et. al.*, 2003) (Figure 3). From the element composition the chemical makeup can be deduced to determine the quality of a material. Moreover, laser systems can operate continuously, at stand-off distances, and put low requirements to surface conditioning (Salle et. al. 2004), thus preventing expensive and time-consuming pre-treatments such as required for laboratory samples testing. Technological developments are addressed to design and set up portable versions of **L***aser* **I***nduced* **B***reakdown* **S***pectroscopy* (LIBS) systems, which has already led to breakthroughs in smaller and light-weight laser systems and components (Goujon et. al., 2008).
The challenge of this approach (LIBS), will be to adapt this technology to *on-line* operation, where one can take advantage of the rapid developments in both output power and performance of contemporary off-the-shelf laser technology (Figure 3).

H*yperspectral* **I***maging* **(HSI) based techniques**

HSI is, as Laser based sensor systems, an innovative, simple to apply and reliable technique able to deliver a wide spectrum of information from particulate solids streams and materials (Bonifazi et al., 2008a; Bonifazi et al., 2008b and Bonifazi et al., 2008c). The study was addressed in investigating different EOL concrete products: resulting from building dismantling and demolition. Analyses have been thus carried out to face a specific issue, that is the possibility to realize an “early-on-site” detection of the concrete, before the demolition, in terms of its composition (e. g. “feed” composition, that is different constituents, their assessment and contaminants identification) and a further full characterization of quality of the different flow streams resulting from specific processing actions (e.g. particulate solid characteristics, degree of liberation of the constituents, quality and quantity of fines, presence of contaminants and/or “pollutants”). Such a detection is quite challenging, and almost impossible, to perform, adopting the classical analytical devices and tools commonly utilized in the sector. All the efforts have been thus addressed to develop and set up strategies able to reduce the analytical costs improving the speed of the responses and/or to simplify the procedures in terms of possible *in-situ* and/or *on-line* implementation of fast and robust classification procedures oriented to develop innovative control strategies “human judgments and errors free” as well as innovative certification criteria. To reach this goal a “library” related to the different materials constituting the EOL concrete, was thus built. For each particle its identification with classical methods (FT-IR, Raman spectroscopy, optical and/or electronic microscopy) was performed and the related hyperspectral signature collected and univocally assigned.

<u>**The HSI architecture**</u>

Two different acquisition devices have been utilised, working in two different wavelength spectral ranges, from 400 to 1000 nm (VIS-NIR range) and from 1000 to 1700 nm (NIR range). The first one consists of a CCD camera, a line scan spectrograph (ImSpector™ V10E, SpecIm™, Finland), a lighting architecture. The spectrograph ImSpector™ V10E operates in the spectral range of 400-1000 nm with a spectral resolution of 2.8 nm. The details of the acquisition architecture are reported in Table 1. The second one is a SpecIm’s NIR spectral camera consisting of an ImSpector N17E imaging spectrograph for the wavelength region 1000-17000 nm and a temperature stabilized InGaAs camera and a lighting architecture (Table 2). The two hyperspectral devices were installed to perform the inspection of the waste materials

Table 1: Technical characteristics of the ImSpector™ V10E.

Sensor	- 2/3" CCD Array 780x580, - firewire digital output, - pixel resolution: 12 bit.
Spectral range	400 – 1000 nm
Spectral resolution	2.8 nm
Smile	< 1.5 µm
Keoneyst	< 1 µm
Entrance slit	30 µm x 14.2 µm
Image size	6.5 mm x 14.2 mm
Numerical aperture	F/2.4
Illuminant	- anodised Aluminum cylinder, - Barium sulfate internal coating, - d/O illumination and viewing conditions, - adjustable height and distance, - 150 W cooled halogen lamp, - stabilised power source.

Table 2. Technical characteristics of the ImSpector™ N17E.

Sensor	- TE-cooled INGaAs photodiode array 640x512 - 14 bit, USB_2, LVDS, CameraLink
Spectral range	900 – 1000 nm ± 10nm
Spectral resolution	2.6 nm
Spatial resolution	rms spot radius < 15 µm
Aberrations	Insignificant astigmatism, smile or keystone
Effective slit length	12.8 mm
Numerical aperture	F/2.0
Stray light	< 0.5 % (halogen lamp, 1400 nm notch filter)

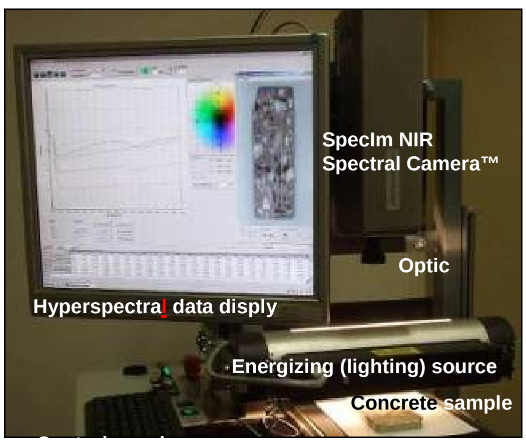


Figure 4. Particular of the architecture set-up utilized to perform a progressive and continuous concrete samples spectra acquisition based on the ImSpector™ series devices.

on a laboratory scale conveyor belt (Figure 4). The two devices are fully controlled by a PC unit equipped with the Spectral Scanner™ v.2.3 (SSOM, 2008) acquisition/pre-processing software.

Spectra acquisition and detection logics implementation

Spectra related to the different investigated samples were collected adopting the acquisition architecture previously described (Figure 4). Such a strategy was adopted because it mimics, at laboratory scale, the real behaviour of the control architecture at industrial scale, that is, the progressive and continuous horizontal translation of the sample and the "synchronized" acquisition of the spectra at a pre-established step, allowing this way a tuning of the detection/inspection frequency of the waste materials according to their characteristics (Bonifazi *et al.*, 2011). Analyses (Figure 4) have been performed to verify the fulfilments of different goals, that is:

1st goal: the possibility to identify specific spectral attributes for each of the constituents of the different EOL concrete, acquired as a slice obtained from an half-drill-core, according to their intrinsic chemical-physical characteristics. Starting from these information, analysis have been carried out performing a characterization of the "shape" of the entire detected spectra and/or identifying, at specific wavelengths, peaks or valley characterising the detected spectral firm.

2nd goal: the definition of fast, reliable and robust recognition-classification procedures, based on different logics as: i) spectral firms correlation, ii) single band intensity comparison at specific wavelengths and iii) specific wavelengths intensity ratio analysis, in order to perform the discrimination of the different constituents constituting an EOL concrete drill core and/or to certify processed waste concrete.

3rd goal: the possibility to perform a correlation among detected spectra, sample textural attributes, presence, characteristics and localisation of different materials. This latter aspect being of great interest to develop innovative sorting strategies. To validate the efficiency of the HSI based technique to perform a topological assessment of the different materials, both in the drill cores and inside the particles resulting from processing following an approach based on **P***rincipal* **C***omponent* **A***nalysis* (PCA), **P***artial* **L***east* **S***quares* **D***iscriminant* **A***nalysis* (PLS-DA), etc.

Modeling of the kiln processes for the new feed

The vast amount of energy associated with industrial cement kiln operation in combination with the large number of coupled chemical and physical processes that take place during clinkerization has driven increased interest to kiln operation modelling (Mastorakos *et al.*, 1999; Mujumdar and Ranade, 2006 Boateng and Barr, 1996). Although several parameters may still remain unknown or difficult to measure inside a kiln, modelling has already improved our understanding of the major phenomena that control the clinkerization process, and has provided satisfactory predictions of the behaviour of the system under certain structural or quantitative changes (Mastorakos *et al.*, 1999). Typical difficulties in accurate modeling of the kiln operation include the uncertainty in the values of the reaction constants, the values of the effective mass and heat transfer parameters, the rheological properties of the solids charge and melt along the kiln, the deviation from the axisymmetrical description of the kiln processes due to the rotation of the kiln and the attachment of clinker throughout the inner walls, the constants of radiation from the walls and the gas, and the lack of data at certain positions in the interior of the kiln. In addition, the wide range of characteristic times in the gas, liquid and solid phases, but most importantly within the flame itself, increases the stiffness of the problem and renders the appropriate discretization procedure extremely difficult. In the present project, a modular simulator (Figure 5) will be developed by FORTH that will take into account the three major components within the kiln, namely, (i) gas phase species and gas phase velocities, (ii) heat transfer among kiln wall, gas phase, and solids bed, and (iii) solids charge along the kiln where clinkerization takes place. In addition to the solution of this model using commercial flow and radiation solvers, the 3D equations will also be solved using BSC in-house code Alya. The Alya numerical solver has been chosen to represent Computational Fluid Dynamics (along with three others) in the FP7 PRACE project: Partnership for Advanced Computing in Europe. It has proven to run efficiently on thousands of processors on heterogeneous clusters in a

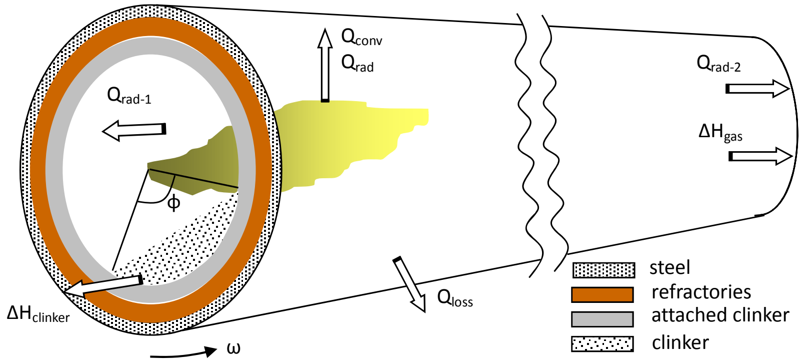


Figure 5. Schematic representation of kiln configuration indicating major heat flow components.

hybrid context (distributed-shared memory clusters). In addition to the additional physics (Figure 5) implemented in Alya during the course of the project (mixing model, solids charge flow, emission effects, melting transition in 3D formulation – all becoming increasingly interesting with the introduction of the additional ADR stream into the kiln feed), the code will be optimized to run on next generation of petascale supercomputers. This capability will enable FORTH and BSC to explore new horizons (more physics, different configurations, optimization) further than what is possible nowadays with current computational infrastructures due to CPU time limitations.

Analysis of sustainability performance

In order to ensure that a real environmental improvement from the new C2CA technology is achieved and documented, the new system approach developed within the project is being assessed in a life cycle perspective through ISO standardized LCA. The economic and social aspects of the sustainability regarding the new technology system is being analyzed by LCC and S-LCA according to a Code of Practice on LCC (SETAC 2010) and the Guidelines on S-LCA (UNEP/SETAC 2009). The assessment results will be used as a basis for formulating policy recommendations at European, national and project levels.

Results and discussion

A first large-scale demolition test of the C2CA project involved a complex of multi-storied office buildings at the city of Groningen, the Netherlands. Analyses of the crushed concrete from the project revealed that smart demolition procedures produce a range of aggregate qualities, of which the 40% material with the top grade had about 1 cm^3 of floating material per kg, thus already satisfying the FL_{2-} norm of EN 12620 for secondary aggregates in concrete, even without additional treatment steps. Attrition tests on the crushed concrete showed that 12 minutes of milling reduces the cement paste at the surface of large aggregate particles by about 50%. ADR separation then removed the -2 mm grains from the mixture (see Figure 6) in order to create an aggregate that is free of fines and has a reduced Ca-content. Preliminary numerical computations using the simulator that was mentioned above showed that a realistic representation of the flow, combustion, clinkerization, and heat exchange can be obtained for a typical industrial kiln. The composition of the clinker product was found to be within 10-20% of the measured one whereas the flame temperature profile calculations reproduced mean and maximum temperature values that are similar to the estimated ones from industrial practice and independent calculations. Following fine-

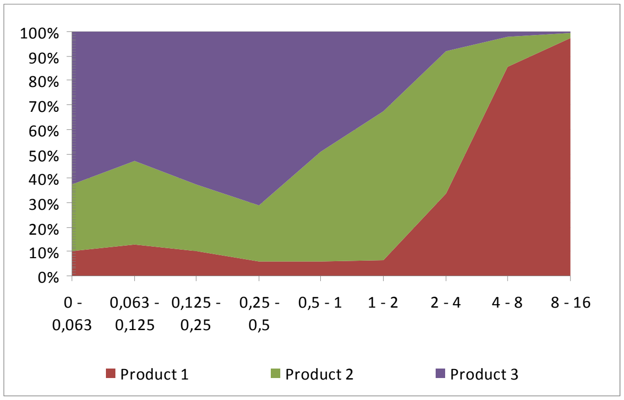


Figure 6. Recovery of mineral particles as a function of size [mm] into the three ADR products (Coarse=red, Middlings=green, Fines=blue).

tuning of the model parameters, including reaction kinetics and heat transfer coefficients, the simulator is capable to predict the response of the kiln operation to changes in raw meal composition, including partial substitution with ADR fines.

The preliminary analyses carried out on EOL concrete samples adopting the HSI based approach clearly evidenced the possibility to identify the different constituting materials (Figure 7) and/or the presence of alteration due to ageing phenomena and/or weathering actions. Following this approach it is thus possible to define, starting from the detected spectral signatures, specific parameters useful to perform waste concrete constituents recognition, as for example the slope of the spectrum in a selected wavelength range or a band ratio among two different wavelengths. It is important to outline as the best materials recognition/topological assessment can be reached adopting more sophisticated and complex statistical analyses, such as (PCA), Partial Least Square (PLS), PLS-DA, Neural Network (NN), etc..

The preliminary economic analysis shows that the new C2CA system approach is decreasing the processing cost for recycling EOL concrete into clean aggregates. The mobile ADR technology shows interesting economic advantages due to the possibility of using EOL concrete as secondary raw material in concrete production.

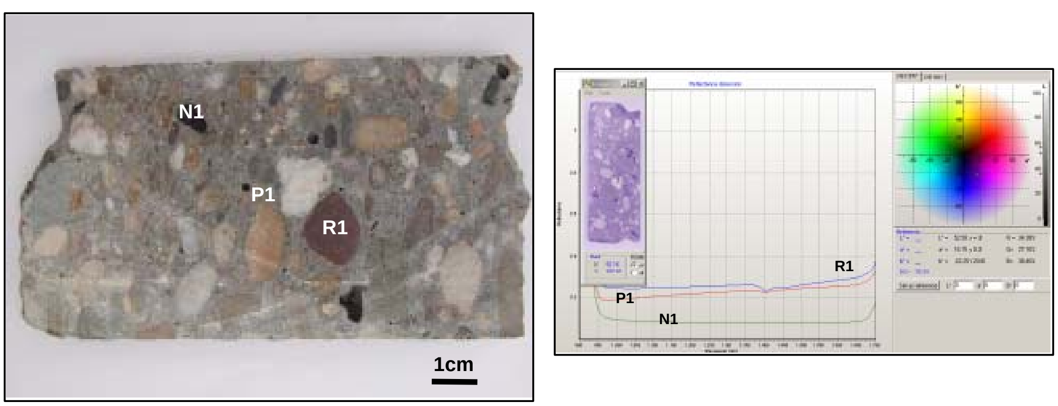


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Figure 7. Example of **H**_yperspectral_ **I**_maging_ (HSI) based approach applied to EOL concrete core samples (4a) collected directly in the structure to demolish. The technique is adopted to identify cement (P1) and different aggregates (N1 and R1). Through the definition of a series of Regions of Interest (ROIs), it is possible, in fact, to detect the spectral signature characterizing the material inside the region defined by the ROI.

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References

Analysis of economic indicators of the EU metals industry: the impact of raw materials and energy supply on competitiveness, SEC 1069 (2006).

Boateng A.A. and P.V. Barr, “A thermal model for the rotary kiln including heat transfer within the bed”, *Int. J. Heat Mass Transfer*, 39, 2131-2147 (1996).

Bonifazi G., A.Dall’Ava and S.Serranti, “Design of an hyperspectral imaging platform for quality control in the MDS-based recycling process of polyolefins”. The 26th Int. Conf. on Solid Waste Technology and Management: ICSWM 2011, SESSION 5A: *Workshop on The W2Plastic Project: Part 1*. March 27-30, Philadelphia, PA, U.S.A.(2011).

Climate Change 2007 Mitigation of Climate Change, Working Group III, Fourth Assessment Report Intergov. Panel on Climate Change. Cambridge University Press, 32 Avenue of the Americas, New York, NY 10013-2473, USA (2007).

Communication from the commission to the Council and the European Parliament the competitiveness of the metals industries, COM 108 final (2008).

Communication from the Commission to the European Parliament and the Council: The raw materials initiative – meeting our critical needs for growth and jobs in Europe. COM 699 final (2008).

de Vries W., Rem, P. and Berkhout, P., *ADR: A new method for dry classification*, Proceedings of the ISWA Int. Conf. (p103), 12-15 October, Lisbon, Portugal (2009).

Earnings, jobs and innovation: the role of recycling in a green economy, European Environment Agency Report No 8/2011, © EEA, Copenhagen (2011).

Ecosystems and Human Well-being. Millennium Ecosystem Assessment. Island Press, Washington, DC. Copyright © 2005 World Resources Institute (2005).

Mastorakos E., A. Massias, C.D. Tsakiroglou, D.A. Goussis, V.N. Burganos and A.C. Payatakes, “CFD Predictions for Cement Kilns Including Flame Modeling, Heat Transfer and Clinker Chemistry”, *Appl. Math. Model*., 23, 55-76 (1999).

Mujumdar K:S:and V.V. Ranade, “Simulation of rotary cement kilns using a one-dimensional model”, *Chem. Engin. Res. Design*, 84(A3), 165-177 (2006).

The raw materials initiative — meeting our critical needs for growth and jobs in Europe, COM 699 final (2008).

Samarin A., *Hydraulic Cements - New Types and Raw Materials and Radically New Manufacturing Methods*, Leader Paper, Proceedings of the Int. Conf., University of Dundee, Scotland, edited by R. K. Dhir and M. J. McCarthy, Volume on Appropriate Concrete Technologies, E & F.N. Spon, London, 265-279 (1996).

SETAC: Society of Environmental Toxicology and Chemistry Swarr TE, Hunkeler D, Klöpffer, Pesonen HL, Ciroth A, Brent AC, Pagan R, editors. *Environmental Life Cycle Costing: A Code of Practice*; New York, USA (2010).

SSOM, *Spectral Scanner Operative Manual (Version 2.0*). DV Optics S.r.l., Italy. http://www.dvoptic.com/index.html (2008).

UNEP/SETAC (2009) Benoît C., Mazijn B., editors. *Guidelines for Social Life Cycle Assessment of Products*. ISBN: 978-92-807-3021-0 (2009)

World Wildlife Fund Living Planet Report, 2006, Avenue du Mont-Blanc CH-1196 Gland, Switzerland (2006).