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Quality assessment for recycling aggregates from construction and demolition waste: An image-based approach for particle size estimation

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ABSTRACT

The size distribution of aggregates has direct and important effects on fundamental properties of construction materials such as workability, strength and durability. The size distribution of aggregates from construction and demolition waste (C&D) is one of the parameters which determine the degree of recyclability and therefore the quality of such materials. Unfortunately, standard methods like sieving or laser diffraction can be either very time consuming (sieving) or possible only in laboratory conditions (laser diffraction). As an alternative we propose and evaluate the use of image analysis to estimate the size distribution of aggregates from C&D in a fast yet accurate manner. The effectiveness of the procedure was tested on aggregates generated by an existing C&D mechanical treatment plant. Experimental comparison with manual sieving showed agreement in the range 81–85%. The proposed technique demonstrated potential for being used on on-line systems within mechanical treatment plants of C&D.

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1. Introduction

Despite its unquestionable contribution to the development of the worldwide society, the construction industry has also been perceived as a major source of environment degradation, with negative effects including land depletion and deterioration, energy consumption, dust and gas emissions, noise pollution and consumption of non-renewable natural resources (Ofori, 1992; Bossink and Brouwers, 1996; Sjostrom and Bakens, 1999; Shen et al., 2007; Poon and Chan, 2007). Among them, the production of large amounts of construction and demolition waste (C&D) is one of the most worrisome. The European Commission defines C&D as the result of 'activities such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road construction and maintenance' (European Commission, 2014). In practice C&D is mainly composed of concrete, stone, bricks, mortar and the like; but other materials such as plastics, metals, wood chips and glass, as well as contaminants like chlorides, sulphates, silicates, silt, clay and organics can also be present (Martín-Morales et al., 2011; Di Maria et al., 2013).

The production of C&D is difficult to track and can be understated. In 2012 the estimated figure for Europe (EU-28) was of about 820 million tons per year (European Commission, 2012), representing 33% of total waste generation; for the United States it was of approximately 480 million tons (Townsend et al., 2014), whereas for India of about 530 million tons in 2013 (Centre for Science and Environment, 2014).

With the aim of reducing the impact of such a huge amount of material, the European Directive 2008/98/EC on waste (also referred to as the 'Waste Framework Directive') has set the objective of no less than 70% recycling and reuse of C&D by 2020 (European Commission, 2008). As a consequence, topics including generation, reduction, reuse, recycling and management of C&D have been attracting increasing research interest in recent years – see Yuan and Shen (2011) for a review.

It is widely accepted that the main obstacles which can make it difficult to reuse C&D as aggregates are economic viability and material quality (Di Maria et al., 2013; Huang et al., 2002; Rao et al., 2007; Tam and Tam, 2006). Duran et al. (2006) observed that for recycling to become economically viable both the following conditions need to occur: (a) cost of landfilling higher than that of conveying the waste to the recycling centre; (b) cost of primary aggregates higher than that of recycled aggregates. As for quality, this depends a great deal on the mechanical treatment and on the properties of the demolished materials (Huang et al., 2002, 2013; Tam and Tam, 2006). Most commonly C&D is recycled by either using it directly as aggregate for new constructions, or by employing it as a component in the industrial production of

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cement, bricks and other building materials. A number of studies confirmed that recycled materials are good enough substitutes for natural aggregates (Robinson et al., 2004; Chang et al., 2010). Martín-Morales et al. (2011) for instance investigated the compliance of recycled aggregates from C&D with the Spanish Structural Concrete Code EHE-08, and showed that particle shape, density, assessment of fines and resistance to fragmentation were in compliance with the standard, whereas water absorption, sulphate and chloride content were not. Bianchini et al. (2005) found that the recycled grain-size fraction 0.6–0.125 mm could be directly employed for new mortar and concrete preparation while finer fractions could be considered as component for industrial processing for cements and bricks preparation.

Among the different properties which determine the quality of aggregates the particle size distribution plays a fundamental role, for it affects important properties of the concrete such as workability, porosity, permeability, strength, compactness and durability (Rao et al., 2007; Martín-Morales et al., 2011). A particle size distribution uniformly graded in all sizes will in fact allow for greater interaction between the particles, thus conferring better compactness and higher mechanical strength to the construction material (Kraemer et al., 2004). The importance of the grain size distribution in recycled aggregates from C&D has been emphasized in a number of studies involving different applications: Fan et al. (2015) for instance investigated how the characteristics of recycled concrete aggregate affect the physical and mechanical properties of the resulting mortars; Ledesma et al. (2014) evaluated the short- and long-term properties of masonry mortar when natural sand is replaced by fine recycled concrete aggregates; Zhou et al. (2014) showed that the size distribution may affect concrete in that overly large particles may impede to form a certain stable packing skeleton structure; Bocci et al. (2016) showed that a percentage up to 30% of C&D materials can be used in asphalt concrete for base layers without penalizing the of mechanical performance of the mixture provided the correct grain-size distribution is given.

Due to the intrinsic heterogeneity of the material, the recycling of C&D requires preliminary treatment aiming at reducing the particle size and removing impurities. Such operations are commonly carried out within industrial plants equipped with dedicated mechanical devices such as crushers, disk and trommel sieves, metal separators and air classifiers (Huang et al., 2002). The resulting aggregate is usually grouped into two or three wide particle size classes that are stored in large heaps before further recycling operations. It is worth noting that the processing of natural and recycled aggregates is essentially the same. However, the issue often associated with recycled aggregates is the inconsistency and variability of feed materials, in addition to the amount of adhered cement paste and contaminants present. As a result, methods for detecting materials such as ceramics and gypsum play an important role in the recycling process. On-line determination of the particle size distribution in the mechanical treatment plant in any case represents a major source of information both for assessing the quality of the recycled C&D and for determining the potential need for additional mechanical treatment. The geometrical properties of aggregates are usually determined through manual sieving, as prescribed by specific standards (British Standards Institution, 2012). When applied to C&D this procedure however shows some significant limitations due to the following reasons:

- Manual sieving can operate on very small amounts on material – in the order of kilos – whereas the quantities processed by waste management plants are in the order of tons.
- The intrinsic variability of C&D waste requires the size distribution after crushing to be checked continuously, whereas manual sieving is typically a one-off procedure.
- Manual sieving is intrinsically slow, and needs to be performed by skilled workers therefore implying additional costs.

To overcome these problems we present a novel methodology based on image analysis for estimating the particle size distribution of aggregates obtained from C&D. We carried out an experimental campaign to test the effectiveness of the procedure by comparing the size distribution of aggregates from C&D obtained through manual sieving with that obtained with the proposed approach.

2. Related research

Applications of machine vision to the characterisation of C&D has been attracting increasing research interest in recent years. A major current focus in this context has been the identification and classification of the materials C&D is composed of, with the aim of producing recycled 'green' concrete. Da Fonseca Martins Gomes et al. (2010) for instance developed a machine vision system based on shape features for detecting mortar, ceramic and concrete within C&D. Gokyuu et al. (2011) used colour features and Bayesian classification to sort byproducts of different size and shape from C&D. Likewise, Anding et al. (2013) proposed a computer vision system based on colour imaging and support vector classification for differentiating phenotypically similar materials such as concrete, aerated concrete, lightweight concrete, porous brick and dense brick. More recently, Palmieri et al. (2014) described a system based on hyperspectral imaging for detecting unwanted contaminants like brick, gypsum, wood and plastics in C&D.

By contrast, little attention has been so far devoted to the problem of assessing the grain size distribution of recycled aggregates from C&D. Yet the use of image analysis for estimating the grain-size distribution of sediments is not new, and its extension to the domain of C&D appears reasonable. The approaches available in the literature fall under two main categories, usually indicated as 'direct' and 'indirect', but also referred to as 'geometrical' and 'statistical' (Buscombe, 2013). Direct methods aim at identifying and isolating each single grain in the input image through suitable segmentation algorithms. Such approaches usually require there be little overlap between the grains: typically they work on particles well separated and scattered on even surfaces; see, for instance, Mora et al. (1998), Frančišković-Bilinskia et al. (2003), and Deidun et al. (2013). These limitations make direct methods difficult to use for *in situ* field measurements, and certainly unsuitable for the application studied herein, where the material is usually rather packed and with large overlap between the pieces. By contrast, indirect (statistical) methods avoid segmentation and do not consider each individual grain separately. Instead, they aim at extracting size-sensitive features from the input image considered as a complex whole. The procedure involves the creation of a set of calibration images of known grain-size (catalogue) as a first step, then the grain-size distribution of an image of an unknown sample is estimated by looking up the calibration samples in the catalogue (Buscombe, 2008). To this end various texture descriptors have been proposed in the literature, including autocorrelation (Rubin, 2004), semivariogram (Carbonneau et al., 2003) and Fourier transform (Buscombe and Masselink, 2009) – a detailed description of the texture features used in this study is provided in Section 4.1. Though the use of image analysis for grain-size assessment of sediments is well established, we are aware of no published studies about the effectiveness of this approach in the domain of C&D. Here the problem can be significantly harder due to the intrinsic large heterogeneity of C&D, and to the consequently high variability of this material in terms of texture, colour and

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