Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

Viability of using fine and coarse recycled aggregates from construction and demolition waste in embankment and capping layer of transport infrastructures

Viabilité de l'utilisation de granulats recyclés fins et grossiers à partir de déchets de construction et de démolition en remblai et en couche d'infrastructures de transport

Paulo Miguel Pereira, Castorina Silva Vieira & Maria de Lurdes Lopes
CONSTRUCT-Geo, Faculty of Engineering, University of Porto, Porto, Portugal

ABSTRACT: The proper use of the natural resources is one of the fundamental pillars for the sustainable development required to modern societies. Construction and Demolition Wastes (C&DW) have been considered as a priority stream because of the large amounts that are generated and their high potential for reuse and recycling. Despite their high potential, reuse and recycling rates vary widely across countries. The use of C&DW in geotechnical works is an interesting alternative from an economic and environmental perspective. Recycled C&DW have been increasingly used as recycled aggregates in pavement sub-bases and other road construction applications. Furthermore, the assessment of performance is vital to ensure confidence in recycled materials. This paper presents the laboratory characterization of two recycled aggregates from C&DW (a fine and a coarse recycled aggregate) to determine whether they meet the technical requirements established in the Portuguese specification LNEC E474, with the intent of their application in embankment and capping layers of transport infrastructures. A series of relevant physical, mechanical and chemical properties are evaluated and the fulfilment of the requirements is subsequently examined and discussed.

RÉSUMÉ : La bonne utilisation des ressources naturelles est l'un des piliers fondamentaux du développement durable nécessaire aux sociétés modernes. Les déchets de construction et de démolition (DC&D) ont été considérés comme un flux prioritaire en raison des grandes quantités générées et de leur potentiel élevé de réutilisation et de recyclage. Malgré leur potentiel élevé, les taux de réutilisation et de recyclage varient considérablement d'un pays à l'autre. L'utilisation de DC&D dans les travaux géotechniques est une alternative intéressante d'un point de vue économique et environnemental. Les DC&D recyclés sont de plus en plus utilisés comme agrégats recyclés dans les fondations de chaussées et d'autres applications de construction routière. De plus, l'évaluation des performances est vitale pour garantir la confiance dans les matériaux recyclés. Cet article présente la caractérisation en laboratoire de deux granulats recyclés de C&DW (un granulat recyclé fin et un granulat recyclé grossier) pour déterminer s'ils répondent aux exigences techniques établies dans la spécification portugaise LNEC E474, en vue de leur application en remblai et en couche d'infrastructures de transport. Une série de propriétés physiques, mécaniques et chimiques pertinentes sont évaluées et le respect des exigences est ensuite examiné et discuté.

KEYWORDS: Sustainability; Construction and Demolition Waste; Embankment; Capping Layer; Transport Infrastructures

1 INTRODUCTION

Minimizing the consumption of non-renewable natural resources for the production of construction materials is considered one of the key aspects to achieve sustainability in the construction sector. The recovery of construction and demolition waste (C&DW) as aggregate is an efficient way to achieve this purpose. Adopting and implementing this principle is particularly relevant for an industry that consumes more raw materials than any other economic activity and produces huge amounts of waste (Vieira & Pereira 2015).

The demand for construction aggregates is increasing worldwide. Recent statistics indicate that the global demand for aggregates is expected to increase from 45 billion tonnes, in 2017, to 66 billion tonnes by 2025 (PMR 2017). The demand for aggregates within the European Union's 28 Member States and countries of the European Free Trade Association was about 3 billion tonnes in 2018 (EAA 2021). Assuming that the total portion of the mineral fraction of C&DW generated in the European Union (EU) in 2018 (Eurostat 2021) could be transformed into recycled aggregates, this would amount to about 12% of the total demand for construction aggregate. This demonstrates that there is considerable scope to develop new ways that can further drive the use of recycled aggregates coming from C&DW in construction.

C&DW accounts for more than a third of all waste generated in the EU. It contains a wide variety of materials such as concrete, bricks, wood, glass, metals and plastic. It includes all the waste produced by the construction and demolition of buildings and infrastructure, as well as road planning and maintenance.

The process of transforming C&DW into recycled aggregates in specialized recycling facilities has existed for several years and gained special relevance after the Second World War. Some components of C&DW have a high resource value, while others may have a lower value, but could still be easily reprocessed into new products or materials. Despite its potential, the level of recycling and material recovery of construction and demolition waste varies greatly across the EU, ranging from less than 10% to over 90%.

The use of recycled aggregates from C&DW in base and sub-base layers of transport infrastructures or unpaved roads have been studied by several researchers over the years (Agrela et al. 2012; Barbudo et al. 2012; Arulrajah et al. 2014; Freire et al. 2019; Pereira et al. 2019). However, C&DW are very heterogeneous and if a selective demolition is not carried out, it is very hard to obtain recycled aggregates of good quality to be used, for instance, in base layers of roadways. Most of the recycled aggregates coming from C&DW produced in Portugal are mixed recycled aggregates, including concrete, ceramics, mortars, masonries and natural stones, since the selective demolition is not really implemented. Particularly the fine grain portion of these mixed recycled aggregates is commonly not considered suitable for concrete production or road construction applications being landfilled instead of reused.

The Portuguese Environment Agency in collaboration with the National Laboratory of Civil Engineering (LNEC) promoted the release of technical specifications to regulate the use of materials from C&DW in different civil engineering works, including the construction of embankment and capping layer of transport infrastructures.

This paper presents a laboratory study carried out to evaluate a series of physical, mechanical and chemical properties of two recycled aggregates coming from C&DW (a fine and a coarse recycled aggregate). The suitability of these materials as alternative aggregates for construction of embankment and capping layer of transport infrastructures was then assessed, taking into account the requirements set out in the Portuguese specification LNEC E474 (2009).

2 MATERIALS AND METHODS

2.1 *Materials*

The study was carried out on two recycled aggregates from C&DW with different grain sizes collected from a Portuguese recycling plant located in the central region of Portugal: a coarse (selected) recycled aggregate (Figure 1a) and a fine (mixed) recycled aggregate (Figure 1b).

The coarse (selected) recycled aggregate comes from large concrete components, resulting from a demolition, which after the previous sorting process were inserted into a mobile crusher. The fine recycled aggregate results from mixed C&DW, coming mainly from maintenance and rehabilitation works of small residential buildings. The constituents of these recycled aggregates will be presented in section 3.

Figure 1. Visual appearance of the recycled aggregates from C&DW used (ruler in centimetres): (a) coarse recycled aggregate; (b) fine recycled aggregate.

2.2 *Laboratory study*

The laboratory study was designed to assess the geometrical, physical, mechanical and environmental properties of the recycled aggregates, in order to evaluate their suitability as aggregates for construction of embankments and capping layers of other transport infrastructures. The tests carried out to characterize the two recycled aggregates were adapted according to their gradation, so there were tests that were carried out for the coarse recycled aggregate and not for the fine recycled aggregate and vice versa.

The constituents of the recycled aggregates were evaluated following the test procedure laid out in the European Standard EN 933-11 (2009), but including some minor changes suggested by LNEC E474 (2009), particularly the separation of the soil portion from the constituent designated as "other materials".

The grain size distribution of the coarse recycled aggregate was determined by the sieving method (Figure 2a) with washing aggregate for remove clay particles and others aggregate fine particles following the standard EN 933-1 (2012). The particle size distribution of the fine recycled aggregate was determined by sieving and sedimentation. The gradation of the fine recycled aggregate was firstly determined following the European standard EN 933-1 (2012) for aggregates. However, since this recycled material has a significant fines content (about 23.5%), the particle size distribution was also evaluated according to EN ISO 17892-4 (2016) adopted for soils.

Geometrical characteristics of the coarse recycled aggregate were evaluated by the flakiness index as recommended in EN 933-3 (2012) and the shape index according to EN 933-4 (2008). Particle density (Figure 2b) was determined according to EN 1097-6 (2013) for coarse recycled aggregate. The particle density of the fine recycled aggregate was determined according to the standard EN ISO 17892-4 (2015).

The assessment of fines of the material under study was evaluated through as the methylene blue test (EN 933-9, 2009) (Figure 2c), taking the 0/2 mm size fraction of the materials. The former test allows quantifying the value of the methylene blue (MB), which is in function of the amount and characteristics of possibly harmful clay minerals.

The mechanical behaviour of the coarse recycled aggregate was evaluated through Los Angeles (LA) abrasion test (Figure 2d) and the crushing test. LA abrasion test is a common test used to indicate aggregate toughness and abrasion characteristics. It is based on the degradation of the aggregate when placed in a rotating drum with steel spheres. During drum rotation the aggregate degrades by abrasion and impact with other aggregate particles and steel spheres. The LA coefficient was estimated based on the European Standard EN 1097-2 (2020)

The aggregate crushing value was evaluated according to the British Standard BS 812-110 (1990). The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load.

Modified compaction tests were carried out, according to EN 13286-2 (2010), to determine the moisture content – dry density curve of the fine recycled aggregate, allowing the subsequent determination of the maximum dry density and optimum moisture content.

The content of water-soluble sulphates was estimated by spectrophotometry, according to Section 10 of the EN 1744-1 (2009). The specimens of the recycled aggregates were sieved through the 4mm sieve and the retained particles were crushed to pass the same sieve. The specimens were mixed with hot water to extract water-soluble sulphate ions and barium chloride was then added so that sulphate ions precipitate as barium sulphate.

Recycled materials used in construction projects must demonstrate an adequate leaching behaviour, complying with the limits imposed by the Directive 2003/33/EC (Council Decision 2003/33/EC). Laboratory leaching test following procedure described in the standard EN 12457-4 (2002) were carried out to assess the potential risk of ground contamination.

Figure 2. Characterization of the recycled aggregates from C&DW: (a) determination of particle size distribution; (b) determination of particle density; (c) methylene blue test; (d) LA abrasion test.

3 RESULTS AND DISCUSSION

3.1 *Constituents of the recycled aggregates*

The constituents of the recycled aggregates, evaluated by visual sorting of particles, are presented in Figure 3. The contents of concrete, concrete products, mortar, concrete masonry units, R_c, unbound aggregate, natural stone, hydraulically bound aggregate, R_u, clay masonry units, calcium silicate masonry units, aerated non-floating concrete, R_b, bituminous materials, R_a, glass, R_g, soils, R_s, and other materials, X, were assessed.

As shown in Figure 3a, the coarse recycled aggregate consists mainly of concrete and mortars, R_c and unbound aggregates, R_u (see also Figure 1a). Figure 3b indicates the fine recycled aggregate is composed mostly of concrete and mortars, R_c, unbound aggregates, R_u and soil, R_s (see also Figure 1b). It is important to point out that the standard EN 933-11 (2009) refers to the constituents of coarse recycled aggregates which means that only the mass comprised between the sieves 63 mm and 4 mm. The classification of the particles with dimensions lower than 4 mm by visual sorting is humanly impracticable.

The floating particles content, FL, estimated during the classification test for the constituents was 0.1 cm^3/kg and 7.6 cm^3/kg for coarse and fine recycled aggregates, respectively.

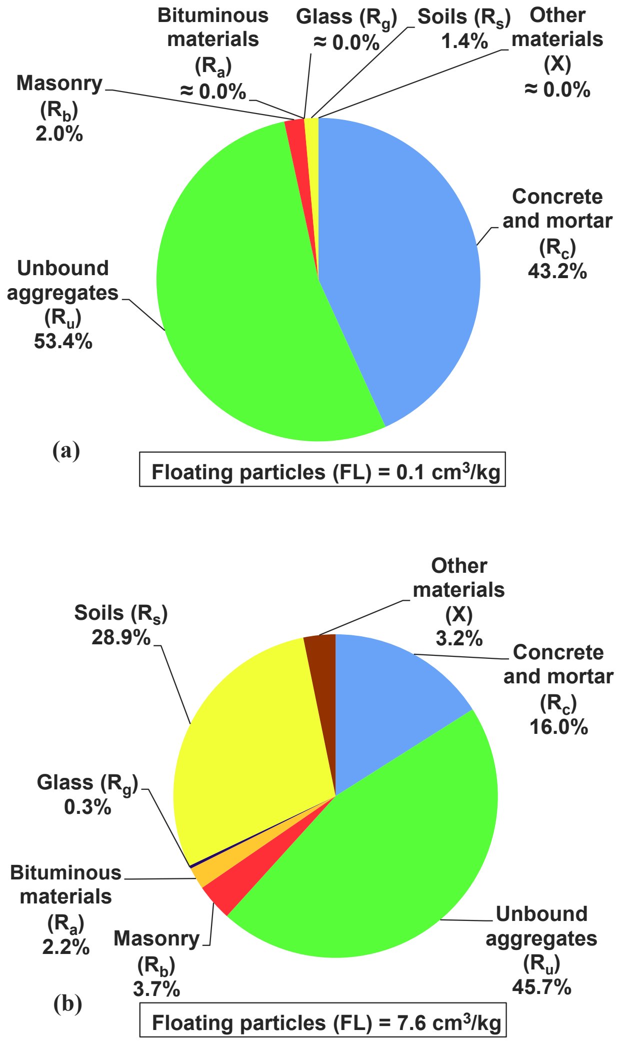

Figure 3. Proportions of the constituents in the recycled aggregates (%w/w): (a) coarse recycled aggregate; (b) fine recycled aggregate.

3.2 *Geometrical, physical and mechanical properties of the recycled aggregates*

The results of the grain size distribution performed on the two recycled aggregates are presented in Figure 4. The values of D_{max}, D_{50} and the fines content are listed in Table 1.

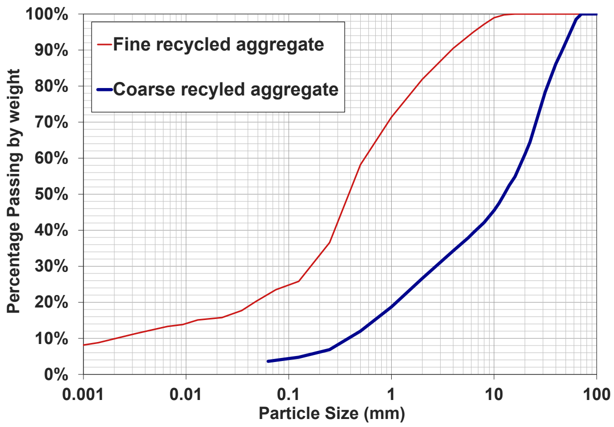

Figure 4. Particle size distribution of the recycled aggregates.

The coarse recycled aggregate is an aggregate with extensive grain size distribution (tout-venant) (Figure 4), comprising particles from 63 mm (D_{max}) to lower than 0.063 mm (fines content = 3.6%). The fine recycled aggregate is commercialized as a recycled aggregate with gradation 0-10 mm. Consequently, the fine recycled aggregate presents a higher percentage of particles with dimension lower than 4 mm (about 90%) (Figure 4). Its fine content is around 23.5%.

Appropriate flakiness and shape indexes are more relevant role in concrete production and bituminous mixtures. Even so, these geometric characteristics were also evaluated for the coarse recycled aggregate (Table 1). Flaky particles interfere with particle packing and tend to break into smaller pieces under load, such as during compaction. Look (2007) recommends that the flakiness index (FI) for aggregates used in sub-base should not be more than 40%, and in this case, the coarse recycled aggregate (FI = 9%) would meet this basic requirement.

The assessment of fines was performed through the methylene blue tests performed on the 0/2 mm size fraction. The value of the methylene blue (MB) and the values of the parameter $MB_{0/D}$ (stipulated in the Portuguese specifications) are presented in Table 1. $MB_{0/D}$ is the value of MB multiplied by the percentage of material passing the 2mm sieve. As shown in Table 1, a significantly higher value of MB was obtained for the fine recycled aggregate (6.0 g/kg), in comparison with that for the coarse recycled aggregate (0.7 g/kg), which is directly related to the larger content of plastic fines stemming from the disintegration of clay masonry units. It should be reminded that the MB value indicates the amount and characteristics of clay minerals, which can be detrimental to the performance of the pavement layers.

The particles density of the recycled materials is also shown in Table 1. It should be noted that the particle densities for both recycled materials are within the range of values for natural aggregates and soils.

Table 1 also presents the resistance to fragmentation of the coarse recycled aggregate through LA abrasion and aggregate crushing tests. The LA abrasion value (35.7%) of the coarse recycled aggregate is higher than those of the natural counterparts. Notwithstanding that, the coarse recycled aggregate conforms to the requirement of having a LA abrasion value lower than 50% as specified by the UK Highway Agency (2016) for the use as general fill and capping materials.

Table 1. Geometrical, physical and mechanical properties of the recycled aggregates.

Parameter	Coarse recycled aggregate	Fine recycled aggregate
D_{max} (mm)	63.0	4.0
D_{50} (mm)	12.6	0.4
Fines content (%)	3.6	23.5
Flakiness Index, FI (%)	9	-
Shape Index, SI (%)	9	-
Methylene blue value, MB (g/kg)	0.7 (0.2)*	6.0 (4.9)*
Particle density, G_s	2.57	2.61
Los Angeles abrasion value (%)	35.7	-
Aggregate crushing value (%)	37.8	-

* The value in brackets is the value of MB multiplied by the percentage passing the 2 mm sieve ($MB_{0/D}$).

Figure 5 presents the results of the Modified Proctor compaction test for the fine recycled aggregate. The maximum dry unit weight (γ_{dmax}) is 20.2 kN/m^3 and the optimum moisture content is around 8.5%. These values are within the range of typical quarry and fine-grain recycled aggregates.

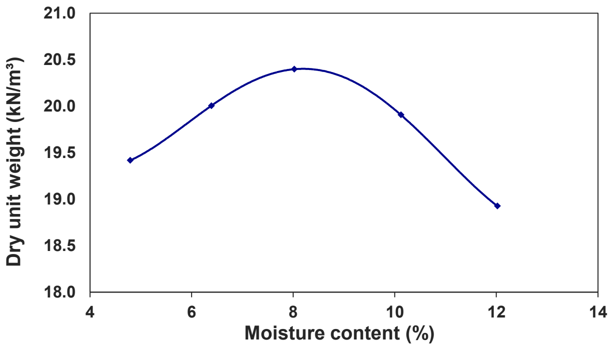

Figure 5. Modified Proctor compaction test results for the fine recycled aggregate.

The flakiness index, shape index, LA abrasion value and the aggregate crushing value were not determined for fine recycled aggregate as these tests are not appropriate for fine grain materials.

3.3 *Environmental and chemical properties of the recycled aggregates*

Table 3 shows the results of the laboratory leaching test carried out on the recycled aggregates as well as the acceptance criteria for leached maximum concentration for inert landfills stipulated by the European Council Decision 2003/33/EC (Council Decision 2003/33/EC).

Table 2. Results of laboratory leaching tests of the recycled aggregates and corresponding acceptance criteria.

Parameter (mg/kg dry matter)	Coarse recycled aggregate	Fine recycled aggregate	Acceptance criteria – Inert landfill
Arsenic, As	< 0.005	0.03	0.5
Lead, Pb	< 0.01	< 0.3	0.5
Cadmium, Cd	< 0.003	< 0.04	0.04
Chromium, Cr	0.45	< 0.5	0.5
Copper, Cu	0.037	< 0.25	2
Nickel, Ni	< 0.01	< 0.3	0.4
Mercury, Hg	< 0.002	< 0.01	0.01
Zinc, Zn	< 0.1	0.52	4
Barium, Ba	0.049	0.16	20
Molybdenum, Mo	0.015	0.03	0.5
Antimony, Sb	< 0.01	< 0.01	0.06
Selenium, Se	< 0.02	0.02	0.1
Chloride, Cl	51	56	800
Fluoride, F	2.3	< 2	10
Sulphate, SO_4	670	**1200**	1000
Phenol index	< 0.05	< 0.05	1
Dissolved Organic Carbon, DOC	29	< 200	500
Total Dissolved Solids, TDS	2090	3500	4000
pH	10.2	8.6	-

When a recycled aggregate fulfils the requirements set for inert landfills, it can be considered as an inert material. As shown in Table 2 only the content of sulphate, SO_4, in the eluate of the fine recycled aggregate exceeded the threshold value. However, the above mentioned European Council Decision states that "if the waste does not meet these values for sulphate, it may still be considered as complying with the acceptance criteria if the leaching does not exceed 6000 mg/kg at L/S = 10 l/kg …", which means that the sulphate content found in the eluate is not of real concern. High concentrations of sulphate in non-selected recycled aggregates have been described by other authors (Townsend et al. 1999; Barbudo et al. 2012).

The pH value of the eluates was 10.2 and 8.6 for the coarse and fine recycled aggregate, respectively. These values are within the expected range. Butera et al. (2014) reported values in the range 9 to 13 from twenty-nine samples of recycled C&DW aggregates collected from different recycling facilities. Roque et al. (2016) achieved values between 9 and 12 from four distinct coarse recycled aggregates coming from C&DW.

The content of water soluble sulphates, estimated by spectrophotometry, for the coarse and fine recycled C&D aggregate was 0.05% and 0.10%, respectively.

4 FEASIBILTY ANALYSIS

The Portuguese specifications for recycled materials coming from C&DW classify these alternative materials on the basis of their constituents and possible applications. Table 3 presents the material classes for use in embankments and capping layer of transport infrastructures (in accordance with Portuguese Specification LNEC E 474:2009). Note that the meaning of R_c, R_u, R_g, R_a, R_b, R_s, X and FL was presented in section 3.1.

The minimum requirements of the recycled materials for embankments and capping layers of transport infrastructures in accordance with Portuguese specification LNEC E 474 (2009) are represented in Table 4. For this application there are two material categories (MAT1 or MAT2). MAT1 materials can be used in embankments of transport infrastructures, while MAT2 can also be applied in capping layers (except for MB class).

To assess the feasibility of using the studied recycled aggregates in the construction of embankments and capping layer of transport infrastructures, a comparison is made between the material properties (Section 3) and the corresponding requirements set out in the specification LNEC E474 (2009) (Tables 3 and 4).

Table 3. Classification of recycled materials coming from C&DW based on their constituents in accordance with LNEC E 474 (2009)

Material Class	Constituents					
	R_c+R_u+ R_g (%)	R_g (%)	R_a (%)	R_b+R_s (%)	X (%)	FL (cm^3/kg)
B	≥ 90	≤ 10	≤ 5	≤ 10	≤ 1	≤ 5
MB	≤ 70	≤ 25	≥ 30	≤ 70	≤ 1	≤ 5
C	No limit	≤ 25	≤ 30	No limit	≤ 1	≤ 5

From the comparison between the relative proportions of the constituents (Figure 3) and the limits reported in Table 3, it can be concluded that the coarse recycled aggregate belongs to Class B and Class C. On the other hand, the fine recycled aggregate could be included in two established classes, MB and C, if it wasn't for the high value of the floating particles, which is higher than the maximum established value of 5 cm^3/kg.

Although it was not possible in due course evaluating the resistance to wear (MDE), it is admitted based on Los Angeles abrasion value (Table 1), that MDE is also lower than 45. In this case this recycled material can be included in the highest category, MAT2 (Table 4). Being a MAT2 material, its application in embankments construction as well as in capping layers of transport infrastructures is feasible

Furthermore, the fines content of 25.5% and the high value of the parameter $MB_{0/D}$ do not allow the use of the fine recycled aggregate in embankments and capping layers of transport infrastructures. However, the fine recycled aggregate can be used in less demanding geotechnical applications such as backfilling material of trenches (under pavements of transport infrastructures, walkways and green spaces).

None of the recycled aggregates raised any concern in terms of chemical properties (i.e. water-soluble content and leaching behaviour).

Table 4. Minimum requirements of recycled C&DW materials to be used in embankments and capping layers of transport infrastructures in accordance with LNEC E 474 (2009).

		Material category/class		
		MAT1	MAT2	
Parameters	Property	B, MB, C	B, C	MB
Geometry and nature	D_{max}	≤ 150mm	≤ 80 mm	
	Fines content (≤ 0.063 mm)	≤ 10%	≤ 10%	
	Assessment of fines ($MB_{0/D}$)	< 2.0	< 1.0	
Mechanical behaviour	Resistance to fragmentation (LA)	-	LA ≤ 45	-
	Resistance to wear (MDE)		MDE ≤ 45	
Chemical behaviour	Water-soluble sulphates	≤ 0.7%	≤ 0.7%	
	Release of dangerous substances	Classification as inert waste for landfill		

5 CONCLUSIONS

This paper presented the laboratory evaluation of two recycled materials (a coarse and a fine recycled aggregate from C&DW) and discussed their suitability as aggregates for construction of embankments and capping layers of transport infrastructures.

Based on Portuguese specifications, the coarse recycled aggregate is suitable for application in embankments and capping layers of transport infrastructures.

The high value of floating particles of the fine recycled aggregate resulting from impurities such as wood, plastic and foams, does not allow its integration in any of the defined classes. This fact highlights the importance of promoting a selective demolition to produce good quality recycled aggregates. The high content of fines of this recycled aggregate is also a drawback for its usage.

This study also shows that the use of fine recycled aggregates can encounter major obstacles, if the recycling plants and the build contractors do not devote more attention to the previous sorting of C&D wastes. Overcoming this drawback regarding the contaminants, the mixture of the fine aggregates with natural aggregates or coarse recycled aggregates may be a sustainable alternative.

3 ACKNOWLEDGEMENTS

This work was financially supported by: Project PTDC/ECI-EGC/30452/2017 - POCI-01-0145-FEDER-030452 - funded by FEDER funds through COMPETE2020 - Programa Operacional Competitividade e Internacionalização (POCI) and by national funds (PIDDAC) through FCT/MCTES. Base Funding - UIDB/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC). Paulo Miguel Pereira would also like to thank Fundação para a Ciência e Tecnologia (FCT) for his research grant: SFRH/BD/147838/2019 (grant supported by POPH/POCH/FSE funding).

The authors wish also to thank RCD, SA for providing the recycled aggregates used in this study.

4 REFERENCES

Agrela, F., Barbudo, A., Ramírez, A., Ayuso, J., Carvajal, M.D., Jiménez, J.R. 2012. Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. *Resources, Conservation and Recycling* 58, 98-106.

Arulrajah, A., Disfani, M.M., Horpibulsuk, S., Suksiripattanapong,C., N. Prongmanee, N. 2014. Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications. *Construction and Building Materials* 58, 245-257.

Barbudo, A., Galvín, A.P., Agrela, F., Ayuso, J., Jiménez, J.R. 2012. Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. *Waste Management* 32, 1229-1235.

Butera, S., Christensen, T.H., Astrup, T.F. 2014. Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds. *Journal of Hazardous Materials*, 276, 302-311.

BS 812-110 1990. Testing aggregates. Methods for determination of aggregate crushing value (ACV), BSI.

Council Decision 2003/33/EC 2003. Council Decision 2003/33/EC: Council Decision establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. *Official Journal of European Union L11/2*.

EN 933-11 2009. Tests for geometrical properties of aggregates - Part 11: Classification test for the constituents of coarse recycled aggregate, CEN.

EN 933-1 2012. Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method, CEN.

EN 933-3 2012. Tests for geometrical properties of aggregates - Part 3: Determination of particle shape. Flakiness index, CEN.

EN 933-4 2008. Tests for geometrical properties of aggregates - Part 4: Determination of particle shape. Shape index, CEN.

EN 1097-2 2020. Tests for mechanical and physical properties of aggregates – Part 2: Methods for the determination of resistance to fragmentation, CEN.

EN 1097-6 2013. Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water absorption, CEN.

EN 12457-4 2002. Characterisation of waste – Leaching – Compliance test for leaching of granular waste material and sludges – Part 4. CEN.

EN 1744-1 2019. Tests for chemical properties of aggregates – Part 1: Chemical analysis, CEN.

EN 13286-2 2010. Unbound and hydraulically bound mixtures - Part 2: Test methods for laboratory reference density and water content - Proctor compaction. CEN.

EN ISO 17892-3 2015. Geotechnical investigation and testing - laboratory testing of soil - Part 3: Determination of particle density. CEN (in collaboration with ISO).

EN ISO 17892-4 2016. Geotechnical investigation and testing - laboratory testing of soil - Part 4: Determination of particle size distribution. CEN (in collaboration with ISO).

European Aggregates Association (EAA) 2021. *A Sustainable Industry for a Sustainable Europe - Annual Review 2019-2020*. Brussels, Belgium.

Eurostat 2021. European Commission, Eurostat, Waste statistics. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics last accessed in 25/05/2021.

Freire, A.C., Neves, J., Roque, A.J., Martins, I., Antunes, M.L. 2019. Feasibility study of milled and crushed reclaimed asphalt pavement for application in unbound granular layers. *Road Materials and Pavement Design*, DOI: 10.1080/14680629.2019.1701539.

Highway Agency 2016. *Manual of Contract Documents for Highway Works. Specification for Highway, Series 600 Earthwork, vol. 1*. London, UK.

LNEC E474: 2016. Guide for use of recycled materials coming from construction and demolition waste in embankment and capping layers of transport infrastructures. LNEC (Portuguese Laboratory of Civil Engineering) (in Portuguese).

Look, B. 2007. *Handbook of Geotechnical Investigation and Design Tables*, Second Ed. Taylor & Francis, London, UK.

Pereira, P.M., Ferreira, F.B., Vieira, C.S., Lopes, M.L. 2019. Use of Recycled C&D Wastes in Unpaved Rural and Forest Roads - Feasibility Analysis. In *Proceedings of the International Conference WASTES: Solutions, Treatments and Opportunities*, CRC Press: Boca Raton, FL, USA, 161–167.

Persistence Market Research (PMR) 2017. *Global Market Study on Construction Aggregates: Crushed Stone Product Type Segment Projected to Register High Value and Volume CAGR during 2017 – 2025*. New York, USA.

Roque, A.J., Martins, I.M., Freire, A.C., Neves, J.M., Antunes, M.L. 2016. Assessment of Environmental Hazardous of Construction and Demolition Recycled Materials (C&DRM) from Laboratory and Field Leaching Tests Application in Road Pavement Layers. *Procedia Engineering* 143, 204-211.

Townsend, T.G., Jang, Y., Thurn, G. 1999. Simulation of construction and demolition waste leachate. *Journal of Environmental Engineering,* 125(11), 1071–1081.

Vieira, C.S. & Pereira, P.M. 2015. Use of recycled construction and demolition materials in geotechnical applications: A review. *Resources, Conservation and Recycling,* 103: 192-204.