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Evaluation of attached mortar on recycled concrete aggregates by hyperspectral imaging

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HIGHLIGHTS

- Innovative hyperspectral imaging approach for quality control of recycled concrete aggregates.
- Hyperspectral images were analysed adopting chemometric methods.
- Aggregate and residual mortar automatic classification was carried out by PLS-DA.
- The quantity of residual mortar paste on the surface of recycled concrete aggregates was evaluated.

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ABSTRACT

The presence of mortar attached to the surface of recycled aggregates strongly affect their quality, especially in order to reuse them for making new concrete. In this perspective, an innovative sensor-based quality control strategy was developed using hyperspectral imaging (HSI) in the near-infrared range (1000–1700 nm), to evaluate the residual mortar content on the surface of coarse recycled concrete aggregates. Hyperspectral data processing was carried out applying first principal component analysis (PCA) for data exploration and then partial least square-discriminant analysis (PLS-DA) to build classification models. Micro X-ray fluorescence (micro-XRF) maps were also obtained on the same aggregate samples in order to validate the HSI classification results. The developed procedures allowed to correctly identify the mortar attached on aggregate surface and to quantify its percentage. The proposed approach can be profitably applied to certify recycled aggregates quality, increasing their economic value.

1. Introduction

Construction and Demolition Waste (CDW) generation is perceived as one of the main worrisome negative effects of the construction industry together with land depletion and deterioration, energy consumption, dust and gases emissions, noise pollution and consumption of non-renewable natural resources [1–4]. The direct utilization of natural resources, both in terms of hard rocks milling and classification and/or alluvial sediments exploitation, deeply impacts on the environment; in this second case for example, modification of the river profiles can be produced [5]. Furthermore, natural resources exploitation always affects the hydrological and hydrogeological characteristics of the areas, generating in some cases large “instability problems” [6].

On the other hand, the demand for cement-based materials to be involved into the building sector is expected to increase within the next years especially in developing countries [7]. More and more the need to produce good quality aggregates can lead to a massive non-renewable resources exploitation, with all the related environmental problems mentioned before as well as the associated economical drawbacks.

In order to provide sustainable solutions, able to combine the necessity of raw materials with waste reduction, the concept of *Urban Mining* (UM), referred to CDW, has to be applied. UM concerns all the activities recovering compounds, energy and elements from end-of-life products [8], requiring the transition from a linear approach (i.e. materials are definitively disposed after use) to a circular approach, in which secondary raw materials are obtained from the waste stream [9–11].

In particular, regarding CDW, the latest EU Waste Framework Directive (WFR 2008/98/EC) imposes European countries to achieve at least 70% of recycling and/or recovery of CDW by 2050 [12].

In these last years, many efforts were addressed to find systems able to maximize CDW conversion into secondary raw materials

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for high-grade building materials. More in detail, the recycling of end-of-life concrete aggregates for the production of new concrete is one of the most interesting options. Indeed, in many countries the largest part of the CDW recycled products is recycled concrete aggregates (RCA) [13] and different studies confirmed that recycled materials, when satisfy specific quality standards, are good substitutes for natural aggregates [14,15].

Several studies related to the production of recycled concrete are widely reported in literature e.g.: [16,17], with particular reference to coarse aggregates [18,19], but also to the use of mixed aggregates [20–23] and sometimes to the utilization of fine aggregates [24,25].

In order to use RCA for new concrete production, they have to be "competitive" in terms of their "intrinsic" quality when compared with primary raw materials [26]. The two main problems affecting RCA quality are: 1) presence of different contaminant particles (i.e. brick, gypsum, wood, plastic, etc.) and 2) attached mortar not completely removed from the aggregate surface.

The quality control related to contaminant detection in RCA flow streams was faced in previous studies [27–30]. In this work the attention was focused on the evaluation of residual mortar paste attached to RCA (Fig. 1).

More in detail, the presence of adhered mortar on the surface of aggregates can influence the density, the water absorption, the sulphate content, the consistency and the strength of aggregates and therefore the performance of the new produced concrete [31,32,17]. In terms of water absorption, for instance, RCA often present higher values than those of the natural aggregates [33]. This phenomenon, probably related to the residual mortar adhering the aggregate, increases the RCA porosity, decreasing their density. Lower aggregate density raises its absorption capacity and reduces its strength [34]. As a result, a greater amount of water and cement is needed in concrete production, making more difficult to achieve the required levels of concrete characteristics. The new concrete, produced starting from mortar covered aggregates, can undergo a critical impact both on its fresh properties, as workability, and on its hardened characteristics, as mechanical strength and durability [35]. Moreover, some researches showed as the presence of adhered mortar on RCA surface can decrease bond strength between RCA and cement matrix in new concrete production [36].

Based on what previously reported, it is clear that in order to be competitive with natural aggregates, standard procedures for the evaluation of the quality of RCA in terms of attached mortar content should be established.

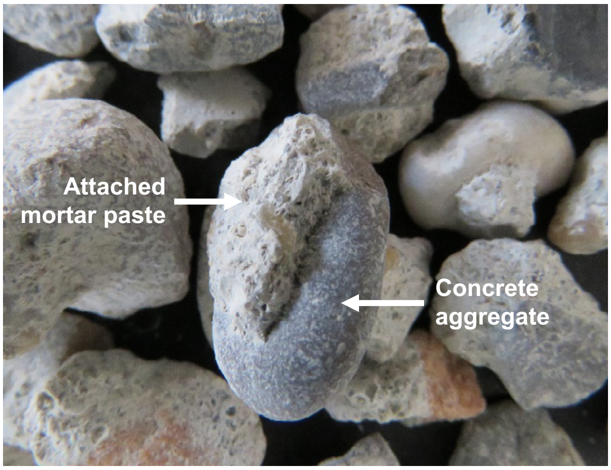

Fig. 1. A pictorial example of recycled concrete aggregate sample with attached mortar paste.

The aim of this work is the implementation of a sensor-based procedure for quality control of RCA, with specific reference to the evaluation of attached mortar on aggregate particle surfaces. The adopted sensor technique is based on H*yper*S*pectral* I*maging* (HSI), carried out in the NIR (1000–1700 nm) wavelength range. The NIR-HSI technique is spreading in the solid waste sector in the last years and its application in the DW recycling field is beginning to emerge. Indeed, HSI system represents a good solution for characterization, classification and quality control of different materials in all industrial sectors, especially where it is important to apply effective but easy to implement and to use low-cost methods.

2. Materials and methods

2.1. Investigated recycled concrete aggregate samples

Investigated RCA samples come from the demolition of two towers located in Groningen (NL) [37]. The samples are constituted by the coarse fraction (−16 + 8 mm) of RCA, obtained by an innovative dry separation process, called Advanced Dry Recovery (ADR), carried out at TUDelft (Delft, NL) [38,39]. In order to evaluate the presence of residual mortar on RCA, the samples were divided in three classes: 1) clean aggregates, 2) mortar-covered aggregates and 3) partially liberated aggregates (Fig. 2).

2.2. Hyperspectral imaging

HSI acquisitions and data processing were carried out at the Laboratory of Raw Materials Engineering of La Sapienza – University of Rome (Latina, Italy) using a specifically designed platform by DV srl (Padova, Italy).

HSI is based on the utilization of an integrated hardware and software architecture able to digitally capture and handle spectra, as they result along a pre-defined alignment on a surface sample properly energized [40].

The adopted device works as a push-broom type line scan camera and acquires spectral information for each pixel in the line [41]. Both spatial and spectral information can be collected at the same time from the investigated material. Such information is contained in a 3D dataset, characterized by two spatial dimensions and one spectral dimension, the so-called "hypercube". Several physical-chemical characteristics of a sample can thus be investigated, according to the different wavelengths of the source and the spectral sensitivity of the device.

The HSI acquisition device (Fig. 3) is constituted by a moving conveyor belt (width = 26 cm and length = 160 cm) with adjustable speed (variable between 0 and 50 mm/s), a NIR Spectral Camera™ embedding an ImSpector N17E™ (SPECIM Ltd, Finland) working in the spectral NIR field (1000–1700 nm) and a diffused light cylinder providing the required energy to the samples in order to allow a correct spectra acquisition. A PC unit controls the HSI system and a specialized software was used for acquisition/pre-processing steps: Spectral Scanner™ v.2.3.

Hyperspectral images were acquired in the 900–1700 nm wavelength range, with a spectral resolution of 5 nm, for a total of 161 wavelengths. The spectrometer was coupled with a 15 mm lens. The image width was 320 pixels, the length varied according to the sample size. HSI acquisition time depends on the conveyor belt speed and the acquired frames (i.e. image size). In this case study, each acquisition took about 25 s.

In order to remove effects due to the background noise, the raw spectra were cut at the beginning and at the end: spectral variables were thus reduced from 161 to 131 obtaining a new investigated wavelength interval (1000–1650 nm).