Assessment of the contaminants level in recycled aggregates and alternative new technologies for contaminants recognition and removal

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Abstract

One of the main challenging problems associated with the use of Recycled Aggregates (RA) is the level of mixed contaminants. For utilizing RA in high-grade applications, it is essential to monitor and minimise the content of the pollutants. To this extent the C2CA concrete recycling process investigates a combination of smart demolition, followed by new innovative technologies to produce high-grade secondary aggregates with low amount of contaminants. This paper firstly reports the level of contaminants in different fractions of recycled aggregates coming from a real case study. Results show that the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard. However, there are still large visible pieces of wood and plastic in the +16 mm RA fraction which, albeit within the standards, does not satisfy the users. In order to solve this problem the feasibility of applying two existing technologies (near infrared sensor sorting and wind sifting) to remove contaminants, is studied. Furthermore, two types of online quality control sensors (hyper spectral imaging and laser induced breakdown spectroscopy) are introduced and a summary of their recent developments towards the quality control of RA are presented.

Keywords: construction and demolition waste (C&DW), recycled aggregate, contaminants, quality control

I. Introduction

The efficient high-grade recycling of Construction and Demolition Waste (CDW) is of increasing interest from an environmental and economic perspective. From an environmental point of view, the urgency of saving resources and reducing humanity's impact on the environment is evident. The need of increasing recycling and improving the quality and homogeneity of recycled materials to minimize environmental pollution and the use of primary resources is a topical subject for European Community (Enterprise and Industry reports of the EC).

In order to enhance the quality of RA for high-grade applications, the content of contaminants such as organic materials (wood, plastic and foams), gypsum and glass must be minimised (Vegas, et al. 2015). Many organic substances such as wood are unstable in concrete when submitted to drying and wetting or freezing and thawing (Hansen, 1990). Water-soluble sulphates (coming from gypsum plaster) in RA are reactive and may produce expansive reactions (Silva, et al. 2014) while structural concrete containing RA with high chloride content may deteriorate more rapidly due to the corrosion of reinforcement bars (RA coming from concrete subjected to marine may have high soluble chloride content). Plate glass from windows has the density similar to the stone's and brick's and therefore it complicates its separation. Thus pre-sorting of the glass is essential also because of the alkali- silica reactions which can take place due to non-crystalline metastable silica (Hansen, 1990).

Considering the importance of upgrading the quality of the RA and removing the contaminants, currently different technologies and procedures such as smart demolition and dismantling of End-Of-Life (EOL) buildings, automated sensor sorting and online quality control sensors have been developed (Serranti, et al. 2012) and (Palmieri, et al. 2014) and (Xia, et al. 2014). A novel concrete recycling process developed within an European funded project (Lotfi, et al. 2015), aims at a cost-effective system approach for recycling high-volume EOL concrete streams into high-quality aggregates and cement. The best practices and technologies implemented are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product and a cement-paste concentrate that can be processed (off-site) into a low-CO2 input material for new cement production. Sensor-based on-line quality assurance allow for a proper monitoring of the output. Achieving in-situ recycling of the EOL concrete is one of the main goals of this process. Therefore, the liberation of the cement paste as well as the sorting and size classification of the aggregate, is performed purely mechanically and in the moist state, i.e. without prior drying or wet screening. This choice reduces process complexity and avoids problems with dust or sludge while providing economic benefits in terms of process costs and logistics. After crushing, liberation of the cement paste is promoted by several minutes of grinding in a small-diameter (D = 2.2 m) autogenous mill and at the same time producing as little as possible fine silica. Then a new low-cost classification technology, called Advanced Dry Recovery (ADR) is applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and is able to classify materials almost independently of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the input aggregate is concentrated in two main streams: a coarse aggregate product and a fine fraction which includes the cement paste and contaminants (e.g. wood, plastics and foams).

In the current study, the influence of different recycling steps in C2CA process (See Figure 1) in the level of contaminants is investigated and solutions to make clean final products are presented. The aim is to enrich our understanding of the importance of existing recycling steps with respect to eliminating the contaminants in recycled aggregate.

II. End of life building (case study in Groningen)

The case study of the C2CA project involved the demolition of a governmental complex in the province of Groningen in the Netherlands and the building of an underground garage from concrete with recycled aggregate. The scope of the demolition part of the project mainly consisted of two identical high-rise towers (KB2 and KB6) with the blue dotted line in Figure 2. The section plan of the towers can be seen in Figure 3.

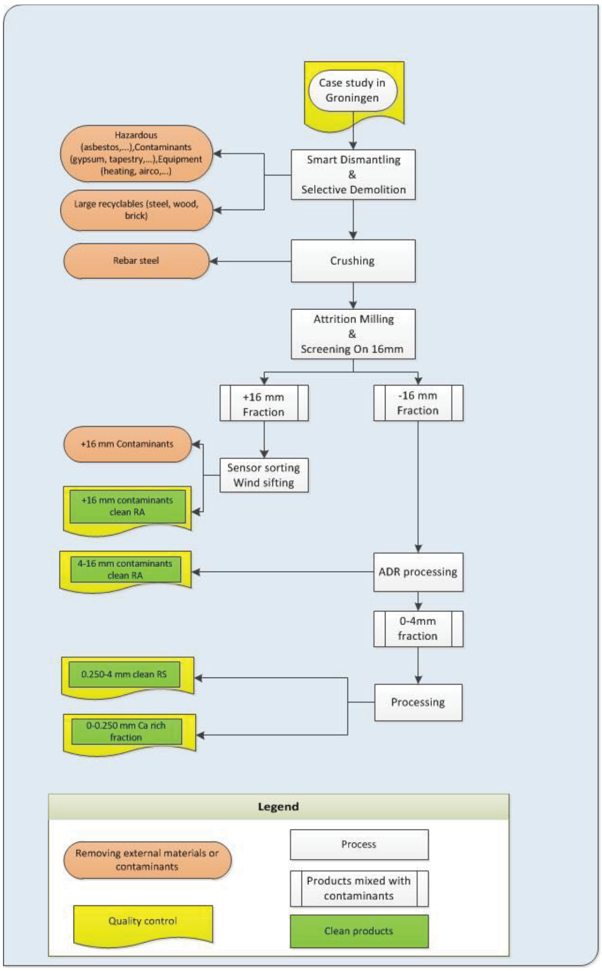


Figure 1: General layout of the C2CA technology showing different steps for contaminants removal. Two developing sensors (HSI and LIBS) are being developed for the quality control of the products.

III. Smart dismantling and selective demolition

An EOL building may be conventionally or selectively demolished. Although the construction and demolition industries still see the concept of the selective demolition doubtful from economic point of view, it may be more profitable than the conven-

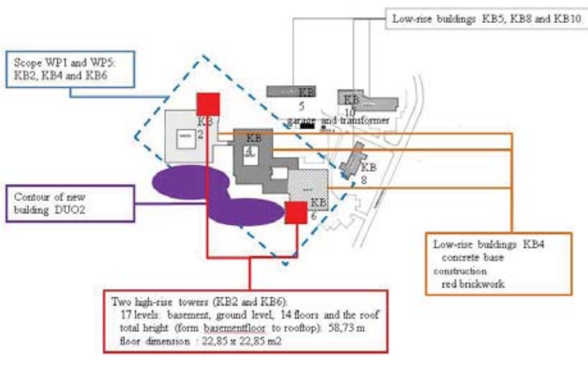


Figure 2: Overview of the end of life buildings

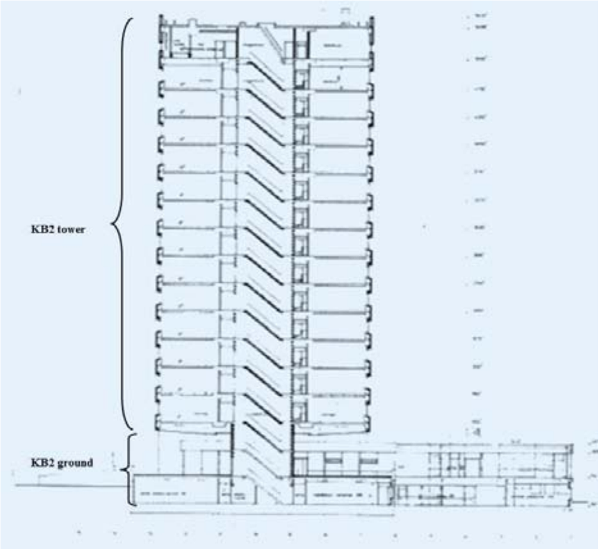


Figure 3: Section plan of the EOL building

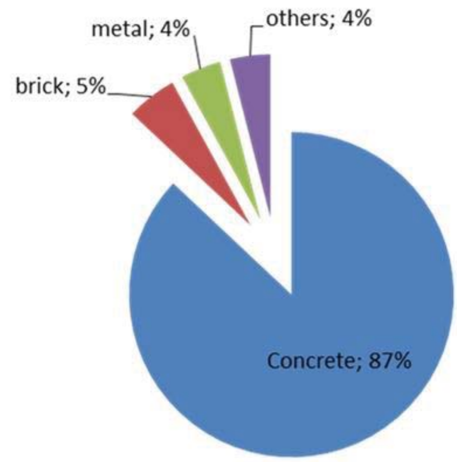


Figure 4: Material composition (wt%) of KB2/KB6 tower.

tional demolition approach and the most effective way of minimising the amount of contaminants in CDW materials (Coelho, et al. 2011).

In the 70's and 80's the Dutch construction sector used asbestos in the buildings. Therefore prior to the dismantling and demolition of KB2 and KB6 buildings, asbestos was removed and collected in the total amount of 40 tons. The further strategy for the dismantling of the KB2 and KB6 involved the detailed removing of all materials from the concrete skeleton before starting the demolition: air-conditioners, radiators, lamps, piping systems of water and heating, electric cables, carpets, gypsum plates from ceilings and walls, window glass, frames of doors and windows etc. For the demolition, two methods were applied: the top-down method to demolish the top 12 floors, and short-reach method to demolish the lowest 2 floors of the towers. The materials composition of KB2/KB6 tower can be seen in Figure 4. It demonstrates that the amount of EOL concrete was 87wt% of the whole CDW materials.

IV. Autogenous milling

Autogenous milling of the crushed End of Life (EOL) concrete is a mechanical method to remove cement paste from the surface of aggregates. During autogenous milling, the combination of shearing and compression forces, promotes selective attrition and delivers a better liberation of cement. Beside liberation of cement, the acting forces could affect the size of the contaminants. In this regard, a batch test with around 15 tons of crushed EOL concrete was carried out. The residence time of the materials inside of the mill was estimated as 12 minutes. About 2 tons of sample from both mill input and output was taken in order to analyse the constituents. Samples were portioned to 5-10 mm, 10-20 mm and +20 mm fractions and their contaminants were hand-picked according to the procedure previously explained.

Figure 6 shows the mass percentage of the hand-picked contaminants from mill input and output for three aforesaid fractions. Considering the results after milling, the mass of contaminants (bigger than 5 mm) is reduced by 30%. It appears that by milling, contaminants are broken down in smaller parts so that the less than 5 mm fraction increases. There is a clear effect of the milling also on the size reduction of brick (compare Figures 6-A with 6-D). A similar trend can be seen for wood contaminants albeit in a less outstanding way. In general it is observed that milling has an obvious effect on the size reduction of brick and a slight effect on size reduction of other contaminants.

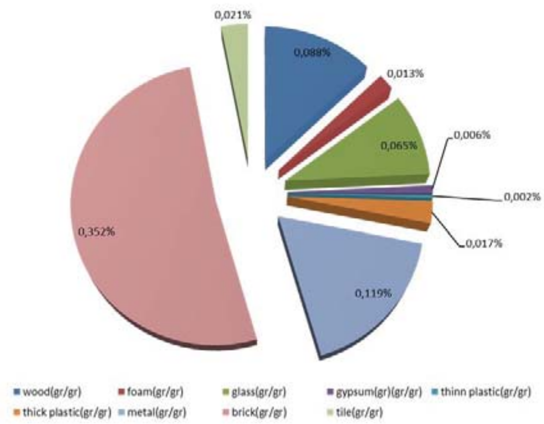


Figure 5: Constituents of the contaminants mixed with concrete.

V. Screening and ADR processing

In the C2CA concrete recycling process, autogenous milling of the materials is followed by a 16 mm screen and an ADR. Materials smaller than 16 mm are fed into the ADR and using a jet, the fines (0-4 mm) are separated from the coarse particles. The air knife installed in ADR helps to concentrate contaminants like wood, foam and plastic in the fines. In order to figure out the amount of wood in the coarse ADR products (4-16 mm RA) a sink floating test on approximately 1700 kg of RA and according to EN 12620 (for application of the material as coarse recycled aggregate) was carried out.

Result shows that the total amount of floating wood in 4-16 mm RA is almost 0.117 cm3/kg which is well within the strictest norm of EU standard (EN 12620). ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction including the cement paste and contaminants such as wood, plastics and foams (see Figure 7B). ADR fines can be used as the input of cement kilns so that the wood and plastics contaminants are even beneficial for the process.

During the first C2CA case study, it became clear that because of the contamination, the +16 mm fraction does not have the market potential as such (see Figure 7A). Therefore it would impair the economic attractiveness of the recycling process being developed. According to the visual evidence, there are big contaminants of wood and non-ferrous metals in +16 mm oversize fraction. In order to satisfy the customers' demands and use +16 mm RA for high-grade applications, contaminants should be removed from this fraction. Since +16 mm RA is a small stream (almost 30wt% a sensor sorter could be a cost effective option to clean this fraction. In this regard, the possibility of applying Near Infrared (NIR) sensor sorting technology to clean +16 mm RA was examined.

NIR sensor sorting and wind sifting to remove contaminants from +16mm RA

Advanced automated sensor-based sorting technologies use physical – chemical properties of different materials such as density, electrical conductivity or magnetic susceptibility, as well as surface and material properties, such as NIR spectrum or the visible colour (Vegas, et al. 2015). For this part of study, NIR sensor sorting facility of TOMRA GmbH sorting in Germany was used (Figure 8 shows the functional principle). Input material (1) is evenly fed onto a conveyor belt, where it is detected by the NIR and/or VIS spectrometer (2). If the sensors detect material to be sorted out, it commands the control unit to blow the appropriate valves of the ejection module at the end of the conveyor belt. The

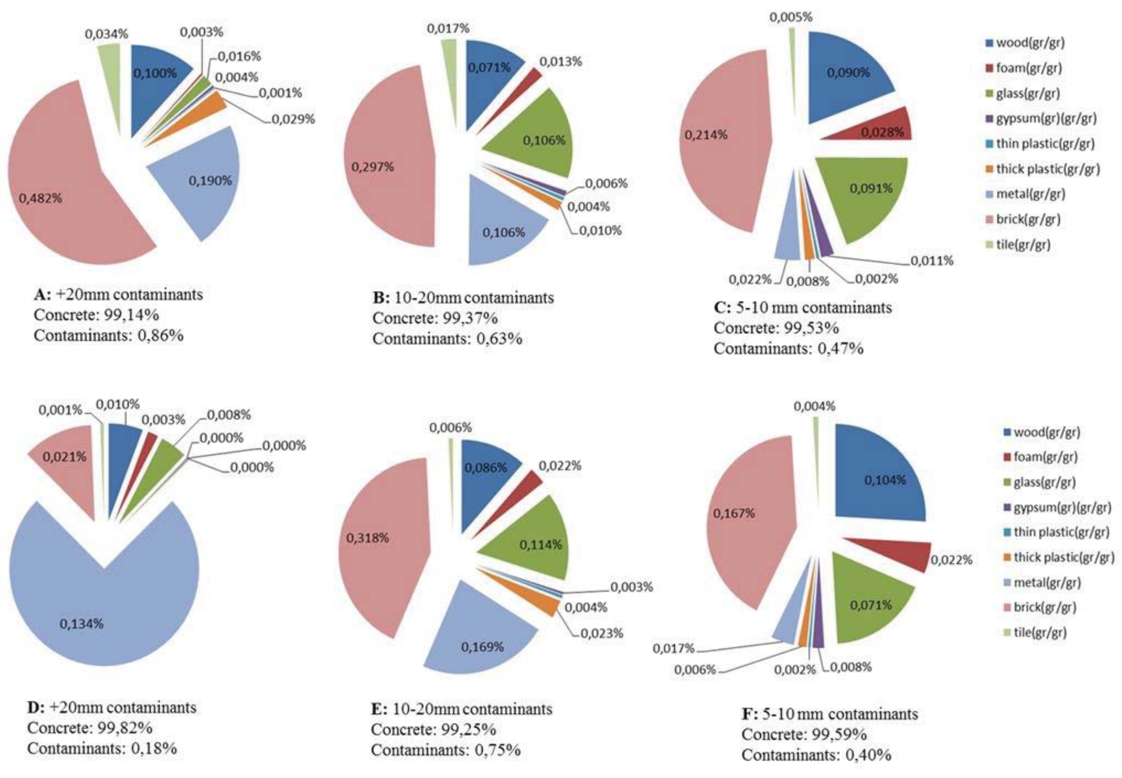


Figure 6: A, B and C show the amount of contaminants in the +5mm input of the autogenous mill. D, E and F show the amount of contaminants in the +5mm output of the autogenous mill.

Figure 7: A) +16mm RA which still contain contaminants, B) ADR fines in which light contaminants like wood and foam are concentrated.

detected materials are separated from the material flow by jets of compressed air. The sorted material is divided into two or three fractions in the separation chamber (3).

For testing the performance of the NIR sensor sorting system, around 900 kg of +16 mm of crushed concrete was delivered to TOMRA sorting GmbH. During the experiment, contaminants (wood, plastic and metal) with size of 10-20 mm and +20 mm were added to the clean crushed concrete. The output of the NIR sensor sorting system consists of an accepted portion (clean concrete) and ejected contaminations. Figure 9 shows an example of the input contaminants to the NIR sensor sorting system and accepted and ejected outputs.

The process flow diagram for 20 t/h/m of the throughput shows that by using NIR sorting, almost 88% mass% of wood is thrown out and small pieces are left in the product. Plastic and metal are also removed (see Table 1 and 2).

The investment cost of a NIR sorting system (including high speed conveyor and separation chamber) vary depending on the width of the system between approximately €95,000 (0.6 m width) to roughly €230,000 (2.8 m width). Considering the investment costs for other equipment which are needed to operate a NIR sorting system (compressor, cables, electrical equipment, conveyors for output fractions, installation) total investment cost would be €140,000 (0.6 m wide system) and €320,000 (2.8 m wide system). It is estimated that for a 2 meter width of the belt (40 t/h), with running time of 1600 hours/year the cost of processing will be 1.2 euro/ton.

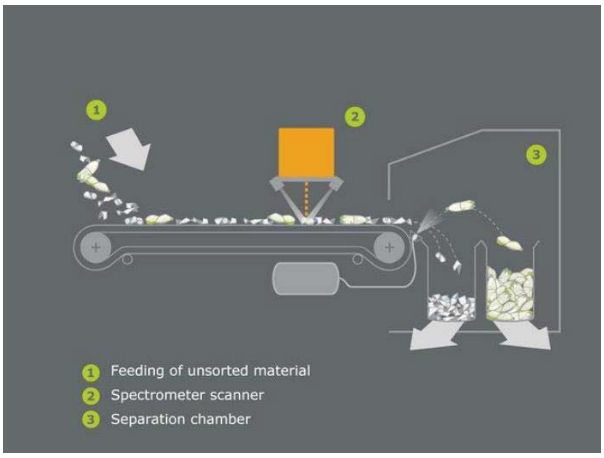


Figure 8: Functional principle of TOMRA NIR sensor sorting technology.

Considering the above mentioned results, the only limitation with NIR sensor sorting system is its current inability to remove small contaminants which therefore remain in the accepted output. To reach a more accurate contaminants removal, the combination of the wind sifting technology with NIR sorting is considered beneficial. In this regard, a test was carried out to examine the performance of a wind sifter to remove plastic and wood. The test was performed at REDOX B.V. in the Netherlands (see Figure 10). The input materials of the wind sifter consisted of almost 500 kg of +16mm crushed concrete mixed with a specific amount of wood and plastic.

According to the process flow diagram (see Table 3 and Table 4), it is concluded that wind sifting is able to remove 80% (by number) of wood and plastic contaminants from the stream (for 35t/h

Table 1: Mass analysis of NIR input.

Materials	Weight(gr)	Mass,%
Clean crushed concrete	278000	99.87
Wood	230	0.08
Plastic	121	0.04
Total	278351	100

Table 2: Mass analysis of NIR output

Materials	Weight(gr)	Mass, %
Crushed concrete in accepted materials	267900	96.24
Crushed concrete mixed in ejected materials	10136	3.64
Wood in ejected materials	203	0.07
Plastic in ejected materials	123	0.04
Total	278362	100

throughput). Big particles which are heavier cannot be removed and remain in the final products. In Figure 11 the remained big pieces of wood in the final product can be seen.

The investment cost of the REDOX wind sifter is €75,000 euro. It is estimated that for a 40 t/h throughput, with running time of 1600 hours/year the cost of wind sifting process will be 0.1 euro/ton.

VI. Sensors for On-line quality control

LIBS

Laser Induced Breakdown Spectroscopy (LIBS) is an optical spectroscopic technique employing a pulsed laser to produce a high power density light beam (>108 W/cm^2) to ablate tiny amounts of material from target material surface, resulting locally in high dissipation and accompanying breakdown of molecules or crystalline structures into a partly ionized plasma with plasma temperature and electron density typically in the order of 104 K and 1018/cm3, respectively. During the cooling-off of the plasma, the fingerprint LIBS spectra including element specific atomic-ionic emission lines can be observed, whereby photon wavelengths may be linked to specific elements, allowing identification of the elements in the plasma which represents the target sample material. The number of photons produced by a certain type of element may in principle be linked to the element concentration therein. The LIBS technique has great potential on real-time process and in-situ quality control: it has relative simple instrumentation, fast measurement with only optical access, needs minute sample preparation etc. The LIBS experimental setup being developed within C2CA is shown in (Figure 12). This set- up consists of a 1064 nm Q-switched YAG-laser (11-25 mJ, 10 ns/pulse, 1-100 pulses/s), fibre-optics and focusing assembly to collect the light, and a spectrograph with attached CCD to disperse and detect the photonic emissions. The timing of the whole system is facilitated by a waveform generator.

One of the quality control steps within C2CA, is inspection of drill cores of concrete coming from the EOL building. Drill cores usually contain information on the type of materials used in the concrete (cement, sand, granulate, rebar), and the possible ingress of chlorines (in case of outside exposure) or degree of carbonation. The possibility to inspect drill cores and detect these properties in-situ constitutes an advance on present practices, since the dismantling and demolition process may be adapted according to the information to produce the highest quality secondary raw materials for recycling.

The laboratory LIBS set-up has been shown to be sensitive enough to perform semi-quantitative surface mappings which enable visualization of elemental distributions of various elements. Figure 13a shows the grayscale LIBS raster scanning results on one of the drill cores (no.7-from the pillar wall in the room 2.03 of the KB2 building) measured in the air compared with the photograph. Starting at the surface, the drilling core was linearly scanned. Each measurement was made per millimetre averaged over ten single laser shots. The distance between two lines was 1 mm. Each spectrum was

A: Example of input contaminants to the NIR sensor sorter, B: Accepted materials (NIR sensor sorting out put), C: Ejected materials (NIR sensor sorting out put)

Figure 9: Input contaminants and accepted and ejected output of NIR sensor sorting system.

Figure 10: Wind sifting facility in REDOX.

Figure 11: Input of wind sifter(upper images) which consists of wood, plastic and clean +16 mm crushed concrete. Downer images demonstrate the removed wood and plastic using wind sifter and remained wood in the products.

Table 3: Mass analysis of the wind sifter input.

Input	weight(gr)	mass,%	number of particles
clean crushed concrete	524000	99.90	
wood	324	0.06	134
plastic	195	0.04	48
total	524520	100	

Table 4: Mass analysis of the wind sifter output.

output	weight(gr)	mass, %	number of particles
crushed concrete in accept materials	513390	97.88	
crushed concrete in eject	10790	2.06	
wood in eject	209	0.04	107
plastic in eject	130.6	0.02	39
total	524520	100	

background subtracted and was normalized to the whole spectral integral against shot-to-shot variations. Ca (Ca 422.4 nm) was abundant in the cement paste, while the Si (288.1 nm) and Fe (274.4 nm) in aggregate and rebar, respectively. In particular, the inverse relation between the Ca and the Si content can be observed by the comparison between aggregate and cement. Si, Al (Al 309.1 nm), Fe, K (K 766.3 nm), Mg (Mg 285.0 nm), Li (Li 670.5 nm), Na (Na 589.0 nm), S (S 922.0 nm) were also present in cement paste. Furthermore, there was higher content of Si in the white (more like quartz) aggregate than that in the dark green aggregate and vice versa for Al and Na. C (C2 516.6 nm) was observed in both cement paste and rebar. O (O 777.2 nm) and H (H 656.3 nm) were mainly in aggregates, possibly as combined H_2O. Cl (Cl 837.7 nm) was mainly detected in the dark green aggregate and rebar. It should be emphasized that the images show the relative distribution of the element, and not the absolute concentration. Comparison with the photograph of the scanned drill core surface proves that cement paste, coarse aggregate and rebar were clearly differentiated. The finer gravel or sand could also be distinguished using higher scanning resolution.

To facilitate the smart dismantling at earliest stage, it was attempted to differentiate between aggregate, cement paste and rebar of the drill cores using LIBS. Successful classification of different types of aggregate, sand and cement paste, as well as rebar using PCA and neural network algorithms were achieved (see Figure 13b). In addition the area ratios of the different materials could be determined (Figure 13c). Drill core concrete samples taken from the building site before demolition at the start of the C2CA project have been successfully categorized according to the used cement types. As a representative of each group, drill core no. 7 (Portland) had a higher content of Ca while no. 15 (blast furnace slag cement, from the floor in the room 0.36 of the KB6 building) had higher contents of Si, Al, Fe and Mg (see Figure 14). Here, the LIBS signal intensity for each element is normalized to the summation over those of all elements and hence, is not proportional to its elemental content. These findings will be instrumental for smart dismantling, because it helps to determine which parts of the concrete structure may be demolished together and which parts should be kept separate to obtain concrete batches of known and consistent quality.

The potential capability of the LIBS system to detect and characterize the waste pollutants in a real-scale setting has been investigated in (Xia, et al. 2014). The classification of eight waste materials with selected types from a stream of demolition concrete produced using their LIBS spectra combined with principal component analysis (PCA) is

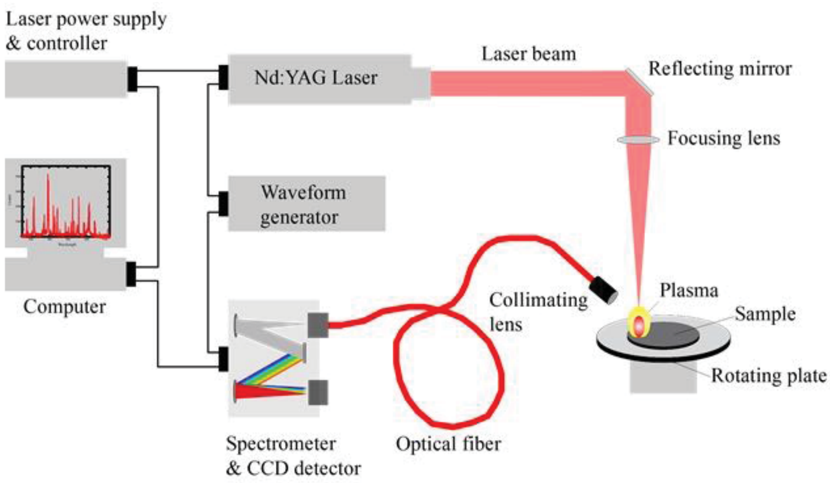


Figure 12: Laboratory LIBS experimental setup.

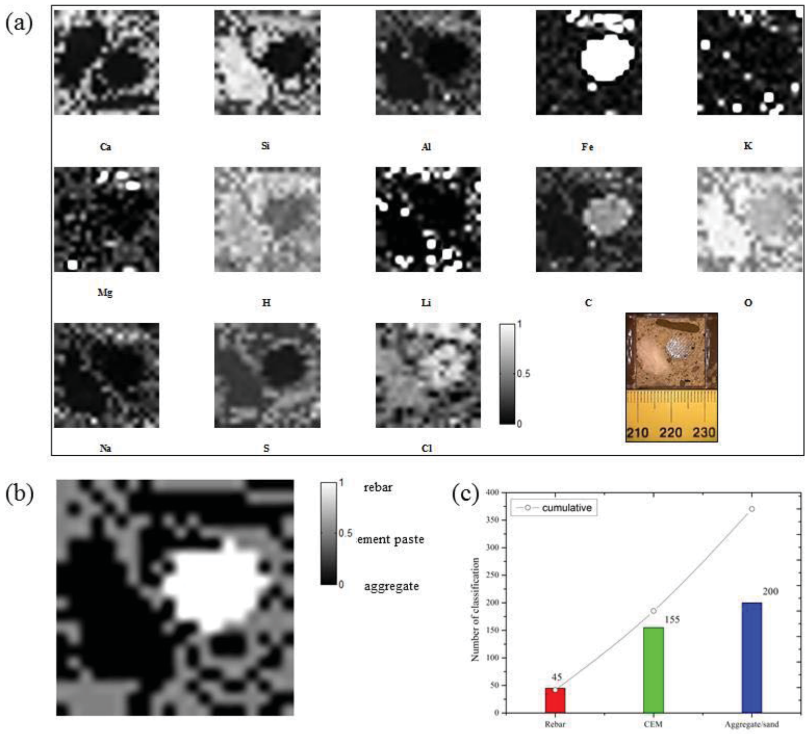


Figure 13: LIBS grid scanning 20×20 mm^2 on drill core no. 7 in 1 mm steps. The laser spot diameter is 300 μm. (a) 2D distribution of Ca, Si, Al, Fe, K, Mg, H, Li, C, O, Na, S and Cl. The data are normalized to unity, corresponding to white in a grey scale. (b) classification of rebar, cement paste and aggregate/sand using PCA-neural network algorithm, corresponding to 1, 0.5 and 0 in the grey colour bar, respectively; (c) cumulative number of shots for each material, indicating the area ratios.

presented in Figure 15. The representative materials for most of the materials found in demolition concrete were: cement (CEM I 42.5 R HS, CEM II/B-S 52.5 N, CEM III/B 32.5 N), brick (yellow, brown and red), gypsum block (white, blue and red), wood (pine, ash and walnut), PVC plastic (grey, black pipe and grey hard plate), glass (white, green and brown), two of the most common types of natural rock used as aggregate (sandstone and gabbro) and steel rebar, of which only one type is used in the Netherlands. All materials could be successfully classified out of a random (data) mixture of these materials using partial least squares discriminant analysis (PLS-DA). As a percentage of the tested data set, the misclassifications made up 0.28% (single-shot), 0.14% (2 fold averaged), 0.56% (4 fold averaged) and 0% (10 fold averaged).

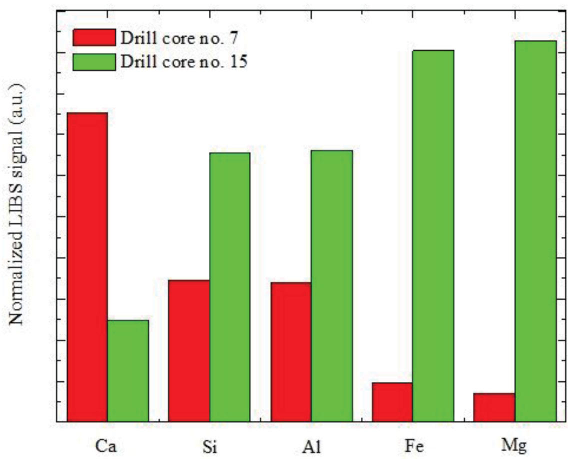


Figure 14: Element-wise comparison of drill cores 7 and 15. Note that the y-axis adds up to unity for each element.

HSI

An Hyperspectral Imaging (HSI) approach, acting in the NIR range (1000-1700 nm) was adopted as quality control tool for the recovered products (i.e. recycled aggregates). More in detail, a system able to recognize concrete aggregates and unwanted contaminants, such as brick, wood, plastic, gypsum and foam after the ADR processing was developed, implemented and set up.

Utilized HSI platform, realized by DV srl (Padova, Italy), is an integrated hardware and software architecture allowing to digitally capture and manage spectra, as they result along a pre-defined alignment on a surface sample properly energized (Hyvarinen, et al. 1998) and (Geladi, et al. 2007).Hyperspectral data are called "hypercube" because of

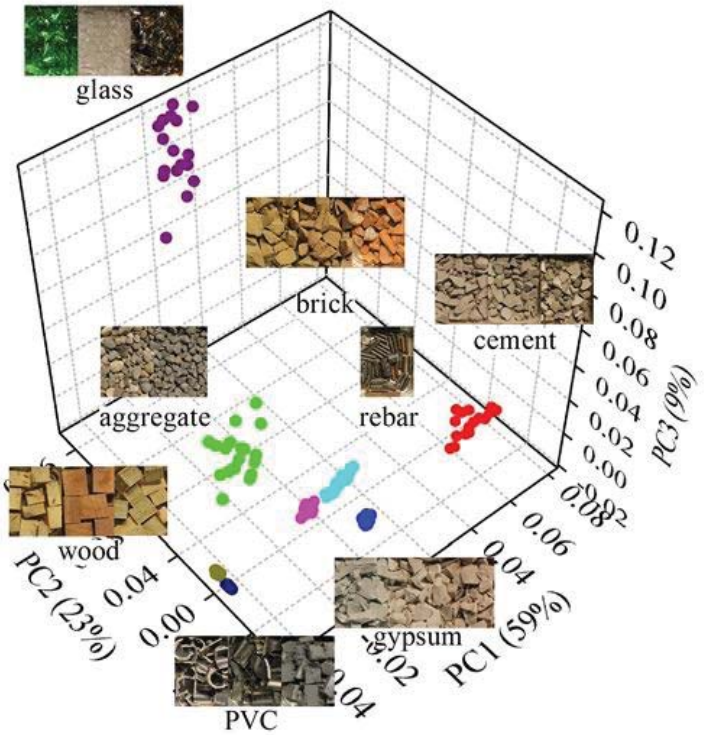
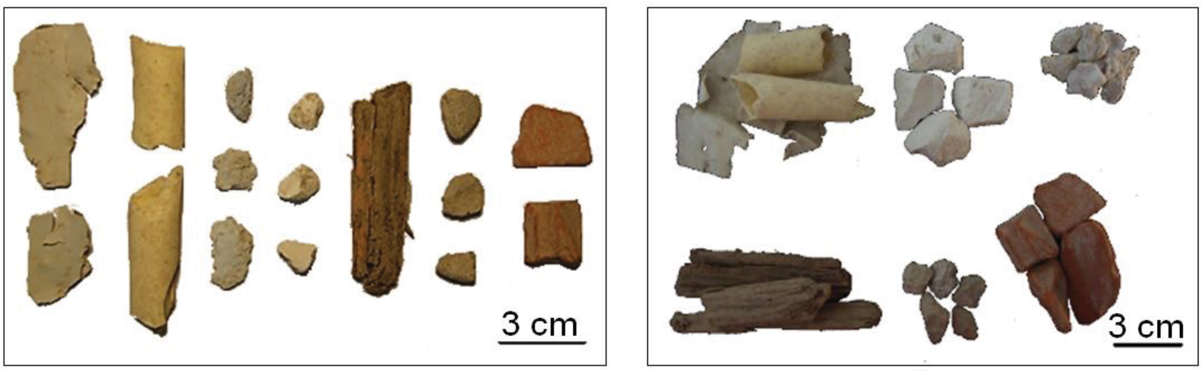


Figure 15: PCA score plot of waste materials using the first three PCs. Indicated in the axis label is the PC contribution to the total variance.

their 3D structure, characterized by two spatial and one spectral dimensions. For each pixel of the hyperspectral image, a full discrete is obtained being the wavelength bands typically an equally spaced sequence (Geladi, et al. 2004). Spectral features are related to the chemical-physical properties of samples, allowing a full characterization. Spectral adsorption mechanisms usually affecting vegetation, mineral, chemical products, etc. also affect secondary raw materials as generated in an Urban Mining context. In this latter case alterations, due to "life-time" related constraints of both materials and/or products, as well as, the frequent presence of "composite", dramatically influence detected spectra characteristics, not allowing and easy identification of specific absorption features. Furthermore, man-made are a source, at the origins, of chemical absorptions which are not readily found in natural materials. Finally, weather alteration can modify the original material and as a consequence their spectra (Roberts, et al. 2004). For all these reasons, acquired spectra interpretation is difficult, but it is simply possible to relate most absorption bands to C-H, O-H and N-H stretching vibrations specific for the NIR range.

Pollutant samples (i.e. wood, plastic, gypsum, brick and foam), provided from C2CA case study, were representative of some contaminant materials



a b

Figure 16: Digital image of Experimental set up 1 (a) and Experimental set up 2 (b).

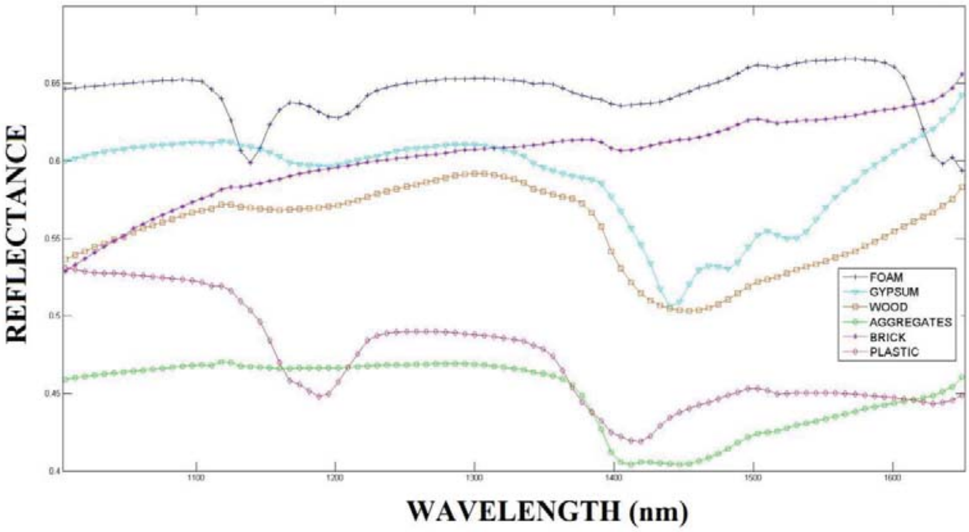


Figure 17: Acquired spectra of the six different analysed materials.

collected after demolition of a building in Groningen (NL). RA samples are 4-16 mm ADR products.

Analysed hyperspectral images were acquired in the 880-1720 nm wavelength range, with a spectral resolution of 7 nm, for a total of 121 wavelengths. In order to remove effects due to the background noise, a preliminary reduction of investigated wavelengths was applied and spectral variables were thus reduced from 121 to 93. The investigated wavelength range was from 1006 nm to 1650 nm. The image width was 320 pixels, while the number of frames was variable according to the length of the desired acquisition.

Two different hyperspectral image sequences have been thus acquired in order to build the classification model and to validate it. A first and a second series, respectively identified as Experimental set up 1 and the Experimental set up 2 (Figure 16). Twelve particles clearly identified as brick (2 particles), aggregates (3 particles), wood (1 particle), gypsum (3 particles), foam (3 particles) and plastic (4 particles) were arranged in lines, forming the Experimental set up 1 used to build the classification model. Experimental set up 2 was used as validation data set: particles were arranged in six groups according to their class membership.

Looking at the acquired raw spectra (Figure 17) related to the Experimental set up 1, differences in the spectral behaviour are visible. In order to highlight them, a combination of three pre-processing algorithms (Detrend, Standard Normal Variate and Mean Center) is applied, the obtained spectra are shown in Figure 18.

After pre-processing, Principal Component Analysis (PCA) was applied to the image corresponding to the Experimental set up 1 in order to explore

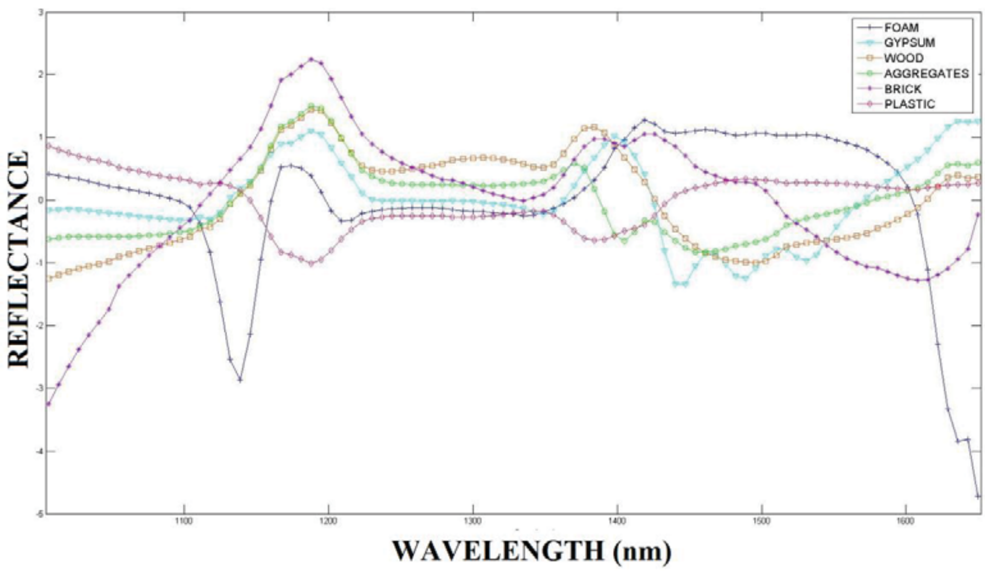


Figure 18: Pre-processed spectra of the six different analysed materials.

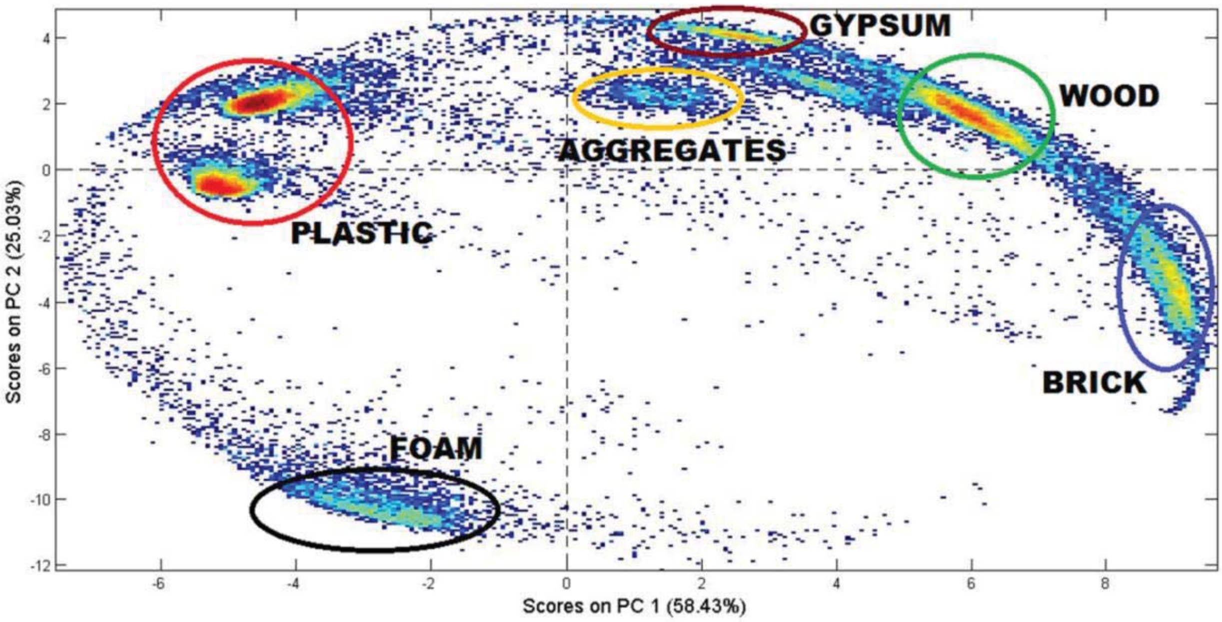


Figure 19: PCA score plot: Experimental set-up 1 pixels projection onto the space of PC1 vs PC2.

the data. PCA projects the samples into a low dimensional subspace, whose axes (the principal components, PCs) point in the direction of maximal variance, compressing the data. Looking at the distribution of samples into the PCs space, it is thus possible to interpret differences and similarities among them: the more they are grouped, the more they have similar spectral features. Furthermore, PCA highlights the trends among samples, giving preliminary information about distribution of different specimen on an image (Amigo, et al. 2013). The obtained score plot is shown in Figure 19: six different clusters, corresponding to the different materials, are recognizable onto the score plot. Therefore the training dataset was easily created by removing some border cluster points "different" from all other spectra of the same category and by setting class of the remaining pixels.

Partial Least-Square Discriminant Analysis (PLSDA) was adopted in order to build a predictive model able to classify the different specimen in the image: recycled aggregates and contaminants. This technique is a linear method based on the partial least squares regression requiring prior data knowledge: it is a supervised classification. The PLS-DA model allows to assign to each unknown sample (in this case, pixel) only one of the available defined classes, according to the similarity among spectra. Prediction maps are PLS-DA results: each class is defined by a different colour. In Figure 20 PLS-DA prediction map of Experimental set up 2 is shown.

A good classification is obtained and it is easy to associate each object in the image to a specific category, but some sporadic misclassified pixels are visible. This phenomenon can be attributed to the rough surface of the samples and the consequent light scattering effect. Moreover, it is necessary to take in account the presence of dust particles, due to the "dirty" nature of the samples, that can influence the analysis because of their own spectrum.

HSI based approach allows to develop an objective, fast and non-destructive method in order to control the quality of ADR products. It is possible to discriminate between recycled aggregates and contaminants in the ADR outputs, evaluating the pollutant content in order to monitor the entire recycling process. The utilization of the proposed approach is preferred in the secondary raw materials sector, where expensive and/or sophisticated quality control devices cannot be practically proposed, both for technical (i.e. particles of different size, shape and composition, etc.) and economic (i.e. environmental constraints, maintenance, etc.) reasons.

VII. Conclusions

According to the results the following conclusions can be drawn out:

- Smart dismantling and selective demolition is the most important step to minimize contaminants in RA. Results show that although the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard, the still visible pieces of wood and plastic in the +16 mm RA fraction reduces the economic potential of the RA. Using selective demolition in this study, the amount of gypsum and wood in the crushed EOL concrete

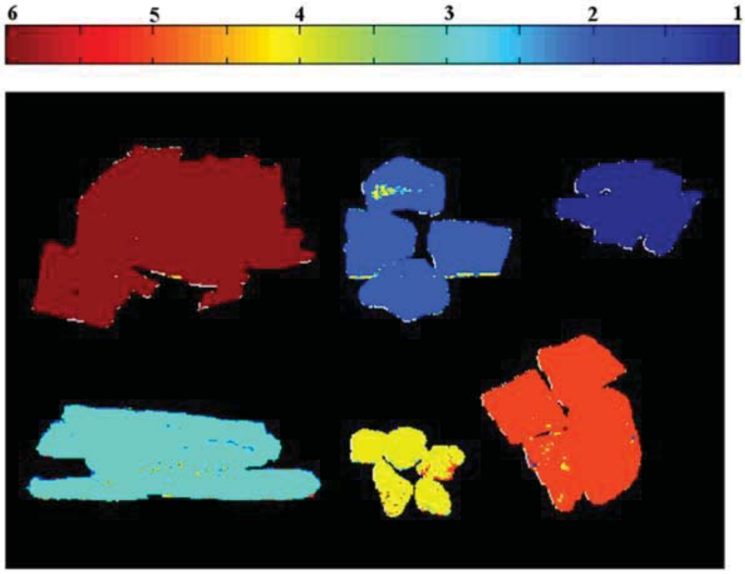


Figure 20: Prediction map based on PLS-DA model built for the classification of foam (1), gypsum (2), wood (3), aggregates (4), brick (5) and plastic (6) in the Experimental set up 2.

was reduced to almost 60 ppm and 2 cm^3/kg respectively.

- Autogenous milling reduces the mass percentage of contaminants bigger than 5mm by 30%. There is a clear effect of the milling on the size reduction of brick. A similar trend can be seen for wood contaminants but in a less outstanding way.
- The amount of wood in 4-16mm ADR product was measured as 0.117 cm^3/kg which is well within the strictest norm of EU standard.
- It is revealed that the combination of two technologies (NIR sensor sorting and wind sifting) will remove most of the contaminants from +16 mm RA.
- Two developing sensors (LIBS and HSI), should allow on-line methods for quality control and quality assurance of the concrete recycling products. The concept is to avoid the need for laboratory analysis and intermediate storage and if possible quality and end- of-waste certification at the site without human intervention. Recent investigations related to the aforesaid sensors show their high potential towards achieving the mentioned goals.

Acknowledgements

This research is funded by the European Commission in the framework of the FP7 Collaborative project "Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste (C2CA)". Grant Agreement No.265189.

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