Solid Waste Material Characterisation and Recognition by Hyperspectral Imaging Based Logics

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Abstract

Waste materials characterization and recognition can be performed through their surface spectral response. Such a goal can be reached using specialized devices able to collect of hyperspectral images allowing to collect information about material surface properties, status and physical-chemical attributes. The approach can be profitably applied with reference to two specific goals: development of specific sorting actions addressed to recognize and separate real-time different materials and set up of control strategies finalized to evaluate the performance of a separation. Case studies related to different recycling sectors, where hyperspectral imaging can be utilized, are described: glass recycling, fluff from car dismantling and bottom ash from solid waste incinerator.

Keywords

Recycling, solid waste, hyperspectral imaging, glass, fluff, bottom ash, sorting.

1 Introduction

Hyperspectral imaging, traditionally used for earth remote sensing applications, has become accessible as a powerful inspection tool for non-destructive analysis in several industrial sectors (GELADI ET AL., 2004). It combines the imaging properties of a digital camera with the spectroscopic properties of a spectrometer able to detect the spectral attributes of each pixel in an image. Thus, a hyperspectral image, is a three dimensional dataset with two spatial dimensions and one spectral dimension. The output of a hyperspectral sensor is a stack of images of a scene acquired in contiguous bands over a spectral range. It is often referred to as the “*image cube*” (Figure 1).

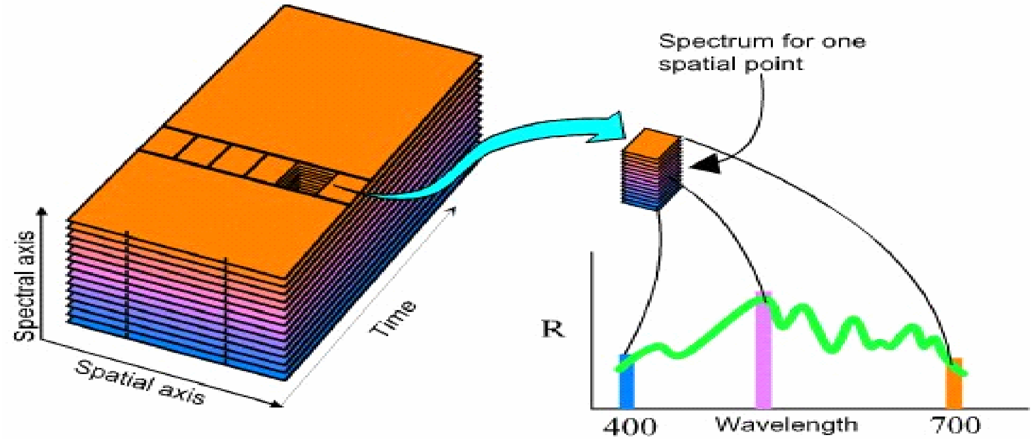


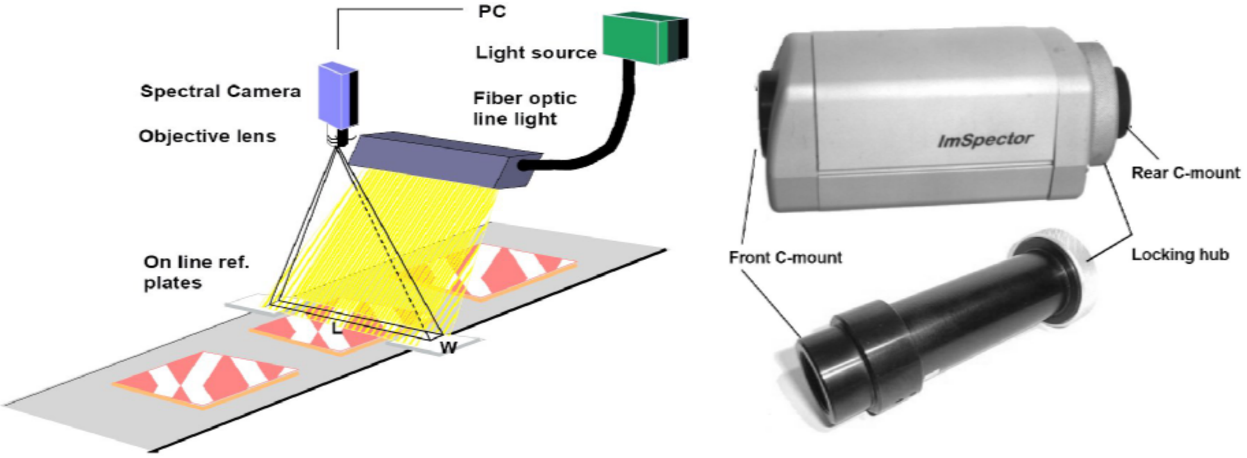
Figure 1 The hyperspectral image cube

The system, in addition to spatial information, provides spectral information in a wide wavelength range for each pixel of the image. The problem for the implementation of on-line applications is the big size of hyperspectral images (usually from 10 to 100 Mb), requiring efficient programming tools for handling, displaying, visualizing and processing files. Such problem can be currently overcome developing processing strategies acting in different steps: the entire wavelength range is usually acquired by an hyperspectral system, the spectra are then analysed to extract the optimal wavebands useful for the detection of the desired characteristics of the investigated samples and, finally, the algorithm to distinguish the desired characteristics from the samples is developed.

This versatile technique has many potential applications in solids waste characterization where the recognition of particles of different nature and composition or different portions of inhomogeneous particles, is required. Waste particles of different nature can present in fact different spectral signatures in different spectral ranges, from the visible to the infrared one. In this paper, specific and "*ad hoc*" applications on waste materials characterization carried out by hyperspectral imaging are reported with particular reference to: glass and ceramic glass classification in recycling plants, fluff sorting from car dismantling and characterization of processed bottom ash from waste incinerator.

2 Hyperspectral imaging architecture set-up

The hyperspectral imaging acquisition system adopted in this study is shown in Figure 2. It consists of a camera (HITACHI KP-M1AP), a line scan spectrograph (ImSpector^{TM} V10, SpecIm^{TM}, Finland), an illuminator (Fiber-Lite PL900-A, Dolan-Jenner Industries), a variable speed conveyor belt (DV srl, Italy) and a PC unit with the data acquisition and pre-processing software, Spectral Scanner v.2 (DV, 2003). The ImSpector^{TM} V10 operates in the spectral range of 400-1000 nm with a resolution of 5 nm.



2a 2b

Figure 2 Architecture set-up (2a) utilized to perform a progressive and continuous surface spectra acquisition. The spectrograph (2b) can be connected to any standard C-mount camera. The same applies to OEM spectrograph models (bottom) that are equipped with C-mounts, but come without housing.

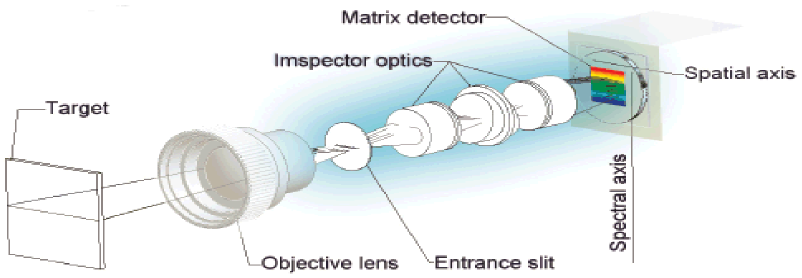


Figure 3 Operating principle of ImSpector™

The acquired images are 592x394 pixel size, corresponding to 20.9x13.9 cm (pixel size: 0.4x0.4 mm). The spectrograph is constituted by optics based on volume type holographic transmission grating (Figure 3) (HYVARINEN ET AL., 1998).

The grating is used in patented prism-grating-prism construction (PGP element) characterized by high diffraction efficiency, good spectral linearity and it is nearly free of geometrical aberrations due to the on-axis operation principle. A collimated light beam is dispersed at the PGP so that the central wavelength passes symmetrically through the grating and prisms and the short and longer wavelengths are dispersed up and down compared to central wavelength. This results in a minimum deviation from the ideal on-axis condition and minimizes geometrical aberrations both in spatial and spectral axis.

The result of acquisition is constituted by a digital image where each column represents the discrete spectrum values of the corresponding element of the sensitive linear array. Such an architecture allows, with a “simple” arrangement of the detection device (“scan line” perpendicular to the moving direction of the objects) to realize a full and continuous control.

A line lighting, as energizing source with uniform spatial distribution, was used. Calibration was performed in three steps: i) spectral axis calibration with spectral lamps; ii) dark image acquisition and iii) measurements of “white reference image”. After the calibration phase: i) the image spectra is acquired and ii) the reflectance (R_{ci}) (at wavelengths i and spatial pixels c of interest) is computed:

$$\mathrm{R}_{\mathrm{ci}} = \left[(sample)_{ci} - (dark)_{ci}\right] / \left[(white)_{ci} - (dark)_{ci}\right] \qquad (1)$$

Such a procedure enables to compensate the offset due to CCD dark current and separates the sample reflectance from the system response.

3 Case studies

In the following three different examples of application of the proposed methodology are reported for different materials where the problem of polluting elements represents one of the key factors affecting their advanced processing for recovery.

3.1 Ceramic glass recognition in glass recycling plants

Ceramic glass contaminants in the cullet (glass fragments) strongly affects the quality of glass recycled products. Such unwanted fragments being characterized by higher melting point than glass, can produce severe damages in the production equipment and on the final manufactured goods (bottles, vases, jars, etc.).

In glass recycling plants, most contaminants (metals, plastics or paper) are commonly removed adopting different on-line sorting strategies as they are characterized by different physical properties from those characterizing glass. However, ceramic glass has similar physical properties to those of glass and even automated optical based sorting techniques, usually utilized for coloured cullet separation, are unable to realize an efficient recognition. Therefore, identifying and removing ceramic glass from the glass waste stream has long been a challenge for glass recyclers.

Different studies have been carried out on glass and ceramic glass fragments in order to evaluate the possibility to correctly classify them by hyperspectral imaging utilizing their different spectral response (Bonifazi and Serranti, 2006a).

The reflectance spectra of selected glass and ceramic glass samples, in the VIS-NIR field (400-1000 nm) are reported in Figures 4 and 5, respectively. A picture of the different fragments is also shown. Investigated materials belong to different products, that is classical container glass and ceramic glass samples resulting from cookware, cook top, etc. and are characterized by different colour, thickness, manufacturing and shape.

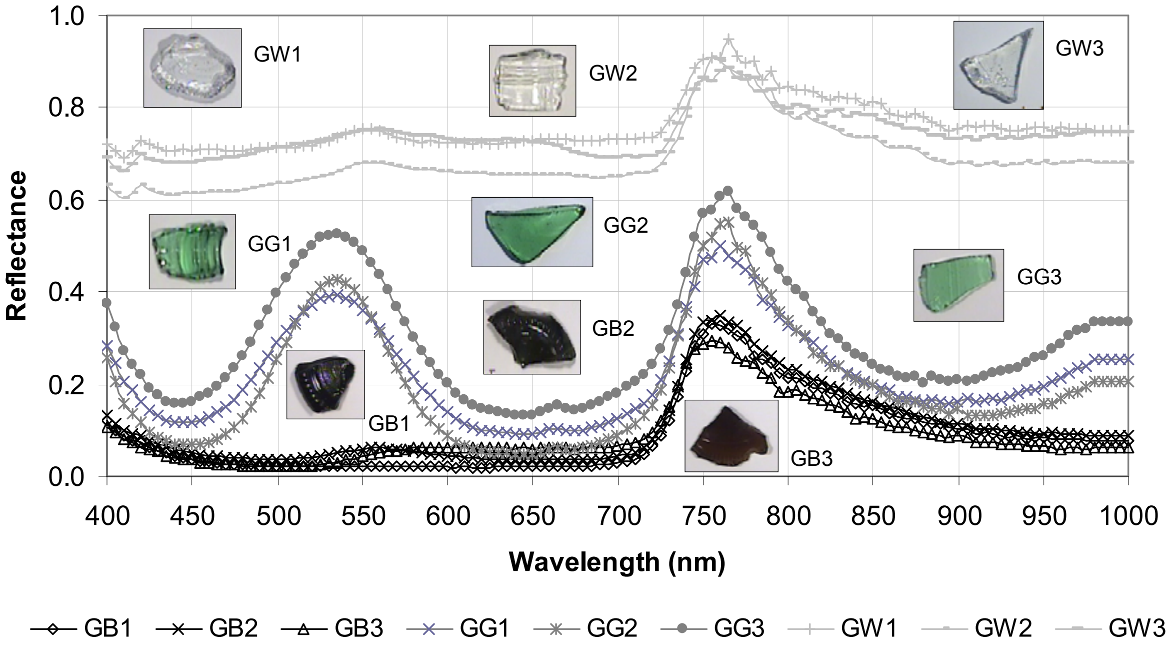


Figure 4 Reflectance spectra of container glass samples characterized by different color (clear transparent, green and amber) in the VIS-NIR field (400-1000 nm) detected by the hyperspectral imaging system.

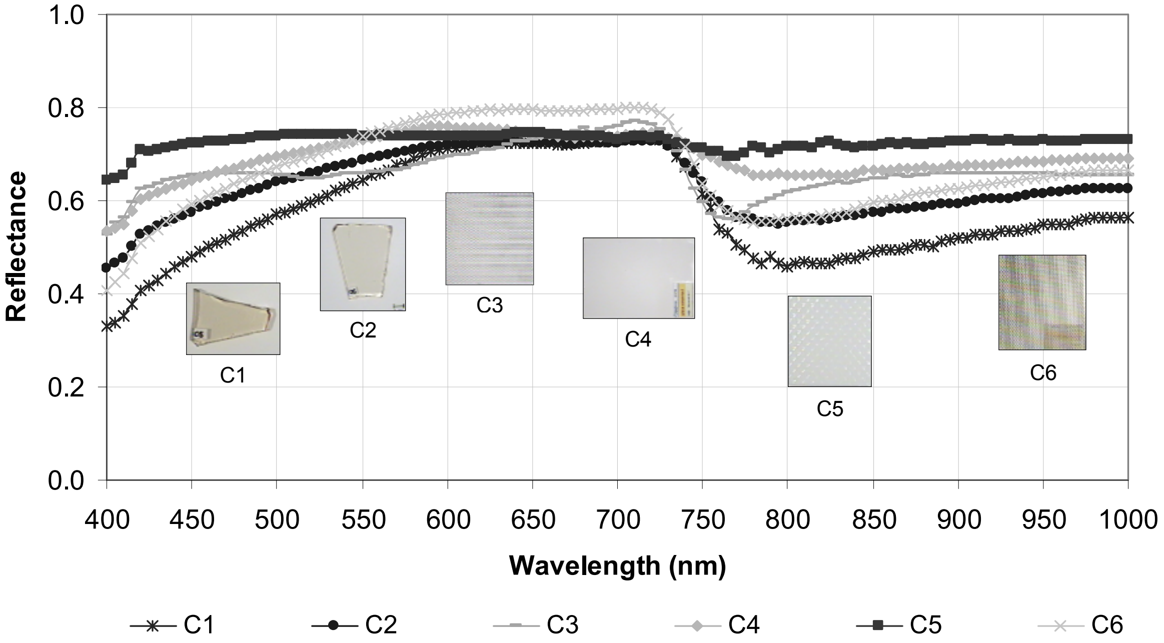


Figure 5 Reflectance spectra of the representative ceramic glass samples in the VIS-NIR field (400-1000 nm) detected by the hyperspectral imaging system.

More in details, glass samples are representative of clear, green and amber color categories, ceramic glass are characterized by those typologies commonly present in waste products, that is clear and opaque white samples.

Considering the reflectance plots of glass fragments (Figure 4), two regions in the spectra can be distinguished: the VIS (visible) field (400-700 nm) and the NIR (near infrared) field (700-1000 nm). In the VIS field, the spectral behaviour is influenced by the colour of the analyzed cullet (clear, green or amber). For example, the spectra of the green cullet show a characteristic peak at 500-550 nm, corresponding to the green visible field. The other samples (both clear and amber) show spectral profiles with more or less constant values in the range 400-700 nm, with differences in the reflectance level strictly related to differences in reflection power. On the contrary, in the wavelength interval from 700 to 1000 nm (NIR), it can be noticed as the curves are characterized by similar shape for all samples. In fact, all glass samples, independently from their colour, show a characteristic peak in the range 750-760 nm. The lower reflectance level in the spectra of amber samples, than that of clear and green samples, is dependent on the dark fragment colour.

Comparing reflectance spectra of ceramic glass fragments (Figure 5), it appears that clear and opaque white samples show curves with a similar shape, indicating a common behaviour at the different wavelengths. Reflectance values of clear and opaque white samples increase from 400 nm up to about 720 nm, then decrease, presenting a minimum value at about 760 nm. After such value, the spectra are characterized by constant or slightly increasing values up to the end of the investigated field (1000 nm).

Comparing the spectra of glass and ceramic glass samples, it is evident that the two materials are characterized by a different spectral signature. Specific wavelength ratios can be selected in order to recognize the two materials especially in the region 700-1000 nm. In this way a fast and easy method can be adopted for the implementation of an automated sorting system working on-line in a glass recycling plant.

4 Fluff sorting in car dismantling industry

Fluff is the name conventionally used for the light fractions produced after vehicles dismantling. It represents about the 25% of the weight of a car and is usually constituted by materials characterized by intrinsic low specific gravity (i.e. plastics, rubber, synthetic foams, etc.). When processed to perform their recovery, fluff results polluted by materials presenting higher specific gravity (i.e. copper, aluminium, brass, iron, etc.), constituting parts of the electrical devices of the vehicle that, for their shape, size (i.e. wires, metal straps, slip rings, wipers, etc.) and utilization remain concentrated in the lighter products. Such “polluting agents”, for their intrinsic characteristics, are not well removed by classical separation techniques.

The demolition process is usually based on a series of preliminary target oriented dismantling steps as: the removal of car fluids, batteries, tires, bumpers, glasses and on the further material comminution.

Products resulting from size reduction are selected, usually by cycloning or venting (air suction or blowing systems), in order to separate the light material from the heavy one. Specific sorting strategies are then applied on the light fractions to sort the different constituting materials.

The possibility to properly separate and clean the lighter fractions could strongly improves the possibility to set up more efficient recycling strategies, reducing waste disposal and environmental pollution and increasing, at the same time, the energy recovery through pure sorted polymer re-use. Furthermore the possibility to utilize finer fluff fractions to produce energy could contribute to increase the recovery of such a kind of products. To reach this goal, the quantity and the quality of the metal contaminants have to be strongly controlled to not prejudicate the quality of the final fluff based fuel.

The need to develop both efficient selection and control strategies to obtain contaminant free fine fluff products assumes a fundamental role in all the processing and control steps of the recycling chain. In this perspective, the use of hyperspectral imaging in order to characterize fluff particles has been investigated (BONIFAZI AND SERRANTI, 2006B). The reflectance spectral signatures of different fluff particles have been acquired and analyzed in order to highlight the differences in spectra that can be then used to design and implement an ejection system to sorting the undesired metal particles in fluff.

RUBBER WOOD METAL PLASTIC FOAM

Figure 6 Examples of fluff samples belonging to five different classes of materials, utilized to perform the spectral analyses.

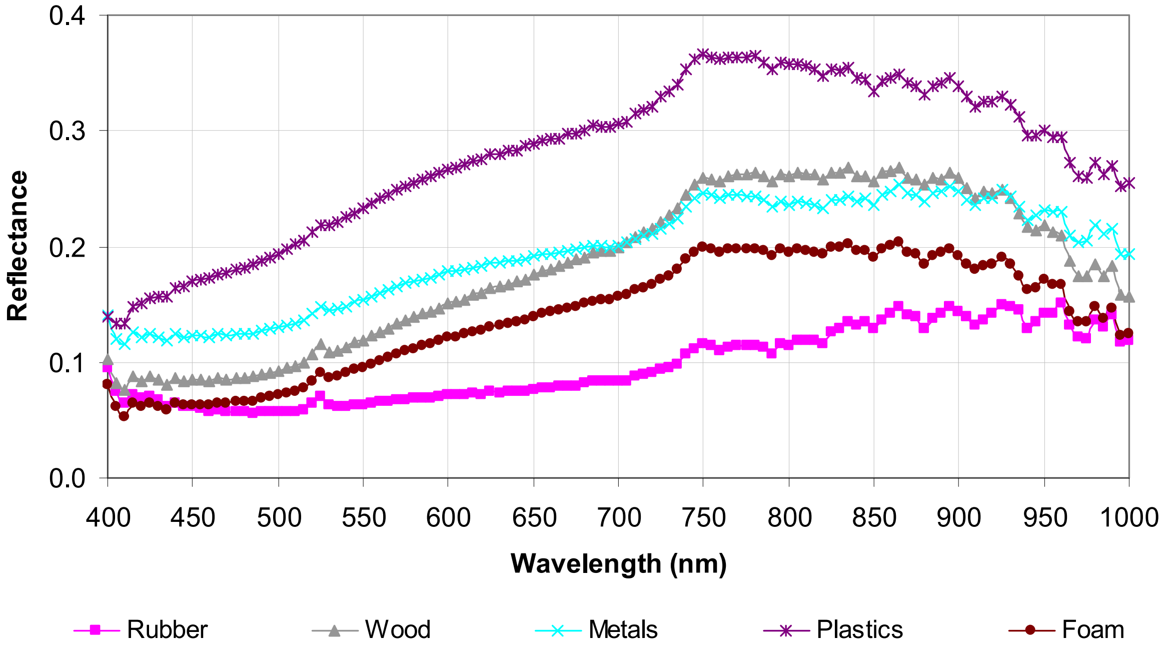


Figure 7 Average reflectance spectra in the VIS-NIR field (400-1000 nm) of the different classes of particles resulting from manual fluff sorting, detected by the hyperspectral imaging system.

In Figure 6 different classes of materials constituting fluff that have been manually selected are shown: rubber, wood, metal, plastic and foam. The corresponding reflectance spectra in the VIS-NIR field (400-1000 nm) of the different classes of materials are summarized in Figure 7.

Comparing the average spectral signatures of the different classes of materials, it appears that they are characterized by different behaviors. The recognition of the different materials could be thus realized selecting specific wavebands in which the differences in reflectance values are best highlighted (Bonifazi and Serranti, 2006b). Different spectral trends can be, in fact, recognized in the NIR region, from 750 nm to 1000 nm. Metals spectra show an intensity decrease in the region between 750 nm and 850 nm, differently from foam and wood that present almost constant reflectance values, and rubber and plastics that present an increasing and decreasing trend respectively. Considering that metal particles represent, not only a fuelling material, but also the main pollutants, the possibility to perform their recognition represents a big step forward to set up innovative selection strategies aimed to produce fine fluff particles to be utilized as a source of energy. Furthermore the possibility to perform a further selection of the other combustible materials can strongly enhance the final characteristics of the recovered products.

5 Quality control of bottom ash resulting from combustion of municipal solid waste

Ash residues from combustion of municipal solid waste (MSW) generally represent about 25% of incoming waste (HASSELRIIS, 2002). Disposal of ash residues imposes an increment to the total cost of operation of a WTE (Waste-To-Energy) combustion facility.

In Europe landfilling of ash residues has been restricted, due to scarcity of land and its potential uses for agriculture or other purposes. Therefore, recycling and beneficiation of bottom ash has been encouraged, both economically and by favorable regulations. Whether placed in landfills or beneficially used, account must be taken of ash residues characteristics and the effect of ash management procedures on their properties, and their environmental impact.

Ash residues are discharged at various locations from the combustion and emission control equipment. Bottom ash consists of inert residues, glass, unburned organic matter and metallic objects and 2 to 20% carbon. Their properties are strongly related to the MSW burned and to the combustion process. Bottom ash residues, after different and specific processing strategies, mainly based on separation (magnetic and eddy current based) and classification (screening and cycloning) actions can be profitably utilized for fill and road base. Considering that for their reuse bottom ash must comply with strict regulations, consisting of civil-technical and environmental requirements, its characterization is thus an important step in view of sustainable waste management. In particular, the presence of the so-called "*organic matter*" fraction represents a strong and severe constraint in respect of their re-use as "*common*" inert material.

In summer 2002 a pilot plant was built and run in Amsterdam (The Netherlands) to test a new wet process on the bottom ash resulting from the Amsterdam MSW incinerator. The process combines a washing step, to remove the residual organic matter, and the fines with separation technology, for recovering the non-ferrous metals (REM ET AL., 2004). The objective was to produce sand and granulate fractions that satisfy the Dutch building materials decree, recovering, at the same time, as much as possible of the non-ferrous metals from the ash.

Selected samples of sand fraction (25 µm – 2 mm) obtained after bottom ash processing in the previous mentioned pilot plant have been collected and analyzed. Both chemical and hyperspectral imaging analyses have been carried out, in order to find a correlation between chemical composition of sand product, with particular reference to

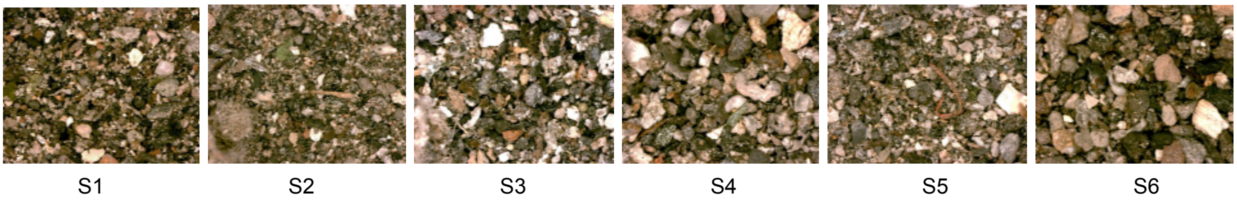

S1 S2 S3 S4 S5 S6

Figure 8 Selected sand product samples characterized by different organic matter content, utilized to perform the spectral analyses.

Table 1 Organic matter (%) content of the analysed bottom ash samples.

	S1	S2	S3	S4	S5	S6
Organic matter (%)	6.9	7.4	3.8	5.2	2.3	4.4

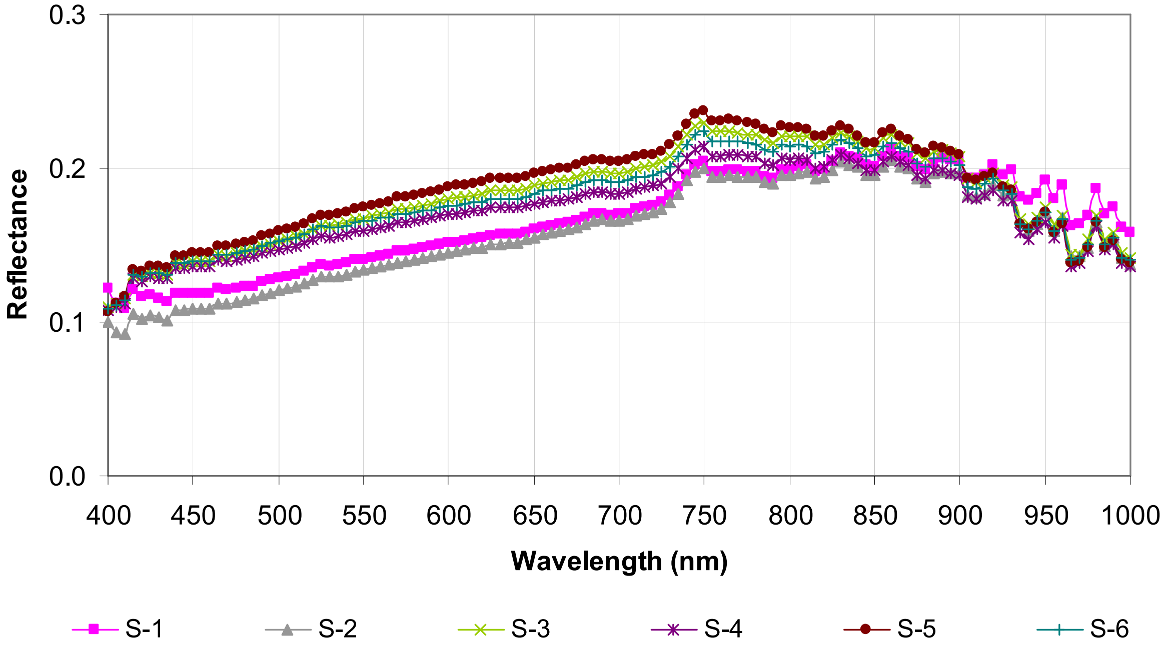


Figure 9 Average reflectance spectra in the VIS-NIR field (400-1000 nm) of the selected bottom ash samples, characterized by different organic matter content, detected by the hyperspectral imaging system.

the organic matter content, and spectral signature in the VIS-NIR wavelength range. In Figure 8 the collected samples are shown. The organic content has been analyzed and the results obtained are reported in Table 1. The reflectance spectra of the sand samples have been acquired using the hyperspectral imaging system and the results are reported in Figure 9.

Comparing the average spectral signatures of the different samples (Figure 9), it appears that they are characterized by curves presenting similar shape but increasing reflectance levels in the following order: S-2, S-1, S-4, S-6, S-3 and S-5. Comparing this order with the results obtained for the organic content in Table 1, it is evident that there is an inverse correlation between reflectance level and organic matter content. Such result is quite interesting as it would involve the possibility to introduce a sensor, based on hyperspectral imaging, on the final section of the bottom ash processing plant for quality control of products to be used as building materials.

6 Conclusions

Hyperspectral imaging based architecture can be considered as a flexible instrumentation that, combining imaging and reflectance spectroscopy, can be profitably utilized in the solid waste sectors to develop innovative control-sorting strategies specifically addressed to solve identification problems related to the detection of polluting agents inside recycled products, usually difficult to “qualify” through the conventional quality control strategies. In fact, hyperspectral technology through the detection of the spectral signature of each investigated particle allows to univocally identify it, simplifying any further sorting. Results demonstrated as:

- in glass recycling sector the development of an automatic ceramic glass sorting equipment will enable the recyclers to maximize profits by turning lower-value glass into high-value contaminant-free cullet;
- in fluff recovery the hyperspectral approach allows to detect the presence of metals and alloys fine particles both to perform sorting actions and/or to develop quality control strategies addressed to fine particles certification in order to utilize them to produce energy;
- in bottom ash characterization the proposed procedure allows to perform a full detection of the organic fractions inside the products object of separation-classification procedures allowing this way the possibility to control the quality of the resulting products in terms of reduced environmental impact when utilized as inert material.

Finally, in more general terms, the characteristics of the devices and the related analytical techniques allow to utilize such an approach to set-up innovative, flexible, reliable and low cost detection/control devices and strategies that can be easily integrated, at industrial level, inside existing processing plants layouts.

7 Literature

Bonifazi G., Serranti S.	2006a	Imaging spectroscopy based strategies for ceramic glass contaminants removal in glass recycling. Waste Management, 26, 627-639.
Bonifazi G., Serranti S.	2006b	Hyperspectral imaging based techniques in fluff characterization. Optic East 2006, Proceedings of SPIE

		#6377, October 3-4, Boston, Massachusetts, USA, 63770O-1-63770O-10.
Geladi P., J. Burger J., Lestander T.	2004	Hyperspectral Imaging: Calibration problems and solutions. Chemometrics and Intelligent Laboratory Systems, 72, 209-217.
Hasselriis F.	2002	Waste-to energy combustion, Part 13B Ash Management and disposal. In: Handbook of solid waste management 2nd Ed., G. Tchobanoglous and F. Kreith Eds., Mc Graw-Hill, New York, 13.85-13.119.
Hyvarinen T., Herrala E., Dall'Ava A.	1998	Direct sight imaging spectrograph: a unique add-on component brings spectral imaging to industrial applications. SPIE Proceedings of Symposium on Electronic Imaging: Science and Technology, January 25-30, San Jose, California, USA, 3302, 165-175.
Rem P.C., De Vries C., van Koov L.A., Bevilacqua P., Reuter M.A.	2004	The Amsterdam pilot on bottom ash. Minerals Engineering, 17, 363-365.

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