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Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review

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ABSTRACT

The use of recycled aggregates (RA) in construction constitutes a significant step towards a more sustainable society and also creates a new market opportunity to be exploited. In recent years, several case-studies have emerged in which RA were used in Geotechnical applications, such as filling materials and in unbound pavement layers. This paper presents a review of the most important physical properties of different types of RA and their comparison with natural aggregates (NA), and how these properties affect their hydraulic and mechanical behaviour when compacted. Specifically, the effects of compaction on grading size distribution curves and density are analysed, as well as the consequences of particle crushing on the resilient modulus, CBR and permeability. The paper also contains an analysis of the influence of incorporating different RA types on the performance of unbound road pavement layers as compared with those built with NA by means of the International Roughness Index and deflection values. The results collected from the literature indicate that the performance of most RA is comparable to that of NA and can be used in unbound pavement layers or in other applications requiring compaction.

1. Introduction

Almost all industrial and human activities produce waste and its increasing accumulation is the cause of serious environmental and economic issues around the world. In 2010, the total waste generated in European Union amounted to 2.51 billion tonnes (Eurostat, 2014). Construction and demolition activities (859 million tonnes, 34% of the total) and mining and quarrying activities (672 million tonnes, 27% of the total) are the major economic sectors that generated most waste in 2010. Of the total waste generated by these two sectors, 97% was mineral waste or soils (excavated earth, road construction waste, construction and demolition waste, dredging spoil, waste rocks, tailings, and others). The share of mineral and solidified wastes in relation to the total waste and total hazardous waste produced was 76% (Eurostat, 2014).

It is still common practice to dispose of waste from construction or demolition sites in landfills; however, there have been several cases in which substantial amounts of waste materials have been recovered. Some examples of applications are their use as general bulk fill, sub-base, base or surface material in road construction, hydraulically bound materials or new concrete manufacture (Hansen, 1992), provided that these waste materials do not have hazardous contaminants (EU WFD, 2015). As an alternative to depositing them in landfills, the use of recycled aggregates (RA) creates a new market opportunity to be exploited, and one that is also favourable to the environment. For geotechnical applications, however, the use of RA is not very common and natural aggregates (NA) are preferred. This can be explained by the following reasons:

- From an economic point of view, except in some particular cases, the use of NA is more advantageous than RA because it is more readily found, while RA must be transported to the construction site, sometimes from far distances.
- The variability of composition of RA is much higher than that of NA due to the different sources of RA. The composition and grading size distribution of RA must fit those of the NA usually

Abbreviations: RA, recycled aggregates; NA, natural aggregates; CDW, construction and demolition waste; RCA, recycled concrete aggregates; RMA, recycled masonry aggregates; RMC, residual mortar content; MRA, mixed recycled aggregates; CDRA, construction and demolition recycled aggregates; RAP, reclaimed asphalt pavement; CBR, California Bearing Ratio; IRI, International Roughness Index; FWD, falling weight deflectometer.

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used for that purpose; therefore RA must be subjected to rigorous selection and calibration procedures, which can be time-consuming and expensive.
- RA compaction may change their properties (due to crushing mainly) and therefore their performance for a given application requires previous investigation done by experimental tests in the laboratory and in the field.
- In the case of pavements and embankments, the number of trial tests when using recycled materials is expected to be higher than those necessary for NA, because RA properties are not well known. Adding to this, the compaction procedure must be updated according to the RAs' variability as well as their changes during construction and exploitation.
- For some countries and applications (for example, ballast in railways and earth and rockfill dams), the design rules are very restrictive and the use of recycled materials is still not allowed.
- When mixing RA with NA, besides the need to define the most adequate replacement levels (which depend both on RA and NA characteristics), their incorporation may have negative impact in soil stiffness and strength.
- Designers and contractors have large experience in the behaviour of NA for several types of geotechnical structures and applications and know how to deal with their natural variability. Since they normally favour conservative approaches, this way of thinking may not be easily changed while natural resources are still abundantly available.
- Although Geotechnical Design Codes such as Eurocode 7 (EC7) accept design based on comparable experience, there are no specifications concerning the use of RA in geotechnical applications, where safety issues are fundamental.

Nevertheless, owing to their size distribution reproducing that of natural soil, there have been several attempts to incorporate RA in geotechnical applications mainly as filling material or in pavement layers (e.g. base and sub-base layers in roads). Provided that the amount of hazardous contaminants is kept to a minimum, when compacted, these materials must also exhibit the minimum values for mechanical (stiffness and strength) and hydraulic (permeability, expansiveness and frost-free) related properties necessary for any given application.

The properties of aggregates define the compaction conditions and the behaviour of the compacted material (Barata and Cardoso, 2013; Cardoso et al., 2012; Mitchell and Soga, 2005), as it happens in the particular case of pavement layers. Understanding the effect of RA on the behaviour of the compacted material, in comparison to that observed when NA are used, is fundamental to validate and promote the wider use of these materials in that particular application.

This paper presents a review of the most important physical properties of different types of RA from construction and demolition and their comparison with NA, and how these properties affect the hydraulic and mechanical behaviour of compacted materials. The analysis is focused mainly on unbound pavement layers because this is, by far, the major application of RA in Geotechnical works. The behaviour of the compacted material made with different kinds of RA and compositions of RA and NA is reviewed and some properties are quantified. The paper ends with some comments about the use of different types of RA in current unbound applications and the main differences when compared with conventional compacted materials. It is believed that the information provided will be very useful to Contractors and Geotechnical engineers to evaluate alternative solutions and to explore the rational use of such non-traditional material in Geotechnical applications in general.

2. Properties of recycled aggregates

There are four main types of material (Fig. 1) derived from most construction and demolition waste (CDW) and road renovations: crushed concrete; crushed masonry; mixed demolition debris; and road planings. After crushing and beneficiation, the resulting aggregates may be assigned to one of the five following categories:

- Recycled concrete aggregate (RCA) – Some of the existing specifications (DIN-4226, 2002; LNEC-E471, 2006; NBR-15.116, 2005; PTV-406, 2003) have reached a consensus that, in order to be considered as RCA, they must comprise a minimum of 90%, by mass, of Portland cement-based fragments and NA.
- Recycled masonry aggregates (RMA) – Sourced from crushed masonry, these materials may include: aerated and lightweight concrete blocks; ceramic bricks; blast-furnace slag bricks and blocks; ceramic roofing tiles and shingles; and sand-lime bricks (Hansen, 1992). RMA are composed of a minimum of 90%, by mass, of the summation of the aforementioned materials.
- Mixed recycled aggregates (MRA) – Aggregates acquired from mixed demolition debris are a mixture of the two main components obtained from the beneficiation process of CDW: crushed and graded concrete and masonry rubble. Some specifications (BS-8500, 2006; NBR-15.116, 2005) state that they are composed of less than 90%, by mass, of Portland cement-based fragments and NA.
- Reclaimed asphalt pavement (RAP) – When mainly composed of asphalt-based materials (more than 90% in composition). The literature shows that this material has been successfully used in the production of bituminous mixtures, but it is highly detrimental to cement bound materials (Silva et al., 2014).
- Construction and demolition recycled aggregates (CDRA) – In a study carried out by Silva et al. (2014), the authors found that the literature contains limited information on the origin and composition of aggregates or that these had high levels of contaminants (e.g. glass, plastics, wood). Therefore, since the composition of these materials differed greatly from the others (RCA, RMA, MRA), they were called CDRA.

RA from crushed concrete, RCA, may be used for concrete production and in high performance pavements, while those containing materials from crushed masonry, RMA and MRA, may be applied in the construction of certain types of pavement, where strength and size requirements are usually less demanding, and safety and risk are less significant than those in structural concrete.

CDRA can be comprised of various contaminants that affect handling and properties of the final product (Buyle-Bodin and Hadjieva-Zaharieva, 2002), and therefore must be analysed prior to processing in order to determine the most suitable and cost-effective recycling procedure. Recycling plants have progressed to a point that minimizes the content of contaminants (wood, soil, asphalt, glass, metal, and plastic) by subjecting these materials to various processing techniques developed for this purpose, which are extensively described in the literature (Chen et al., 2003; Cho and Yeo, 2003; Dhir et al., 1999; Dosho et al., 1998; Eguchi et al., 2007; Gokce et al., 2011; Li, 2009; Mas et al., 2012; Muscalu and Andrei, 2011; Nagataki et al., 2004; Nagataki and Lida, 2001; Sim and Park, 2011; Yanagi et al., 1998; Zhao et al., 2010). However, the use of the term "contaminant" depends on the intended application of the RA containing it.

High quality RA can be produced nowadays by CDW recycling plants, which are not very different from plants that produce crushed NA. The basic method of recycling, employed in most recycling plants, is crushing the CDW debris to produce a granular product of a given particle size. The process for removing