Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-50

Use of Construction and Demolition Wastes in embankments and their geoenvironmental characterization in Spain

M. Santana[1], and J. Estaire[2]

[1]*Laboratorio de Geotecnia-CEDEX, Madrid, Spain, email: Maria.S.Ruiz@cedex.es*

[2]*Dr. Ph, Laboratorio de Geotecnia-CEDEX, Madrid, Spain, email: Jose.Estaire@cedex.es*

ABSTRACT

The use of wastes for the construction of embankments is a measure that increases the sustainability of these earthworks and is related to the circular economy policies promoted by the European Union (EU). CEDEX has been working for years with different types of wastes and analyzing their application to embankments. Construction and Demolition Wastes (CDW) represent an important volume of the wastes generated. Their use for the construction of embankments must be preceded by the verification of the compliance of these materials with the technical and environmental requirements of the corresponding standards, the latter not being clearly defined in Spanish regulations. The usual way of proving that the wastes do not harm the environment is to carry out leaching tests. The problem arises in the choice of the type of leaching test to be used and the interpretation of the results obtained. This work includes the classification and uses of CDW, the most common leaching tests for their environmental characterization, and the criteria with which the results of these tests can be compared for their correct interpretation. Finally, a note is made on possible scenarios in which CDW is used in embankments to avoid affecting the environment.

Keywords: Circular Economy, Construction and Demolition Wastes, earthworks, leaching tests

1 INTRODUCTION

According to Eurostat 2021, the European Union (EU) generated 2018 a total of 5.2 tons of waste per inhabitant. 38.5% of these wastes are deposited in landfills. For this year, Construction and Demolition Waste (CDW) represented 36% of the total waste generated in the EU and, in the specific case of Spain, almost 28%. The European Green Deal aims to boost the efficiency of resources by shifting to a circular economy model among different plans such as fostering the market for secondary raw materials. The aim of this paper is related to the use of these secondary raw materials, specifically for the construction and demolition wastes, for embankment constructions.

CDWs are defined in Directive 2008/98/CE (Waste Framework Directive) as *"waste generated by construction and demolition activities".* To enforce the general purposes of this Directive, the Spanish government developed some plans to adapt material recycling procedures. These plans include guidelines to achieve these goals, among which is "Promoting the use of materials from recoverable CDW in construction works, such as earthworks, structural layers (road sub-bases, form layer and sub-ballast in railroad works), as well as the production of concrete, as long as it is guaranteed that the recycled materials meet the quality requirements and prescriptions of the regulations in force in each case".

The use of CDW as a material for the construction of embankments requires the prior determination of its geotechnical properties, as well as guaranteeing that its use is not dangerous for the environment. The technical requirements for materials, whether natural or recycled, are clearly defined according to the type of application in the corresponding regulations. However, it is not clearly established how to ensure that using these materials does not cause environmental problems.

This paper compiles part of the regional, Spanish, and other European countries' regulations concerning recycled aggregates and focuses on analyzing how they address and analyze the impact of recycled aggregates on the environment for their use as a material in embankments.

2 THE USE OF CDW AGGREGATES IN CIVIL ENGINEERING AND EARTHWORKS

2.1 Classification of CDW aggregates

CDW is a waste of a fundamentally inert nature generated in excavation, new construction, repair, remodelling, rehabilitation, or demolition works. The generation process is, therefore, very heterogeneous and gives rise to materials of very varied composition, consisting mainly of concrete, cement, natural stone, bituminous material, ceramics, paper, plastic, and gypsum. The work of Gálvez-Martos et al. (2018) collects the average variability of each CDW component in the EU, being the mix of concrete and masonry the most abundant (40%-84%).

Using the CDW in earthworks requires transforming the waste into aggregates. According to standard EN 12620, recycled aggregate (RA) is "*the aggregate resulting from the treatment of inorganic material previously used in construction*". This treatment can be just a crushing or include more processes such as washing or extraction of some harmful elements such as plasterboards. Due to their heterogeneous composition, the use of these recycled aggregates requires the classification of major components to try to achieve a good correlation between the composition and the behaviour. Taking as a reference the European standard EN 13242, the composition of recycled coarse aggregates must be carried out with the EN 933-11 standard, whose constituents are shown in Table 1.

Table 1. *Major constituents for recycled aggregates according to EN 933-11*

Constituents	Description	Constituents	Description
Rc 	Concrete, concrete products, mortar Concrete masonry units	**Rb** 	Clay masonry units (i.e. bricks and tiles) Calcium silicate masonry units Aerated non-floating concrete
Ru 	Unbound aggregate, natural stone Hydraulically bound aggregate	**Ra** 	Bituminous materials
FL 	Floating material in volumen	**X** 	Other: cohesive (i.e. clay and soil) Miscellaneous: metals Non-floating wood, plastic and rubber Gypsum plaster
Rg 	Glass		

The segregation by constituents allows classifying the recycled aggregates. Despite there being no standard for this classification, the common practice is to classify by the main constituents as: recycled concrete aggregates, recycled asphalt aggregates, recycled ceramic aggregates, and mixed recycled aggregates (MRA). MRAs contain a mixture of concrete and ceramic wastes. They represent the largest percentage of the volume generated in the treatment plants and they have been included in EWL (European Waste List) as 17 01 07. Table 2 shows different terms for the MRA included in several documents in Spain and other EU members.

***Table 2.** Examples of mixed recycled aggregates based on their constituents*

Ref.	Country	Nomc.	Rc (%)	Ru (%)	Rg (%)	Rb (%)	Ra (%)	X (%)	FL (cm^3/kg)
[1]Norma firmes	Spain/Basque country	AR-M	[a]	Rc+Ru+Rg≥70[b]	<2	≤30	≤10	≤1c	≤5
[2]Aprr.eus	Spain/Basque Country	ARMh	Rc+Ru+Rg≥70			≤30	-	-	-
		ARMc	Rc+Ru+Rg<70			>30	-	-	-
[3]Borrador PPT[d]	Spain/Extremadura	ARMh	≥70		-	≤30	<5	<1	-
		ARMc	<70		-	>30	<5	<1	-
[4]Guía Andalucía Central	Spain/Andalucía	ARM I	≥55 y Rc+Ru+Ra≥70		-	-	≤15	<1	<1
		ARM I	≥55 y Rc+Ru+Ra≥70		-	-	≤15	<2	<2
[5]Redacción Pliegos[e]		ZR RCD	≥70	-	-	≤10	≤5	≤1	≤10
NF-P-18-545	France	ARM	Rc+Ru+Rg≥70 y Rg<2			-	-	<1	<5
BRL-2506-1[f]	The Netherlands	Type B	>70		<2	<30	<5	<2	<2
		Tipo C	-	-	<2	>85	<5	<2	<2
DIN 4226-101[g]	Germany	Type 2	≥70		≤3	≤30	≤1	≤0.5	-
		Type 3	≤20		≤5	≥80	≤1	≤0.5	-
PTV-406[g]	Belgium	ARM	>50		<2	<50	<5	<1	<5
		ARM[h]	<40		<2	>60	<5	<1	<5
		ARM[i]	>70		<2	<30	<5	<1	<2
Cinderela Project[6]	EU	High quality	Rc+Ru+Rg≥70		≤1	≤30	≤5	≤1	≤1
		Low quality	Rc+Ru+Rg≥50		≤2	≤50	≤10	≤1	≤5

[1] Norma para el dimensionamiento de firmes de la Red de Carreteras del País Vasco. Gobierno Vasco. 2012
[2] Usos del Árido Reciclado de RCD Dossier Fichas Técnicas de unidades de obra donde se pueden utilizar Árido Reciclado de RCD y Ejemplos de obras donde se han utilizado Árido Reciclado de RCD en alguna de sus unidades de obra. 2019
[3] Borrador de Decreto por el que se aprueba el Pliego de Prescripciones Técnicas para el uso de áridos reciclados procedentes de RCD en Extremadura. Junta Extremadura. 2019
[4] Guía de áridos reciclados de residuos de construcción y demolición (RCD) de Andalucía Central. Junta de Andalucía. 2015
[5] Recomendaciones para la redacción de: Pliegos de Especificaciones Técnicas para el uso de materiales reciclados de residuos de construcción y demolición (RCD). Junta de Andalucía. 2010
[6] Cinderela. (2021). D5.5. End of Waste criteria protocol for waste used as aggregates
[a]Not requirements; [b]Rg<2%; [c]Gypsum <0,8% and Others <0,8%; [d]GEX-ET-02; [e]Articulo Zahorra de RCD; [f]Material for filling; [g]values for recycled mixed aggregates; [h]recycled ceramic mixed aggregate; [i] recycled ceramic mixed aggregate with quality

As can be seen in the table above, each document shows different percentages for each constituent. The Netherlands and Germany also include a type of aggregate where the Rb content exceeds 80%. Generally, all documents require the content of other "X" components (including gypsum) to be lower than values ranging from 0.5 to 2%. The content of floating particles is also diverse, with a range that prevents the presence of more than 1 to 10 cm^3/kg.

The heterogeneity in the composition of recycled aggregates is due to both the origin of the construction and demolition wastes and the treatment or cleaning methods to which they were subjected in the treatment plants. A greater homogeneity in constituents can be achieved by a selective demolition at the site and a good selection and cleaning process in the treatment plants. One key point of cleaning treatment is the removal of gypsum plaster.

As reported in the literature, the limitation in the content for different constituents is justified by their effect on the technical properties. Thus, high contents in floating particles (FL) can arise long-term problems due to the degradation of materials such as wood. The X constituent includes gypsum, which may be disrupted by volume change, dissolution, and leaching phenomena. Finally, the Rb constituents, which include, for example, bricks and other materials with high porosity, affect the absorption properties, involving, among other consequences, the need for a greater amount of water for compaction operations (Herrador et al. 2012).

2.2 Use of Mixed Recycled Aggregates in civil engineering

In recent years, numerous papers have been published related to the use of recycled aggregates in geotechnical applications. For CDWs, most of them are devoted to the use of recycled aggregates in concrete (Garzón et al. 2022, Cantero et al. 2022), as road base and sub-base (Barbudo et al., 2012; Jiménez et al., 2012; Arulrajah et al., 2013, Tefa et al. 2021) or as trench backfill (Rahman et al., 2014). It is also interesting to highlight studies on the use of CDW in geosynthetic reinforced fill structures, (Vieira et al., 2016), as gabion fill (Nawagamuwa et al. 2012), pipe trench backfill (Rahman et al. 2014), landfill cover (Harnas et al. 2013), or material for ground improvement by vibration (McKelvey et al. 2002).

In Spain, the regional authorities of Andalucia, Castilla y León, Euskadi, Cantabria, and Extremadura drafted documents for the use of recycled aggregates resulting from CDW, where specific criteria for the use of RMA for earthworks were included. By now, there are no standards or rules from the Spanish government to apply in the whole country. Most of these documents consider the RMA as granular material to be used in the upper capping layers or mixed with lime or cement to obtain a stabilized layer. They approve the use of this stabilized material on roads with medium traffic rates, for walking and cycling structures, trenches, backfillings, and landfill covers.

MRAs account for 80% of the total volume of recycled aggregates produced in CDW treatment plants (CEDEX, 2014). Such high quantities of this type of recycled aggregate make it necessary to study its use in geotechnical applications with large volumes of material. One alternative is their use in earthworks, and this option was studied previously by GEAR project (2012) and by Santana et al. (2019). The most relevant conclusions of these studies indicated the technical feasibility of using recycled aggregates from CDW (including RMA) for embankment construction. The main drawback was the presence of environmental problem due to the leaching of sulfates. The present work extends the investigation of the environmental requirements that must be analyzed for their use in earthworks.

2.3 Physical and chemical requirements for the use of RMA in earthworks

In Spain, the requirements of materials to be used in earthworks are included in Article 330 "Embankments" of Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (referred to as PG3). As stated in the article, these requirements are applicable to both natural aggregates and those from industrial processes, explicitly stating: "*in addition to natural soils, products from industrial processes or human manipulation may be used in embankments, provided that the specifications of this article are met and that their physical-chemical characteristics guarantee the present and future stability of the whole*". In this regard, it should be pointed out that the laboratory tests included to determine properties to classify the materials according to their validity for use in embankments are tests developed for soil type materials.

On the other hand, it should be highlighted that the European standard EN 13242 also includes a list of tests for the characterization of aggregates, including recycled aggregates for use as road construction material. In addition, these are the reference tests used for the CE marking of aggregates. The tests prescribed in the standard are related to aggregate classification. Determining the potential use of recycled aggregates in embankment construction, therefore, requires testing the material to both sets of standards.

3 ENVIRONMENTAL CHARACTERIZATION FOR RECYCLED AGGREGATES

3.1 Scope of the environmental characterization

The employment of materials in earthworks must comply with the technical specifications required by the regulations for its specific use, in addition to the evaluation of their environmental characteristics. These requirements must be met by natural materials and by other products such as recycled aggregates. The purpose of the environmental evaluation is to verify that the materials used will not generate adverse impacts on the environment or on people's health. These two aspects (technical and environmental) are included in Article 330 of PG-3 for embankments for Spanish earthworks.

The usual methodology to determine the effect of the aggregates on the environment is the execution of leaching tests in the laboratory. However, the practical development of this methodology presents the following problems: a) there are several types of leaching tests. The Spanish regulation does not specify the one to employ, and b) once there is a result from any leaching tests, it is necessary to compare this value with a limit value to determine if the application is possible or not.

3.2 Leaching tests

3.2.1 General ideas

Most of the environmental assessment studies of the use of materials in earthworks are carried out by means of leaching tests. The aim of them is to determine, in different situations, the release to the water of components that may be contained in these materials and that could generate adverse impacts on the environment or health. In a leaching test, chemical elements present in the solid phases can be transferred to the aqueous phase with which they are in contact. In earthworks, the material may be in contact with water (surface or groundwater) so this phenomenon can appear (Barbudo, 2012). According to Saveyn et al. (2014), leaching tests are more suitable than total content tests for these purposes.

There are several test methods to study the leaching of granular materials, which are performed with different conditions concerning the particle size used, the amount of material, the liquid-to-solid ratio (L/S), or the duration of the test. In addition, leaching will depend on variables such as pH, particle size, contact time, or L/S ratio (Quina et al. 2011). The L/S ratio of the test must be taken into account in the interpretation of the results obtained. It should also be noted that, for most of the components analyzed in leaching tests, the maximum values obtained appear during the early stages of leaching, i.e., with small L/S ratios. However, for those components whose leaching is controlled by solubility, their results vary with the L/S ratio (Saveyn et al., 2014).

3.2.2 Leaching tests for aggregates

There are three European Technical Committees for Standardization (CEN/TC) that are in some way related to aggregates: CEN/TC 154 for aggregates, CEN/TC 292 for waste, and CEN/TC 351 for construction products. When analyzing the standards developed by these committees, it can be seen that each one of them has developed its own European standards (EN) for leaching tests:

- TC 154 – Aggregates:
    - EN 1744-3: Tests for chemical properties of aggregates - Part 3: Preparation of eluates by leaching of aggregates
- TC 292 – Characterization of waste:
    - EN 12457-1/2/3/4: Characterisation of waste - Leaching - Compliance test for leaching of granular waste materials and sludges
    - EN 14405: Characterization of waste - Leaching behaviour test - Up-flow percolation test
    - EN 14997: Characterization of waste - Leaching behaviour test - Influence of pH on leaching with continuous pH control
- TC 351 – Construction products:
    - prEN 16637-1/2/3: Construction products: Assessment of release of dangerous

The materials under study are, as indicated previously, aggregates resulting from the construction and demolition wastes. This material also is intended to be used as a construction product. Therefore, the most appropriate leaching test for their environmental characterization could be any of those mentioned above.

According to Naka et al. (2016), EN 1744-3 serves as a quick and preliminary check on aggregate behaviour, but their extrapolations, as they are only tested with a single L/S ratio, cannot be considered to faithfully reflect actual conditions. In addition, the short period of contact with the liquid (24 hours) cannot be sufficient to reach equilibrium for certain metals so leaching is underestimated (Löv et al., 2019).

EN 12547 test is the first approach to the leaching problem. Its use as a reference test in landfill disposal of materials makes it a well-known and widely implemented method.
On the other hand, EN 14405 and EN 16637 percolation tests more closely model the real conditions and the long-term behaviour of the chemical compounds of aggregates in contact with water. They will simulate the processes of percolation and infiltration of water through the material and its leaching into the environment (Chai et al., 2009).

Finally, pH dependence tests provide additional information and allow the study of different scenarios caused, for example, by carbonation.

Several European countries have regulations on the use of recycled aggregates for the construction of earthworks, such as France, Finland and the Czech Republic in which the leaching test to be used to characterize recycled aggregate is established. On the other hand, other countries have also developed either guidelines or regulations to determine the end-of-waste criteria of different materials, which prescribes the leaching test to be used. Despite there is no unanimity on the type of leaching test to be used to characterize recycled aggregates, the majority seems to favour the EN 12457 test.

3.3 Criteria to evaluate the environmental impact of recycled aggregates

3.3.1 General ideas

Once the leaching tests have been carried out, the results obtained must be compared with limit values that determine their impact on the environment. In this respect, there are currently two possible criteria for limit values that could be used: those indicated in the Landfill Directive, and those for the determination of end-of-waste criteria specified in different European documents.

Most of the scientific articles that analyze the use of recycled aggregates in roads in Spain compare the values of leaching tests with the limits for landfill (GEAR project, 2012, Barbudo et al., 2012, Galvín et al., 2013, Galvín et al., 2014, Vegas et al., 2015 and Santana et al., 2019).

3.3.2 Landfill Directive

Landfill Directive 1999/31/EC regulates the disposal of waste by landfilling and classifies the landfill into three types: Landfills for Inert Waste, for Non-Hazardous Waste, and for Hazardous Waste. In each case, the acceptance criteria are established according to leaching limit values and the content of organic components. Two leaching tests are employed: EN 12457-3 test with an L/S ratio of 10 l/kg (it is the compliance method), and EN 14405 test with an L/S ratio of 0,1 l/kg. The procedure consists of comparing the values of the leached elements, according to the indicated procedures, with the limit values established for the different types of waste.

Saveyn et al. (2014) compile, for various types of recycled aggregates, a list of the components released by leaching that exceed the limit values established for their deposit in a landfill for inert wastes indicated in the Landfill Directive. In the specific case of RMA, it is indicated that the limits for Cd, Pb, and chlorides are usually exceeded and further, according to pH leaching dependence tests, Sb, V, and sulfates are also exceeded. It should be remembered that elements such as As, Sb, Se, Mo, V, and sulfates are less leachable at pH between 7 and 10.

3.3.3 End-of-Waste criteria

The Waste Framework Directive defines, in article 6, the concept of end-of-waste status. When certain types of waste have been subject to a recovery operation, including recycling, and comply with some requirements, they may cease to be considered as waste. The directive indicates that "*possible categories of waste for which 'end-of-waste' specifications and criteria should be developed are, among others, construction and demolition waste, some ashes and slags, scrap metals, aggregates, tyres, textiles, compost, waste paper, and glass".*

The EU, aware of the problem generated by CDW, has been for years promoting projects to study its recovery and reuse: RE4-project, VEEP, Interreg, Cityloops, Green Instruct, Hiser, C2CA, CDWaste-ManageVET, among others. The work published by Saveyn et al. (2014) is a first approximation to the attempt to set limit values for the components that can produce environmental impacts caused by the leaching of aggregates from different wastes, that included, among others, recycled aggregates resulting from CDW. Moreover, the European Cinderela project included in its tasks the drafting of the document "End of Waste criteria protocol for waste used as aggregates" (Cinderela, 2021).

The values from Cinderela project (2021) and the work of Saveyn et al. (2014) as well as the limit values for the deposit of inert materials in landfills according to the European Directive have been compiled and integrated into Figure 1. In this figure, the cells are coloured according to whether the limit values required by each country are higher (green), lower (red), or equal (yellow) to those required for landfilling. In this compilation, only the values for leached inorganic compounds are included.

Country	Categ	Constituent – Leaching Limit Value (mg/kg en L/S=1/10 l/kg)															Standar
		As	Ba	Cd	Cr	Cu	Hg	Pb	Mo	Ni	Se	Sb	Zn	Cl-	F-	SO_4	EN
[1]Spain (Euskadi)		0,5	20	0,04	0,5	2	0,01	0,5	0,5	0,4	0,1	0,06	10	800	10	6000	1
Italy		0,5	10	0,05	0,5	0,5	0,01	0,5		0,1	0,1		30	1000	15	2500	2
Slovenia		0,1	5	0,025	0,5	0,5	0,005	0,5	0,5	0,4	0,6	0,3	2	800	10	1000	
Belgium		0,8		0,03	0,5	0,5	0,02	1,3		0,75			2,8				
Netherlands	a-c	0,9	22	0,04	0,63	0,9	0,02	2,3	1	0,44	0,15	0,17	4,5	616	55	1730	4
	b-d	2	100	0,06	7	10	0,08	8,3	15	2,1	3	0,7	14	8800	1500	20000	4
[2]Germany	Z0/Z1.1	0,14		0,015	0,125	0,2	0,005	0,4		0,15			1,5	300		200	2
	Z1	0,2		0,03	0,25	0,6	0,01	0,8		0,2			2	500		500	2
	Z2	0,6		0,06	0,6	1	0,02	2		0,7			6	1000		2000	2
Austria	[e]A	0,5	20	0,04	0,3	0,1	0,01	0,5		0,4	0,1	0,06	4	800	10	1500	1
	[f]A+	0,5	20	0,04	0,5	1	0,01	0,5		0,4	0,1	0,06	4	800	10	2500	1
	[g]B	0,5	20	0,04	0,5	2	0,01	0,5		0,6	0,1	0,1	18	800	15	5000	1
Denmark	[h]Cat1	0,071	1,8	0,006	0,055	0,2	8E-04	0,045		0,043	0,037		0,44	440		1000	3
	[i]Cat2	0,071	1,8	0,006	0,055	0,2	8E-04	0,045		0,043	0,037		0,44	440		1000	3
	[i]Cat3	0,45	24	0,13	2,8	9	8E-04	0,45		0,3	0,11		6,6	8800		16000	3
France	[j]1A	0,5	20	0,04	0,5	2	0,01	0,5	0,5	0,4	0,1	0,06	4	800	10	1000	1/2
	[k]1B	1	40	0,08	1	4	0,02	1	1	0,8	0,2	0,12	8	1600	20	2000	1/2
	[l]1C	1,5	60	0,12	1,5	6	0,03	1,5	1,5	1,2	0,3	0,18	12	2400	30	3000	1/2
	[m]Excl.	2	100	1	10	50	0,2	10	10	10	0,5	0,7	50	15000	150	20000	1/2
	[n]2A	0,8	56	0,32	4	50	0,08	0,8	5,6	1,6	0,5	0,4	50	1000	60	10000	1/2
	[o]2B	0,5	28	0,16	2	50	0,04	0,5	2,8	0,8	0,4	0,2	50	5000	30	5000	1/2
Sweden	p	0,09		0,02	1	0,8	0,01	0,2		0,4			4	130		200	4
Directiva UE-Inerte		0,5	20	0,04	0,5	2	0,01	0,5	0,5	0,4	0,1	0,06	4	800	10	1000	1

[1]Orden 12 de enero 2015 with requirements for the use of recycled aggregates resulting from CDW in unbound applications. [2] Depends on earth-structure location.
[a] Without cover (infiltration 300 mm/año); [b] Covered (infiltration 6mm/año); [c] Sn= 0,4 mg/kg; [d] Sn=2,3 mg/kg; [e] Class A without cover and no problematic hydrological conditions, or covered Surface and hydrological sites that needs to be protected, [f] Class A+ covered surfaces and sensitive hydrological sites, [g] Class B covered Surface and not sensitive hydrological sites. [h] Category 1 for road construction, paths, parking lots, noise barriers, dams, trechs. [i] Category 2 and 3 for more restrictive situations. [l] Material for road construction. [j] Must be for 80% of samples. [k] Must be for 95% of samples. [l] Must be for 100% of samples. [m] Can´t be used for road construction. [n] Covered by an impermeable Surface (bituminous, concrete...) minimum slope of 1%. [o] Embankments covered at least 30 cm of natural materials and minimum slope of 5% to limit the wáter entrance. [p] Use without restrictions
1 EN12457-4; 2 EN 12457-2, 3 EN 12457-1; 4 EN 14405

Figure 1. *Limit values given by different documents for the use of recycled aggregates*

As can be seen in the figure above, the most restrictive conditions are given by Denmark and Germany, while the less demanding is France.

3.4 Related aspects to consider for the environmental affection of recycled aggregates

3.4.1 Location of recycled aggregates inside the embankment

Some European countries have developed the use of recycled aggregates in civil engineering and specifically, in earthworks. They have documents that include the physical-chemical and environmental requirements for its use and differentiate situations where the material is placed under an impermeable or semi-impermeable surface or, without any protection against water infiltration. These conditions of use of the recycled aggregates will determine the greater or lesser exposure of the material to water and therefore the relevance of the phenomena related to the leaching of components. These conditions have been reflected in the adoption of different limit values for leached components, as happened in German and Dutch regulations.

3.4.2 Hydro-geological restrictions

The existence of areas particularly sensitive to contamination by leached components of recycled aggregates makes it necessary to consider the possibility of prohibiting its use on certain sites. These limitations are aimed at avoiding environmental impacts. These areas are in direct contact with water, areas with any type of special protection within the regulations for the conservation of nature, potentially flood-prone areas, areas close to a watercourse, lake, or reservoir, perimeter protection of drinking water catchment areas, and areas forming part of the public domain, and, areas forming part of the public water domain.

Some countries have included more specific restrictions, such as France, where it is stated that recycled aggregates must be placed more than 50 cm above the highest flood level for a 50-year return period, or the highest known, and at a distance of more than 30 m from watercourses, lakes or ponds. This limit is extended to 60 m when the elevation of the watercourse is more than 20 m below the base of the structure, also in areas of special protection and may not be used in karst areas. German regulations set placing the recycled aggregate more than 1 m above the piezometric level and requires the placement of a low permeability layer between the material and the piezometric level.

4 RECOMMENDATIONS FOR THE USE OF RECYCLED AGGREGATES IN EMBANKMENTS

As mentioned above, the study on the impact of the use of recycled aggregates in embankments and its consequences on the environment presents two major problems: the choice of the most appropriate leaching test to analyze this phenomenon and the determination of the limit values with which the results of these tests should be compared. Moreover, these two factors are also conditioned by the hydrological site factors where the embankment is site and by the possible measures that can be taken to isolate the recycled aggregates from contact with water.

Regarding the most suitable leaching test for the study of the environmental impact, it seems advisable to use the standard EN 12457-4, which is the reference test used in landfill regulations. This is a quick test (24 h) and is used in most of the works analyzed in this paper.

In order to determine the limit values with which to compare the results obtained in the leaching tests, it seems appropriate to take into account the limit values of leached components proposed in Cinderela project (2021), depending on whether the recycled aggregates will be in direct contact with water or protected in some way, by being placed under an impermeable or semi-impermeable layer. In this respect, Table 3 shows the values proposed in Cinderela project and, as a reference, those established for the deposit of the material in an inert landfill. In order to facilitate their interpretation, the cells have been coloured following the same criteria as in Figure 1.

Table 3. *Limit values for leaching test for the use of recycled aggregates for granular applications (from Cinderela project, 2021)*

Element	**Leaching limit value with EN 12457-4 (mg/kg with L/S=10l/kg)**		
	Unbound applications covered with surfacing layer considered semi/impervious	Unbound applications. Unpaved or uncapped usage	Inert landfills
As	0.9	0.5	0.5
Ba	25	5	20
Cd	0.05	0.025	0.04
Cr	2	0.5	0.5
Cu	3	0.5	2
Hg	0.01	0.005	0.01
Mo	2.8	0.5	0.5
Ni	0.75	0.1	0.4
Pb	2.3	0.5	0.5
Sb	0.3	0.06	0.06
Se	0.6	0.1	0.1
Zn	10	2	4
F^-	55	10	10
Cl^-	5000	600	800
SO_4^{2-}	6000	1000	1000

As can be seen in Table 3, the limit values for the end-of-waste condition proposed in Cinderela project for granular applications under an impermeable layer are less restrictive (green) than those of the landfill directive for inert material. In case of use in areas without any protection, the values are more restrictive (red colour) or identical (yellow colour) than in such landfills.

In addition, the Spanish experience in the encapsulation of soils with problems due to their interaction with water (collapsible, expansive soils, soils with gypsum, soils with soluble salts) could be taken into account when recycled aggregates are used as construction materials for embankments. These encapsulations manage to avoid the contact of the encapsulated materials with water and, in the case of recycled aggregates, would avoid the generation of leachate and its related problems. Soriano (2006) is the best example of this use in Spain. It includes typical sections used in embankments with gypsum which could serve as a basis for the design of embankments with recycled aggregates in their core (Figure 2).

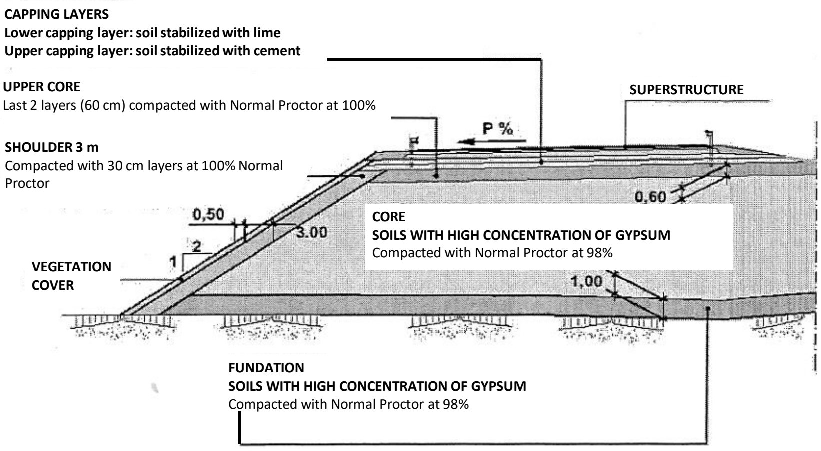

Figure 2. *Example of an embankment section constructed with gypsum (from Soriano, 2006)*

Therefore, as a first approach to the problem, the construction of an experimental embankment could be considered, in which the recycled aggregates are encapsulated and which has leach meters to collect the leached water for subsequent analysis and detection of components.

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