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Laboratory assessment of recycled construction and demolition waste for transport infrastructure applications

C. R. Salvi[1], F. B. Ferreira[2], and M. L. Lopes[3]

[1]PhD Student, CONSTRUCT, Faculty of Engineering, University of Porto, Porto, Portugal, email: up201609850@fe.up.pt

[2]Postdoctoral Researcher, CONSTRUCT, Faculty of Engineering, University of Porto, Porto, Portugal, email: fbf@fe.up.pt

[3]Professor, CONSTRUCT, Faculty of Engineering, University of Porto, Porto, Portugal, email: lcosta@fe.up.pt

ABSTRACT

Nowadays, topics related to recycling and reuse of waste materials, particularly those generated by the construction industry (i.e. construction and demolition waste, CDW) are often addressed. The overall aim is to protect the environment by reducing the detrimental impacts of waste disposal to landfill, while also preventing natural resource depletion. In the context of CDW management, an alternative that arises is the reuse of this waste material as recycled aggregate for transport infrastructure applications. The use of recycled CDW in road and railway construction can be considered as one of the simplest and most economical ways of employing this recycled material. However, the substitution of natural aggregates with recycled CDW is generally subject to the verification of a series of requirements, as well as to a tighter control of the characteristics of the product. This paper presents the laboratory assessment of a commercially available recycled CDW to be used as a sustainable alternative material in transport infrastructure construction. The classification of the constituents of this recycled CDW and the determination of relevant physical, mechanical and chemical properties were carried out in accordance with the applicable European Standards. The laboratory results indicate that this particular recycled CDW meets the performance recommendations of Portuguese specifications for application in embankments of transport infrastructure, as well as subbase layers of rural and forest roads. The use of recycled CDW in lieu of natural quarry products in the aforementioned applications would represent a valuable contribution towards the implementation of circular economy in the construction sector.

Keywords: Recycled construction and demolition aggregates, transport infrastructure foundations, environmental protection, sustainability, circular economy

1 INTRODUCTION

The increasing amount of construction and demolition waste (CDW) produced by the construction industry has been of concern worldwide due to major environmental, social, economic, and public health problems. In this context, the incorporation of recycled CDW into a variety of civil engineering applications has been vigorously studied in the last decade. Most of these studies have demonstrated that recycled CDW can exhibit mechanical properties equivalent or superior to typical quarried granular materials, allowing for greater confidence regarding its performance (Ferreira et al., 2023).

The possibility of valuing this waste appears as an excellent ally of the construction sector, in the sense of reducing part of the environmental impacts generated. After all, this sector is responsible for a large amount of waste generated within the ecosystem in which we live, as well as for the excessive consumption of natural resources and the numerous waste deposits in landfills. Thus, the successful use of recycled CDW turns these wastes into valuable resources as they significantly reduce the overall carbon emissions of the construction industry as well as the demand for natural materials from quarries (Dhir et al., 2004; Barbudo et al., 2012; Pereira et al., 2020; Zhang et al. 2022; Ferreira et al., 2023).

The European Union (EU) is striving to move from its traditional linear resource and waste management system in the construction industry towards a circular development model. Based on the circular economy theory, a new paradigm called waste hierarchy was introduced by the EU Waste Framework Directive 2008/98/EC (EU, 2008). The R-based principles of the circular economy are highly related to the waste hierarchy. From a life cycle perspective, both the waste hierarchy and the circular economy consider the entire life cycle of a product. The small difference is that the waste hierarchy still allows for disposal, whereas the framework of circular economy does not (Zhang et al. 2022).

Construction and demolition waste has very peculiar characteristics because it is produced in a sector where there is a wide range of production techniques and methodologies, and whose quality control of the production process is still recent. The composition of CDW, originating from each of the activities that comprise the civil construction work, is different in each type of structure, country and stage of the work, so that CDW is in general a quite diversified waste. Nevertheless, usually there is a percentage of products that stands out, which corresponds to the inert fraction of the waste. Notably, concrete debris generally comprises 40 to 50% of the total waste (Aghililotf et al. 2021).

Earthworks and foundations for transport infrastructure present possibly the greatest opportunity for the reuse of materials, hence reducing the usage of virgin materials as engineered fill (Fleming et al., 2006). However, the use of recycled CDW aggregates in the construction of transport infrastructure requires in-depth knowledge of the properties and minimum requirements for their application, in order to ensure adequate performance and durability throughout their life cycle. In fact, aggregates account for the largest proportion of the materials incorporated into many transport infrastructure foundations, so the performance of aggregates will be reflected in that of the infrastructure. It is therefore essential to assess their relevant characteristics and mechanical behaviour taking into account their prospective application.

In view of the above, a series of laboratory tests was conducted in this study to evaluate the main physical, mechanical and chemical properties of a commercially available recycled CDW collected from a specialised recycling plant. The suitability of this material as an alternative aggregate for transport infrastructure construction was then evaluated on the basis of the requirements set out in the Portuguese specifications LNEC E 474 (2009) and LNEC E 484 (2016).

2 LABORATORY STUDY AND RESULTS

2.1 Constituents of the recycled aggregate

2.1.1 Analysis of constituents

The recycled aggregate used in this study (Figure 1) was collected from a Portuguese recycling plant. It consists of a commercially available recycled material resulting from the recovery and processing of mixed CDW that meets the end-of-waste criteria according to the EU Waste Framework Directive (EU, 2008). As opposed to the selected materials employed in most of the previous related studies (e.g. recycled concrete aggregate, recycled crushed brick, etc.), a mixed recycled aggregate was used because it corresponds to the recycled CDW widely available on the Portuguese market.

The classification of the constituents was performed in accordance with the European standard EN 933-11 (2009), which specifies the procedure for estimating the relative proportions of constituents of coarse recycled aggregates. As shown in Table 1, this recycled CDW was mostly composed of concrete and mortar products (51.0%), aggregates (23.2%) and masonry elements (19.5%).

Figure 1. *Recycled aggregate from construction and demolition waste (CDW)*

Table 1. *Recycled CDW constituents determined on the basis of EN 933-11 (2009)*

Abbreviation	Constituents	Values
R_c	Concrete, concrete products, mortar, concrete masonry units	50.99 (%)
R_u	Unbound aggregate, natural stone, hydraulically bound aggregate	23.15 (%)
R_g	Glass	0.32 (%)
R_a	Bituminous materials	1.54 (%)
R_b	Clay masonry units, calcium silicate masonry units, aerated non-floating concrete	19.50 (%)
R_s	Soils	4.14 (%)
X	Other materials: plastics, rubbers, metals (ferrous and non-ferrous), non-floating wood, and stucco	0.17 (%)
F_L	Floating particles	0.3 (cm^3/kg)

2.1.2 Framework of constituents according to LNEC E 484 (2016)

The Portuguese specification LNEC E 484 (2016) is a guide for the inclusion of materials resulting from CDW in rural and forest roads. This specification provides recommendations and sets minimum requirements for the use of materials from CDW in the various layers that compose the foundation of rural and forest roads, including soils and rocks, even if they come from civil engineering works other than the one in which they will be used.

For inclusion in rural and forest roads, the recycled materials from CDW covered by the aforementioned specification are grouped into three classes (CRA, CRB and CRC), which are defined based on the relative proportions of each of the constituents, as indicated in Table 2. The values obtained for the recycled CDW used in this study are also included in Table 2 for direct comparison.

It can be concluded that the studied recycled CDW fits only into the CRA class, since the sum of masonries and soils (R_b+R_s) exceeds 10%. In fact, this is the only reason why the material is excluded from the CRB and CRC classes.

Table 2. *Classification of recycled materials from CDW based on constituents (LNEC E 484:2016) and values obtained in this study*

	Class	**R_c+R_u+R_g (%)**	**R_g (%)**	**R_a (%)**	**R_b+R_s (%)**	**F_L (cm^3/kg)**	**X (%)**
Classification criteria (LNEC E 484:2016)	CRA	No limit	≤ 25	No limit	No limit	≤ 5	≤ 1
	CRB	≥ 20	≤ 5	≤ 80	≤ 10	≤ 5	≤ 1
	CRC	≥ 50	≤ 5	≤ 30	≤ 10	≤ 5	≤ 1
Tested material	CRA	74.46	0.32	1.54	23.64	0.3	0.17

2.1.3 Framework of constituents according to LNEC E 474 (2009)

The specification LNEC E 474 (2009) establishes minimum requirements for the use of recycled materials from CDW in the construction of embankments and capping layers of transport infrastructures, namely roads, airfields and railways. As shown in Table 3, for the purpose of use in embankments and capping layers of transport infrastructures, the materials from CDW covered by this LNEC specification are grouped into three classes (B, MB and C), which are defined on the basis of the relative proportions of each of the constituents.

According to Table 3, the studied recycled CDW fits only in class C, since the sum of concrete/mortar products, unbound aggregates and glass ($R_c+R_u+R_g$) is less than 90% and greater than 70%, which is why the material is excluded from classes B and MB, respectively. However, in addition to this, the B class would be excluded due to the excessive amount of masonries and soils (R_b+R_s) and the MB class would also be excluded since the proportion of bituminous materials (Ra) is less than 30%.

Table 3. *Classification of recycled materials from CDW based on constituents (LNEC E 474:2009) and values obtained in this study*

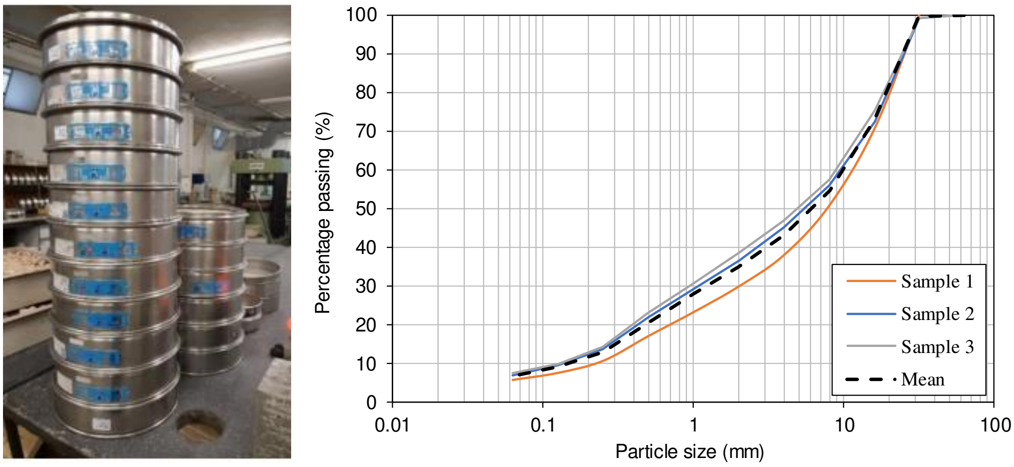
	Class	$R_c+R_u+R_g$ (%)	R_g (%)	R_a (%)	R_b+R_s (%)	F_L (cm³/kg)	X (%)
Classification criteria (LNEC E 474:2009)	B	≥ 90	≤ 10	≤ 5	≤ 10	≤ 5	≤ 1
	MB	≤ 70	≤ 25	≥ 30	≤ 70	≤ 5	≤ 1
	C	No limit	≤ 25	≤ 30	No limit	≤ 5	≤ 1
Tested material	C	74.46	0.32	1.54	23.64	0.3	0.17

2.2 Properties of the recycled aggregate

The following sections detail the tests performed in this study to evaluate the physical, mechanical and chemical properties of the recycled CDW. The respective results are presented and compared with the requirements established in the specifications LNEC E 484 (2016) and LNEC E 474 (2009).

2.2.1 Analysis of geometrical properties

The particle size distribution of the recycled aggregate was determined according to the standard EN 933-1 (2012) by washing, drying, sieving and then determining the mass of each partial sample retained on each of the various sieves (Figure 2a). This procedure was carried out on three samples and the mean particle size distribution curve was then derived, as illustrated in Figure 2b. The mean values of the maximum particle size (D_{max}) and fines content (≤0.063 mm) were 22.4 mm and 6.7%, respectively.



(a) (b)

Figure 2. *(a) Set of sieves; (b) Particle size distribution of the recycled CDW*

Apart from the gradation, other laboratory tests were performed to assess the geometrical properties of the recycled CDW. The particle shape was evaluated by quantifying the flakiness (Figure 3a) and shape (Figure 3b) indexes, following the standards EN 933-3 (2012) and EN 933-4 (2008), respectively. These parameters characterise the aggregate in terms of the presence of flaky and non-cubical particles, respectively, which are undesirable in transport infrastructure layers due to their higher susceptibility to break. The obtained values of the flakiness and shape indexes were 22% and 18%, respectively.

The analysis of fines was conducted using the sand equivalent (Figure 3c) and the methylene blue (Figure 3d) tests considering the 0/2 mm fraction of the recycled CDW, in accordance with the EN 933-

8 (2012) and EN 933-9 (2009), respectively. The sand equivalent (SE) reflects the relative proportions of sand versus plastic fines and dust, whereas the methylene blue (MB) is a function of the quantity and characteristics of potentially harmful clay minerals. A SE value of 27% and a MB value of 3.25 g/kg were obtained (average value from three samples). The parameter $MB_{0/D}$, which corresponds to the value of MB multiplied by the percentage of material passing the 2 mm sieve, as defined in the Portuguese specifications, was also evaluated and the average value was determined as 1.14 g/kg.

(a) (b) (c) (d)

Figure 3. *Geometrical properties tests to determine: (a) Flakiness index; (b) Shape index; (c) Sand equivalent value; (d) Methylene blue value*

2.2.2 Analysis of mechanical and physical properties

To determine the mechanical and physical properties of the recycled aggregate from CDW, particularly the resistance to fragmentation and the values of particle density and water absorption, a series of tests was performed following the European standards EN 1097-2 (2010) and EN 1097-6 (2013), respectively.

The European Standard EN 1097-2 (2010) describes the reference method (Los Angeles test) to determine the resistance to fragmentation of aggregates (Figure 4a) that consists of the aggregate's ability not to break while being handled. This property is particularly relevant when evaluating the suitability of recycled materials for transport infrastructure applications, since the breakage of aggregates may compromise the strength and drainage capacity of the foundation layers. The obtained Los Angeles coefficient values from two repeatability tests were 49% and 46%.

The test to determine the particle density and water absorption (Figure 4b), on the other hand, is described by the EN 1097-6 (2013). The test procedure depends on the particle size fraction of the aggregate. The obtained results (average values) for different particle size fractions (0.063/4 mm and 4/31.5 mm) of the recycled CDW are presented in Table 4.

(a) (b)

Figure 4. *(a) Los Angeles method; (b) Particle density and water absorption test*

2.2.3 Analysis of chemical properties

The use of recycled aggregates in transport infrastructure applications may rise environmental concerns with respect to the groundwater contamination. The chemical composition of CDW, apart from presenting a great variability, may contain significant percentages of hazardous substances that may be harmful to the environment and public health. The chemical and environmental characterisation is therefore a mandatory requirement imposed by EU policies for the valorisation of these alternative materials.

Table 4. *Values of particle density and water absorption of the recycled CDW*

Parameters	Particle size fraction (mm)	Test result
Apparent particle density (Mg/m^3)	4/31.5	2.58
Oven-dried particle density (Mg/m^3)		2.23
Saturated and surface dried particle density (Mg/m^3)		2.37
Water absorption (%)		6.0
Apparent particle density (Mg/m^3)	0.063/4	2.68
Oven-dried particle density (Mg/m^3)		2.41
Saturated and surface dried particle density (Mg/m^3)		2.51
Water absorption (%)		4.2

In this study, the content of water soluble sulphates (Figure 5) was estimated by spectrophotometry in accordance with the standard EN 1744-1 (2009). The average value of the water soluble sulphates was 0.034% for this particular recycled CDW. In addition, laboratory leaching tests were conducted as per the EN 12457-4 (2002) to investigate the potential release of hazardous substances. The obtained results (not included herein due to space constraints) showed that this recycled CDW complies with the acceptance criteria for inert landfills according to the European Council Decision 2003/33/EC.

Figure 5. *Determination of water soluble sulphate content*

2.2.4 Framework of geometrical, mechanical and chemical properties according to LNEC E 484 (2016)

Table 5 presents the properties and minimum requirements for a recycled CDW to be considered suitable for inclusion in the foundation of rural and forest roads, as per the specification LNEC E 484 (2016). The results obtained for the recycled aggregate analysed in this study are also included in this table for comparison purposes.

As indicated in Table 5, the aforementioned specification establishes four different categories (CR1 to CR4) that can be used to classify the recycled aggregate depending on its geometrical, mechanical and chemical properties. From the test results obtained in this study, it can be concluded that the studied recycled CDW is a CR2 material.

2.2.5 Framework of geometrical, mechanical and chemical properties according to LNEC E 474 (2009)

The properties and minimum requirements for the inclusion of recycled CDW in embankments and capping layers of transport infrastructures, as recommended by LNEC E 474 (2009), are presented in Table 6, along with the test results obtained in this study. This specification defines two different categories for the recycled aggregate, based on its properties, specifically MAT1 and MAT2. Comparing the test results with the compliance requirements, it becomes apparent that the studied recycled CDW is categorised as a MAT1 material.

Table 5. *Test results and minimum requirements for inclusion of recycled CDW in rural and forest roads as per LNEC E 484 (2016)*

			Material category			
			CR1	CR2	CR3	CR4
Parameter	**Property**	**Test result**	CRA, CRB, CRC	CRA, CRB, CRC	CRB, CRC	CRC
Geometrical	D_{max}	22.4 mm	≤ 180 mm	≤ 80 mm	≤ 40 mm	≤ 40 mm
	Fines content (≤ 0.063 mm)	6.7 %	-	≤ 12%	≤ 12%	≤ 12%
	Assessment of fines ($MB_{0/D}$)	1.14 g/kg	-	≤ 2.0	≤ 2.0	≤ 1.0
Mechanical	Resistance to fragmentation (LA)	48	-	LA ≤ 50	LA ≤ 45 or MDE ≤ 45	LA ≤ 40 or MDE ≤ 40
	Resistance to wear (MDE)	-				
Chemical	Water-soluble sulphates	0.034 %	≤ 0.7 %	≤ 0.7 %	≤ 0.7 %	≤ 0.7 %
	Release of hazardous substances		Classification as inert waste for landfill			

Table 6. *Test results and minimum requirements for inclusion of recycled CDW in embankment and capping layer of transport infrastructures as per LNEC E 474 (2009)*

			Material category		
			MAT1	MAT2	
Parameter	**Property**	**Test result**	B, MB, C	B, C	MB
Geometrical	D_{max}	22.4 mm	≤ 150 mm	≤ 80 mm	
	Fines content (≤ 0.08 mm)	7.3 %	≤ 10%	≤ 10%	
	Assessment of fines ($MB_{0/D}$)	1.14 g/kg	< 2.0	< 1.0	
Mechanical	Resistance to fragmentation (LA)	48	-	LA ≤ 45	-
	Resistance to wear (MDE)	-		MDE ≤ 45	
Chemical	Water-soluble sulphates	0.034 %	≤ 0.7 %	≤ 0.7 %	
	Release of hazardous substances		Classification as inert waste for landfill		

3 APPLICATION CRITERIA

According to LNEC E 484 (2016), the recycled aggregates from CDW classified using the categories CR1 to CR4 (Table 5) can be applied in rural and forest roads as per the criteria presented in Table 7. As mentioned earlier, the recycled CDW used in this study is included in the CR2 category, and thus it may be considered suitable for embankments and subbase layers of rural and forest roads (Table 7).

It is noteworthy that the recycled aggregate does not meet the required performance to be used in the base layer of rural and forest roads due to the insufficient resistance to fragmentation. In fact, only a CR3 (or higher category) recycled CDW would fulfill the criteria for application in the base layer (Table 7). As shown in Table 5, the recycled CDW is excluded from the CR3 category only because the LA coefficient exceeded 45. This is believed to be due to the relatively high proportion of clay masonry elements (R_b = 19.50%), which are more prone to breakage, and hence negatively affected the resistance to fragmentation of the recycled material.

Furthermore, this material is not considered appropriate for the unsealed wearing layer of rural and forest roads, which would demand a recycled CDW classified as CR4 (Table 7). As can be seen from the data presented in Table 5, both the resistance to fragmentation and the obtained $MB_{0/D}$ value do not comply with the established requirements for a CR4 material. A possible way of applying this recycled CDW in base and unsealed wearing layers of rural and forest roads would be by considering its blend with a natural aggregate. However, the feasibility of this solution and the required proportion of the natural aggregate would need to be assessed through further investigation.

Table 7. *Application criteria of recycled CDW according to specification LNEC E 484 (2016)*

Place	Category
Embankment for rural and forest roads	CR1, CR2, CR3 and CR4
Subbase layer	CR2, CR3 and CR4
Base layer	CR3 and CR4
Unsealed wearing layer	CR4

Table 8 shows the criteria defined by LNEC E 474 (2009) concerning the application of recycled CDW in embankments and capping layers of transport infrastructures. As indicated earlier, based on the laboratory characterisation carried out in this study, the recycled CDW can be included in MAT1 category, which means that it can be employed in the construction of embankments for transport infrastructures, such as roads, railway and airfields.

According to the criteria presented in Table 8, to fulfil the required performance for a capping layer material, the recycled CDW would have to be classified as a MAT2 material of classes B or C. Similar to what was previously concluded from the analysis of the minimum requirements for inclusion in rural and forest roads, the resistance to fragmentation and the quality of fines were determinant factors for the classification of the recycled aggregate, hampering its inclusion in the superior category (i.e. MAT2).

The significant proportion of clay masonry elements may have detrimentally affected the resistance to fragmentation and the quality of fines, thus limiting the use of the recycled aggregate to the construction of embankments for transport infrastructures, as per the specification LNEC E 474 (2009). In fact, relatively high values of Los Angeles coefficient for mixed recycled CDW have also been reported in previous studies as a constraint as regards the application of these materials in structural layers of transport infrastructure (e.g., Agrela et al., 2012; Pereira et al., 2020).

Table 8. *Application criteria of recycled CDW according to specification LNEC E 474 (2009)*

Category	MAT1			MAT2		
Class	B	MB	C	B	MB	C
Capping layer	×	×	×	✓	×	✓
Embankment	✓	✓	✓	✓	✓	✓

Similar to the results obtained in this study, other authors have also reported satisfactory results with recycled materials from CDW. Barbudo et al. (2012) studied a wide range of recycled CDW and concluded that, among recycled aggregates, concrete aggregates exhibit higher abrasion resistance. According to the authors, although mixed and ceramic recycled aggregates are not allowed for use in pavement layers as per the Spanish regulations, 14 of the 23 materials studied (61%) met the requirements related to the Los Angeles coefficient (i.e. values below 40). The remaining mixed and ceramic materials presented slightly higher values, but not exceeding 45. The authors further deduced that recycled aggregates with less than 25% of masonries can be used in road sub-bases.

In addition, a research project carried out in Portugal by the Nacional Laboratory of Civil Engineering in collaboration with IST (University of Lisbon), using different recycled aggregates from CDW, showed that the application of recycled CDW in unbound pavement layers is generally a technically feasible alternative (LNEC, 2013). Del Rey et al. (2016) analysed the behaviour of mixed recycled aggregates from CDW in the structural layers of an unpaved rural road under real field conditions. The results from the experimental road sections constructed with recycled CDW complied with the technical requirements of the Spanish General Technical Specifications for Roads and Bridge Works (PG-3). Esfahani (2020) conducted a laboratory study to verify the feasibility of using recycled aggregates from CDW in base and subbase layers of pavements. The results evidenced recycled CDW as a suitable alternative material for subbase layers of roads. More recently, Aghililotf et al. (2021) evaluated six types of natural aggregates and three types of recycled concrete aggregates for potential use in pavement layers. The results obtained with all the recycled aggregates were considered acceptable for general applications in road construction.

4 CONCLUSIONS

This study presented the laboratory characterisation of a mixed recycled aggregate from CDW carried out to evaluate its suitability as an alternative material in transport infrastructure construction. A comparison was established between the material properties obtained through the experimental study and the recommendations provided in the Portuguese specifications LNEC E 484 (2016) and LNEC E 474 (2009).

The feasibility analyses of the use of recycled CDW in transport infrastructure foundations have proven to be very positive. Even with the limitations presented (LA and $MB_{0/D}$ values exceeding the limits for some of the applications addressed in these specifications), the material studied exhibited physical, mechanical and chemical properties compatible with the criteria for inclusion into embankments of transport infrastructures (e.g. roads, railways, airfields), as well as subbase layers of rural and forest roads.

Despite the relatively high proportion of clay masonry elements present in the material investigated that contributed to narrow the range of suitable applications, it was possible to fit the mixed recycled CDW into both specifications, thus enabling appropriate destination to the recycled material.

The results obtained in this study indicate that recycled aggregates from CDW may be regarded as a feasible alternative to traditional materials used in transport infrastructure foundations. The widespread use of these recycled aggregates as a replacement for virgin quarry materials would represent an important step forward towards sustainable construction and environmental protection.

Regarding future work, additional laboratory and field studies involving different recycled CDW, as well as their blends with natural aggregates, would be useful to further investigate and promote the use of recycled CDW in the construction of transport infrastructures, targeting more demanding applications.

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