Analysis of the Properties of Recycled Aggregates for Unbound Granular Asphalt Pavement Layers

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ABSTRACT: The main purpose of this paper is to analyse the most important properties of recycled aggregates from construction and demolition waste (CDW) used in road construction and maintenance, especially in unbound base and sub-base pavement layers. The National Laboratory of Civil Engineering (LNEC), in cooperation with the Technical University of Lisbon (IST), is carrying out a research project concerning the study of crushed concrete, which represents the majority of CDW generated by building and bridge construction in Portugal. Two origins of crushed concrete were analysed: material from laboratory crushing of cubic concrete specimens, used previously in compression strength tests and material from *in situ* crushing of CDW, obtained from a concrete building demolition site near Lisbon. The geometrical, physical and mechanical characterisation of materials in the laboratory was based on standard European tests established for natural aggregates: particle size distribution, shape index, flakiness index, Los Angeles fragmentation, micro-Deval wear, crushed and broken surfaces, sand equivalent, methylene blue and the compaction test. A chemical characterisation of all materials was also undertaken. The paper presents the laboratory test results and also discusses the main critical aspects related to the test procedures in light of the non-traditional nature of the CDW material. In 2006, LNEC published a guide, LNEC E 473, for the use of recycled aggregates in unbound base and sub-base pavement layers. Test results were compared with the requirements covered by this guide. Some main conclusions and recommendations derived from this analysis are presented in the paper.

KEY WORDS: Road pavement, CDW, concrete, recycled aggregate, unbound granular material.

1 INTRODUCTION

The need for sustainable engineering construction and maintenance calls for evermore new and innovative techniques and materials. The re-use of construction and demolition waste (CDW) is an important practice to reduce the depletion of natural resources and minimise the large amount of waste in landfills sites. In addition to these environmental advantages, the use of CDW should continue to ensure technical and economical solutions. Therefore, more laboratory and *in situ* research are essential and must be developed in order to achieve better knowledge about CDW behaviour for civil engineering purposes, including transport infrastructure.

Engineering aspects are included in established standards used in road construction for both natural and recycled materials. Special aspects considered in European countries affect engineering subjects, with the most important being specifications for recycled materials, engineering and environmental performance characteristics, the concept of equal quality for both recycled and natural of materials, testing procedures to predict long-term performance and the use of life-cycle analysis (SAMARIS, 2004).

The present paper deals with the use of recycled aggregates in road construction and maintenance, especially in the case of unbound base and sub-base pavement layers. The National Laboratory of Civil Engineering (LNEC), in cooperation with the Technical University of Lisbon (IST), is carrying out an already developed research project on the properties of recycled aggregates based on the most recent technical requirements published in Portugal. The experimental study described in the paper concerns aggregates obtained from crushed concrete, given that this material represents the majority of CDW generated in Portugal from building and bridge construction and maintenance.

The main recycled aggregate processes adopted in Portugal are described to provide a better understanding of the expected properties of these materials. Heterogeneity and the presence of physical and chemical contaminant elements are among the most relevant factors concerning the viability of the materials for construction and maintenance purposes.

LNEC has participated actively in the development of Portuguese standard specifications relative to the use of recycled aggregates in base, sub-base, capping layers and embankments of transport infrastructures. These requirements include the geometrical, physical, mechanical and chemical properties of recycled materials, such as grading, fines content and quality and their resistance to wear and fragmentation, chemical analysis of the particles and of the leaching. The paper describes LNEC's specifications, specifically the 2009 edition (LNEC E 473), concerning the technical requirements for the use of recycled aggregates in unbound pavement layers.

The first part of the research project involved the laboratory characterisation of the recycled materials: aggregates resulting from the crushing of cubic concrete samples and aggregates from *in situ* crushing of CDW obtained at the early stage of the research. The paper presents the laboratory tests results and analyses the values obtained based on the requirements specified by LNEC E 473 (2009). Conclusions and final remarks are then offered. Further advances will be made within the scope of a scientific project designed to develop practical recommendations for the design and construction of road pavements using CDW, in light of environmental protection.

2 PROCESSES OF RECYCLED AGGREGATES

In Portugal, the average annual production of aggregates is estimated at 88.3 million tonnes, which is mostly consumed by construction and maintenance activities. Specifically, over the last three decades the field of transport infrastructure has been an important consumer of these materials. Portugal is endowed with natural sources of aggregates (e.g., basalt, granite and limestone) of appreciable quantity and excellent quality. However, the long-practised aggregate extraction process is no longer sustainable. Furthermore, the annual production of CDW is 300 kg per capita and the disposal of these quantities is becoming an economic and environmental problem in Portugal. In fact, approximately 95% of these materials are still sent to landfills. Non-traditional alternatives based on recycling techniques, more efficient from an economic and environmental point of view, must expand in order to make use of a more significant proportion of CDW.

In recent years, important developments with regard to CDW processes were made, allowing better quality of recycled materials. This is the case with recycled aggregates obtained from the construction and demolition of buildings, bridges and others structures in the field of civil engineering. The nature of the original CDW plays an important role in determining the quality of recycled aggregates, and the demolition, selection and crushing processes also play a crucial part in their composition. CDW includes materials that are inert (e.g., concrete, brick, tile, asphalt stone and soil), organic (e.g., paper and wood) and composites (e.g., plaster and electric material). Figure 1 compares the composition of CDW in Portugal with the European Union average. It demonstrates that Portugal generally has similar tendencies to those of the European Union. Only one exception can be observed in the case of concrete, stone, soil and aggregates.

CDW processes in Portugal can be achieved with either mobile or fixed recycled plants. In both cases, the plant location should be near the origin of CDW and its final destination. While fixed plants give materials with more quality and diversity, the costs of set-up and operation and the transport of CDW are enormous. Mobile plants are commonplace and have the significant advantage of lower operating and CDW transport costs.

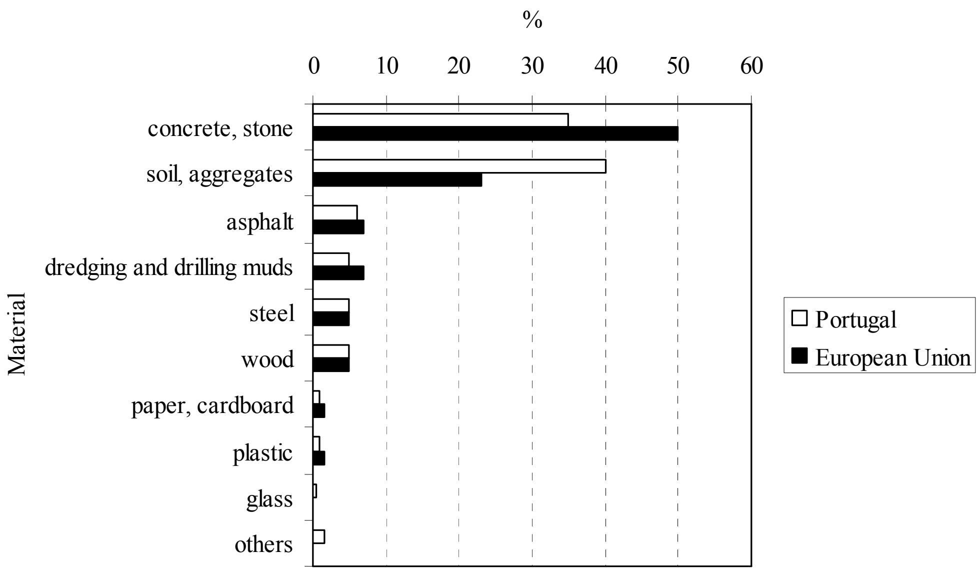

Figure 1: Composition of CDW.

3 PORTUGUESE STANDARD SPECIFICATIONS

The use of recycled aggregates in base, sub-base and capping layers and in the embankments of transport infrastructure requires that those materials' properties correspond to the technical requirements. The requirements include geometrical, physical, mechanical and chemical properties of materials, such as grading, fines content, quality of fines, resistance to wear and fragmentation and chemical analysis of particles and leaching.

LNEC's specifications – E 473: Guide for the use of recycled aggregates in unbound pavement layers and E 474: Guide for the use of recycled materials coming from construction and demolition waste in embankments and capping layers of transport infrastructure – establish the minimum requirements with which recycled aggregates covered by EN 13242+A1 and NP EN 13285 must comply in order to be used in unbound sub-base and base pavement layers or embankments and capping layers of transport infrastructure, respectively.

The recycled aggregates mentioned in these specifications hail from the construction, rehabilitation or demolition of buildings, infrastructure, transport and other civil engineering structures and are referred to as construction and demolition waste (CDW). These aggregates can be made of crushed concrete, aggregates from unbound layers, masonry and asphalt.

The composition of the recycled aggregates from construction and demolition waste should be assessed according to the procedure laid out in EN 933-11.

For unbound layers, recycled aggregates covered by specification LNEC E 473 are grouped into two classes: B and C. The materials covered by LNEC E 474 are classed as B, MB and C (Table 1).

The identification of recycled aggregates should include at least an indication of the producer, the production site, markings of the class and category to which they belong and the size (d/D).

Table 1: Classification of aggregates according to EN 933-11.

Class	Constituent proportions					
	Rc + Ru + Rg	Rg	Rb	Ra	FL	X
B	≥ 90	≤ 5	≤ 10	≤ 5	≤ 5	≤ 1
C	≥ 50	≤ 5	≤ 10	≤ 30	≤ 5	≤ 1
MB	≤ 70	≤ 25	≥ 30	≤ 70	≤ 5	≤ 1
C	no limit	≤ 25	≤ 30	no limit	≤ 5	≤ 1

CONSTITUENTS (EN 933-11):

Rc – concrete products, concrete and mortar

Ru – unbound aggregates, natural stone, aggregates treated with hydraulic binders

Ra – bituminous materials

Rb – masonry units of clay materials (brick, tile, etc.), masonry units of calcium silicates and non-aerated floating

Rg – glass

FL – floating material in volume

X – other: cohesive materials (e.g., clay soils), plastics, rubber, metals (ferrous and non-ferrous), non-floating wood and stucco

4 CHARACTERISATION OF THE MATERIALS

4.1 Chemical characterisation – leaching tests

The major objective in performing environmental tests on recycled aggregates used in road construction is to assess the potential or present impact on the environment caused by these materials. The results may be used both in a specific context and more generally in order to develop a rational method for setting criteria for material quality and road design that ensures adequate protection of the environment.

It is very important to recognise that the testing itself constitutes only part of the impact assessment and criteria development procedures. The tests results obtained must be combined with other information (e.g., water flow, materials conditions of application) to provide answers appropriate to the questions asked before testing. This requires description of the physical contexts in consideration.

Recycled aggregates can be characterised chemically through the assessment of concentrations of their constitutive chemical elements in accordance with the procedure laid out in European Standard EN 12457-4. Values obtained should be compared with the maximum values set out in Council Decision 2003/33/EC for landfills (Table 2). Two types of waste – inert and non-hazardous – are presented. The difference between the two is related to the limits obtained for the different chemical parameters found at the leaching tests. The effects of pH on material properties are not considered.

According to NP EN 13242:2002+A1:2007, the need to test and declare all properties for chemical requirements is limited based on the particular application, final use or origin of the aggregate. When required, the tests specified in clause 6 are carried out to determine appropriate chemical properties.

4.2 Geometrical and physical characterisation

The physical characterisation of recycled aggregates from construction and demolition waste includes particle size distribution, following NP EN 933-1; sand equivalent tests, performed according to NP EN 933-8; and the methylene blue test, performed according to NP EN 933-9. In order to more clearly characterise the geometric properties of the materials, the NP EN 933-5 test should also be performed to determine the percentage of crushed and broken surfaces in coarse aggregates particles.

4.3 Mechanical characterisation

A mechanical characterisation is undertaken in order to evaluate resistance to fragmentation and wear.

To evaluate resistance to fragmentation, the Los Angeles method (NP EN 1092-2) is used. The material tested is stressed by a combination of abrasion and impact from tumbling steel balls within a drum.

With the micro-Deval test (NP EN 1097-1), the resistance to wear is checked by using a rotating drum with small-diameter steel balls and without barriers. Hence, there is no impact from the tumbling steel balls, only abrasion produced by the friction between the steel balls and the sample material. The test can be performed in water.

Table 3 shows the properties and the minimum requirements for recycled aggregates for unbound granular pavement layers according to LNEC E 473.

5 EXPERIMENTAL STUDY

An experimental study undertaken at LNEC focused on the laboratory characterisation of crushed concrete. Two origins of the material were considered:

- material from the laboratory crushing of cubic concrete specimens (CB), previously used in compression strength tests (Figure 2a);

Table 2: Standard requirements for the chemical characterisation.

Parameters	Inert waste	Non-hazardous waste
Cadmium, Cd (mg/kg)	0.04	1
Copper, Cu (mg/kg)	2	50
Total Chromium, Cr (mg/kg)	0.5	10
Nickel, Ni (mg/kg)	0.4	10
Lead, Pb (mg/kg)	0.5	10
Zinc, Zn (mg/kg)	4	50
Chloride, Cl (mg/kg)	800	15,000

Table 3: Properties and minimum requirements of recycled aggregates for unbound granular pavement layers presented at LNEC E 473.

Category		AGER1	AGER2	AGER3
Class		B or C	B or C	B
Geometrical and natural parameters				
Dimension	NP EN 13285	0/31.5	0/31.5	0/31.5
Oversize (NP EN 933-1)	NP EN 13285	OC_{75}	OC_{80}	OC_{85}
Grading class (NP EN 933-1)	NP EN 13285	G_B	G_B	G_A
Fines content (NP EN 933-1)	NP EN 13285	UF_9 LF_2	UF_9 LF_2	UF_9 LF_2
Quality of fines (NP EN 933-9) *	EN 13242+A1	$MB_{0/D} \leq 1.0$	$MB_{0/D} \leq 0.8$	$MB_{0/D} \leq 0.8$
Percentage of crushed and broken surfaces in coarse aggregate particles (NP EN 933-5)	EN 13242+A1	$C_{50/30}$	$C_{50/10}$	$C_{90/3}$
Mechanical behaviour parameters				
Fragmentation and wear resistance (NP EN 1097-2 and NP EN 1097-1)	EN 13242+A1	LA_{45} and MDE_{45} or LA+MDE≤85	LA_{40} and MDE_{40} or LA+MDE≤75	LA_{40} and MDE_{35} or LA+MDE≤70
Chemical properties				
Water-soluble sulfate content (EN 1744-1) **	EN 13242+A1	$SS_{0.7}$	$SS_{0.7}$	$SS_{0.7}$
Release of dangerous substances (EN 12457-4)	---	Classification as waste for land filling of inert waste ***		

* - $MB_{0/D}$ – Methylene blue value expressed in g/kg according to NP EN 933-9, multiplied by the percentage of passing the 2 mm sieve

** - For concentrations of sulphates > 0.2%, these aggregates should be placed at a distance no less than 0.50 m from concrete structural elements

*** - Classification solely based on the leached test results for L/S = 10 l/kg (Section 2.1.2.1, of 2003/33/EC)

– material from *in situ* crushing of CDW (BD), obtained from a concrete building demolition site near Lisbon (Figure 2b).

The laboratory characterisation looked at the chemical, geometrical, physical and mechanical properties of tested samples from both materials: two samples from CB material (CB-1 and CB-2) and only one sample from BD material (BD-1).

Table 4 shows the chemical test results derived from the EN 12457-4 procedure. It could be concluded that all these values are in accordance with the standard limits set out in Council Decision 2003/33/EC summarised in Table 2.

Curves related to particle size distributions obtained through the NP EN 993-1 procedure are presented in Figure 3. These curves are compared with the standard limits – minimum and maximum values – of Portuguese CDW requirements for unbound granular sub-base layers. A high-grade material was achieved with CB material, though there is a tendency for a lower quantity of particles smaller than 16 mm, which is beyond the minimum standard limits. In the case of BD material, all standard limits are respected, though the curve is irregular in shape.

(a) CB – laboratory crushed concrete (b) BD – *in situ* crushed concrete

Figure 2: Appearance of experimental materials after the crushing process.

Table 4: Chemical properties.

Parameters	Results (mg/kg)	
	CB-1 and CB-2	BD-1
Cadmium (Cd)	< 0.45×10^{-3}	< $0,47 \times 10^{-3}$
Copper (Cu)	0.27×10^{-1}	1.36×10^{-1}
Total chromium (Cr)	0.87×10^{-1}	2.67×10^{-1}
Nickel (Ni)	0.30×10^{-1}	0.44×10^{-1}
Lead (Pb)	0.28×10^{-1}	0.11×10^{-1}
Zinc (Zn)	0.23×10^{-1}	0.34×10^{-1}
Chloride (Cl)	128	360
Sulphates (SO_4^{2})	77	353

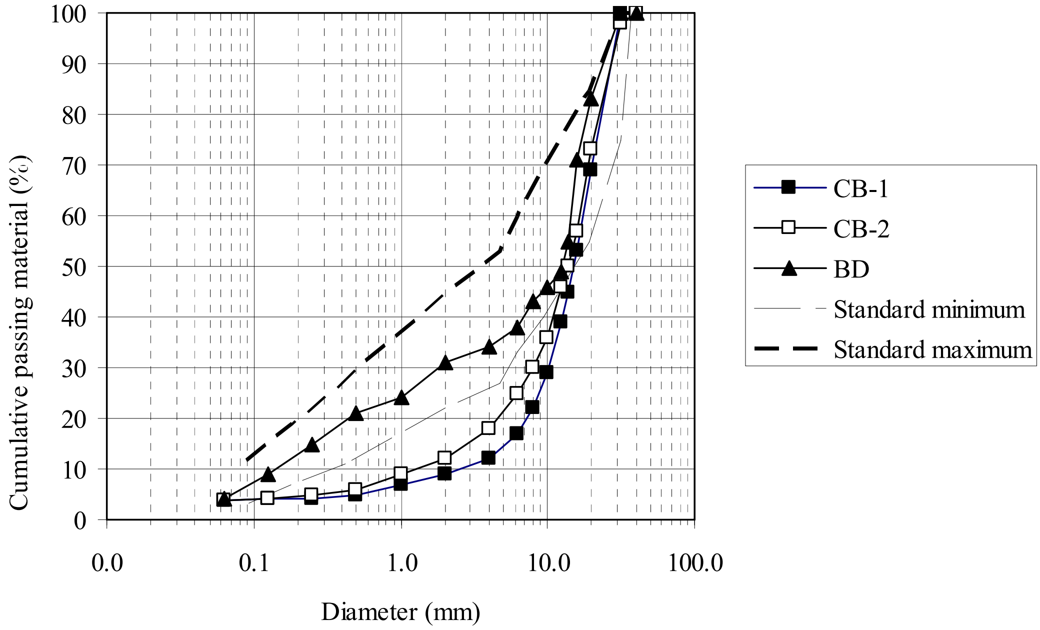

Figure 3: Particle size curves.

Considering the relevance of compaction tests in quality control for road construction and maintenance, modified Proctor tests were carried out in the CB-2 and BD samples. Tests were performed only on material with a maximum diameter of 19.0 mm, truncated at 19.0 mm in size. Figure 4 illustrates the Proctor curves obtained for both materials. Comparing these results with the corresponding ones obtained for natural aggregates, one could conclude that, as expected, there is a tendency for a lower maximum dry density and higher optimum water content in the case of recycled aggregates. This behaviour could be derived from the lowest specific density and the highest water absorption, respectively, of recycled aggregates.

Physical and mechanical tests were also performed on both materials, and the results are presented in Table 5. The same table lists the Portuguese requirements for unbound granular layers. Analysis of the results according the previous edition of LNEC E 473 (2009) addresses the following specific conclusions:

- The maximum dimension was obtained for all the materials;
- The fines content corresponded to 4%, which means that classes of UF_9 and LF_2 were always guaranteed for both materials;
- The quality of fines, measured by Methylene blue value, was only respected by BD material. In the case of CB material, an unexpectedly high value was obtained (MB=3.3 g/kg);
- In the case of the percentage of total crushed or broken surfaces in coarse aggregates, the $C_{90/3}$ class was achieved for both materials. In the case of CB-1 samples, the laboratory crushing process was more efficient in obtaining the highest percentage of total crushed or broken surfaces in the material;
- In the case of mechanical properties, there was a general tendency for high micro-Deval and Los Angeles values.

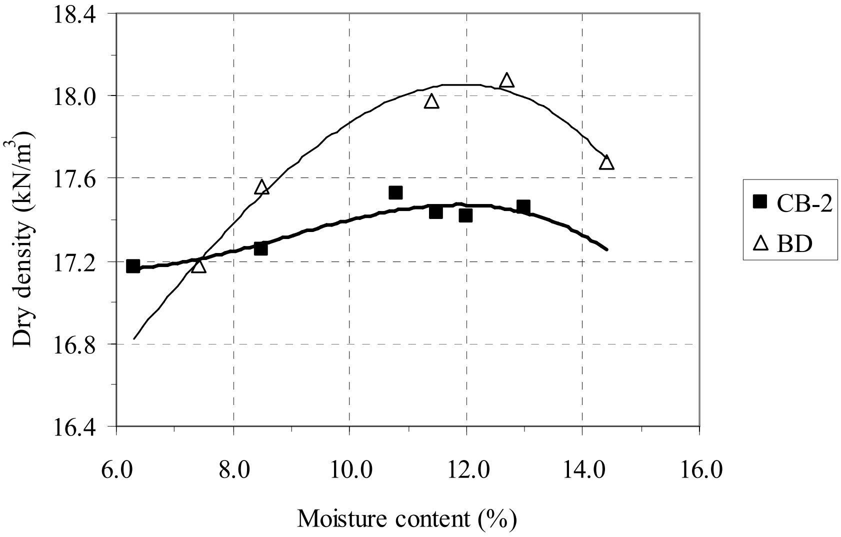

Figure 4: Modified Proctor curves.

Table 5: Physical and mechanical properties.

Parameters		CB-1	CB-2	BD
Flakiness index - FI (%)	NP EN 933-3	(*)	14	(*)
Shape index - SI (%)	NP EN 933-4	(*)	19	(*)
Particles with total crushed or broken surfaces (%)	NP EN 933-5	78.5	(*)	48.0
Particles with crushed or broken surfaces (%)		21.5	(*)	97.0
Sand equivalent - SE (%)	NP EN 933-8	86	83	39
Methylene blue (g/kg)	NP EN 933-9	0.8	0.7	3.3
Micro-Deval	NP EN 1097-1	40	48	37
Los Angeles	NP EN 1097-2	49	44	50

(*) Not determined

Table 5 also includes the flakiness index, shape index and sand equivalent value for each material. Taking the standard values required for natural aggregates as a reference, one could conclude that, in general, both materials could be used in sub-base layers.

Based on an overall analysis of the results, one can conclude that adequate geometrical and physical properties were obtained generally for all recycled materials for application in unbound granular sub-base and base pavement layers. The most difficult parameter seems to have to do with the mechanical properties related to fragmentation and wear resistance. In fact, it was observed that micro-Deval and Los Angeles values are higher than the maximum values required.

Comparing both materials in this experimental study, it seems that lab-processed CB material has achieved an overall behaviour more adequate for use as a recycled material in unbound granular sub-base layers.

Further details concerning test procedures and results are described by Pestana (2008) and Ferreira (2009).

6 CONCLUSIONS AND RECOMMENDATIONS

In light of the results obtained, one can conclude that the two recycled materials are adequate for application in unbound granular base and sub-base layers in spite of the values obtained for mechanical properties regarding fragmentation and wear resistance. In effect, micro-Deval and Los Angeles values are higher than the maximum values required in Portuguese standards references.

However, in terms of recycled material for unbound granular sub-base layer purposes, laboratory crushed concrete material (CB) demonstrates better overall behaviour than *in situ* crushed concrete (BD).

Due to the inability to obtain appropriate values for the mechanical behavior of the materials studied, the evaluation of its overall behavior via laboratory tests (e.g., cyclic triaxial loading tests and *in situ* tests performed on real pavement or in test pit trials) is essential.

Furthermore, more studies on this type of material should be undertaken, particularly examining materials with different origins and different compositions.

Compared to the use of natural materials, recycling is a far better alternative than incineration or disposal of waste generated by the road sector. However, further combined efforts between governments and local industries are necessary to implement and improve recycling.

Technical engineering limitations and economic evaluations, derived from geometrical, chemical, physical, mechanical and long-term performance characteristics, are very important. However, they are not the only factors to consider in the recycling process. Environmental factors, mostly those related to protecting soil and surface or ground water from potential pollution, should also be included when considering the need to implement recycling methods.

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