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Recycled aggregate in road construction following the Spanish General Technical Specifications for Roads and Bridge Works (PG-3): a case study

Un estudio para la aplicación del árido reciclado en obras de carreteras en España siguiendo las especificaciones del Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3)

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SUMMARY

This research characterizes four samples of recycled aggregate for their potential use in road construction projects in consonance with the Spanish General Technical Specifications for Roads and Bridge Works (PG-3). Although some fractions were of sufficient quality for the construction of embankments, backfills, and quarry-run fills, they were ultimately found to be unsuitable for the construction of underground drainage, granular structural layers, soil stabilization and concrete pavements. They were negatively evaluated because of their particle size distribution and sulfate content. Nevertheless, the quality of this recycled aggregate could be substantially improved by manually removing the gypsum before the crushing process at the plant or by selecting the material with greater care at the beginning of the process. Finally, we suggest that Construction and Demolition (C&D) waste plant managers should modify the manufacturing process to obtain a suitable particle size distribution in accordance with PG-3 requirements and the projected use of the aggregate.

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Keywords: Construction waste; demolition waste; recycled aggregate; road construction; Spanish General Technical Specifications for Roads and Bridge Works (PG-3).

RESUMEN

En esta investigación se han caracterizado cuatro muestras de árido reciclado para su potencial uso en obras de carreteras en España siguiendo el Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3). Aunque algunas fracciones presentaron suficiente calidad para la construcción de terraplenes, rellenos localizados y rellenos todo en uno, resultaron inadecuadas para la construcción de drenes subterráneos, zahorras, suelos estabilizados y pavimentos de hormigón. Obtuvieron una evaluación negativa en cuanto a distribución granulométrica y contenido en sulfatos. No obstante, la calidad de este árido reciclado podría mejorar sustancialmente eliminando manualmente el yeso antes de la trituración en planta o seleccionando el material con un mayor cuidado al inicio del proceso. Finalmente, recomendamos que los empresarios de las plantas de residuos de construcción y demolición modifiquen el procedimiento de fabricación para obtener una distribución granulométrica adecuada, de acuerdo con los requisitos del PG-3 y el uso previsto del árido.

Palabras clave: *Residuos de construcción; residuos de demolición; árido reciclado; obras de carreteras; pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3).*

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1. INTRODUCTION AND OBJECTIVE

During the past decades, Construction and Demolition (C&D) waste has been most often disposed of in landfills. However, in recent years, recognition of the potential for the diversion of waste components from landfills has made C&D waste management a focus of interest in European Union legislation. EU policies are based on establishing a hierarchy of options for effective waste management (1) (2). Firstly, waste reduction should take place at the site of origin. Secondly, after reducing waste at the site, priority must then be given to its reuse, recycling, and valorization before opting for its final disposal in landfills (3) (4).

Many European countries and regions have established methods and regulations to foment the collection, evaluation, and reuse of waste in construction (5) (6). In Spain, there is still no national legislation regulating the environmental assessment of secondary materials. Therefore, the environmental agencies of the regional governments in Spain are responsible for regulating the use of secondary materials in roads and other construction applications (3). However, there are sets of technical specifications for construction materials. This is the case of the Spanish General Technical Specifications for Roads and Bridge Works (PG-3) regulates the materials used in road sections profiles (7).

Nowadays, recycled aggregate made from C&D waste offers a viable solution to the problem of waste disposal and environmental pollution. Using this waste also helps to safeguard natural resources, reduce construction cost, and increase the supply of sand and gravel (8) (9). Even though there has been a wide range of studies on the use of recycled aggregate in mortar (10) (11), concrete (12) (13) and precast concrete (14) (15), little research has been done on the use of mixed recycled aggregates in road construction. For example, Jimenez *et al.* (16) showed that recycled aggregate from C&D waste can be used as an alternative to natural aggregate in unpaved rural road construction. Agrela *et al.* (17) studied the use of recycled aggregate from masonry waste as cement-treated recycled aggregate in the construction of the sub-base layers of road surface courses. This waste was used to pave the access ramp to a highway in Malaga (Spain). Studies from Vegas *et al.* (18) and Melbouci (19) can also be highlighted, showing that the application of C&D waste aggregate in road layers contributes to the consolidation of this granular material, as evidenced in the quantity of ceramic fines generated in the crushing process of the ceramic fraction of the recycled aggregate, which improves mechanical resistances. Even though this mixed recycled aggregate is unsuitable for hot mix asphalt because of its poor stripping behaviour (20), the use of recycled brick powder as a replacement for the filler in the asphalt mix was found to have better mechanical properties than limestone filler (21).

In the province of Granada (Spain), a C&D Waste Management Plan has been implemented geared to managing this type of waste. This C&D Waste Management Plan proposed the construction of 16 installations to manage 90% of this waste in the province of Granada. The installations for this purpose consisted of waste treatment and disposal centers, depending on the amount of C&D waste generated. In the case of areas with a waste production greater than 14,000 m^3 per year, the construction of a stationary recycling plant was proposed.

Recycled aggregate for use in construction and other recyclable products (e.g. plastic, wood, and metal) were thus recovered, and the rest of the materials were deposited in landfills. In areas with waste production less than 14,000 m^3 per year, landfills were regarded as the most effective solution for waste disposal.

The aim of this research study is to characterize the mixed recycled aggregates obtained from a C&D waste plant operating in Granada, verifying its potential use in all aspects of road construction. This includes roadbeds (i.e. embankments, backfills, and quarry-run fills) drainage fillers, structural layers (i.e. artificial graded aggregates, lime-stabilized soils, soilcement, and cement-bound gravel) and road surfaces (i.e. prime coats, seal coats, concrete pavement, and lean concrete pavement). In this sense, the PG-3 only recommends the use of recycled aggregates, from C&D waste, in road layers, cement-bound gravel, and lean concrete pavement.

This research will contribute to a more in-depth study on the use of C&D aggregates. Furthermore, the results obtained will provide a basis for the possible modification of current technical standards. This would encourage a more widespread use of recycled aggregate and would also promote secondary markets for this type of waste.

2. MATERIALS AND METHODS

2.1. The C&D waste treatment process

For this study, samples of mixed recycled aggregates were taken from a stationary recycling plant, located in the southern part of the province of Granada (Spain). The

Table 1. Results of properties of recycled aggregates studied

Properties		Fraction 001	Fraction 002	Fraction 003	Fraction 004
Geometrical	Sand equivalent value	-	-	-	69.25±9.75
	Cleanliness				
	Particle shape	No flakiness	No flakiness	No flakiness	No flakiness
	Percentage of crushed particles (%)	100	100	100	100
Physical-mechanical	CBR (%)	81.47±49.74	-	-	-
	Resistance to fragmentation (LA)	-	29±2	-	-
	Free swelling	None	None	None	None
	Plasticity	Non-plastic	Non-plastic	Non-plastic	Non-plastic
Chemical	Water soluble sulfates content (%)	-	-	-	1.52±0.46
	Organic matter content (%)	None	None	None	None

C&D waste treatment process at these installations consists of simple impact crushing, and separation with vibrating screens. Metallic elements are removed by a magnetic conveyor belt, and large impurities, such as plastics, paper, glass, and gypsum are extracted by hand before the crushing process. Three different fractions of recycled aggregate are produced by the plant: 10/50 mm, 6/10 mm, and 0/6 mm. Non-recyclable fractions are deposited in a landfill.

2.2. Sampling program

Our study focused on four mixed fractions from the C&D waste treatment plant. Fraction 001, which was the unselected fraction, was the result of simple impact crushing before the vibrating screen process. The other samples corresponded to the three fractions of recycled aggregate produced by the plant: (i) 002 was a coarse fraction (10/50 mm); (ii) 003 was a medium-size fraction (6/10 mm); (iii) 004 was a fine fraction (0/6 mm). Table 1 shows the state of tests performed. For each one there have been realized three trials per sample in order to obtain an average value.

The samples were collected according to the Spanish Standard UNE-EN 932-1 (22). Since the objective was to obtain a representative bulk sample, a stack sampling procedure was used. Accordingly, sample fractions of similar size were taken from different points, heights, and depths of the stack. Following the procedure described in the UNE-EN 932-2 (23), a laboratory 50 mm sample divider was used to reduce samples, and obtain coarse aggregate, as well as medium and fine fractions.

2.3. Laboratory procedures

The battery of tests run on the aggregate fractions in accordance with PG-3 recommendations were: particle size distribution (24) (25), sand equivalent (26), resistance to fragmentation (27), plasticity (28) (29), CBR value (30), water-soluble sulfates and organic matter content (31).

3. RESULTS AND DISCUSSION

Table 1 summarize the results obtained within the laboratory procedures conducted. Characterization results have been analyzed, according to the specifications of the PG-3, in order to study the feasibility of using the mixed recycled aggregates selected as alternative materials in: roadbeds, drainage fillers, road structural layers and road surfaces.

3.1. Characterization of materials for roadbeds

The PG-3 (7) specifies three types of roadbeds: embankments, backfills, and quarry-run fills. Table 2 summarizes the geometrical, physical-mechanical and chemical properties of materials used in roadbeds.

The technical requirements also include a soil classification system, which defines five levels of soil quality, depending on its organic matter content. This involves testing for water-soluble salts and gypsum content, particle size distribution, liquid limit, plasticity index, normal proctor test and free swelling. These five soil quality groups from the lowest to highest quality are the following: (i) Selected Soils (SS); (ii) Appropriate Soils (AS); (iii) Tolerable Soils (TS); (iv) Marginal Soils (MS); (v) Unsuitable Soils (US). Table 3 summarizes the technical requirements for soil quality. Unsuitable soils are those not included in any of the above categories.

In relation to the soil classification limit values established in the technical requirements (see Table 3), none of the fractions studied could be categorized as Selected and Appropriate Soil because of their high water-soluble salts content (even though they fulfilled the rest of the technical requirements). In addition, fraction 002 did not fulfill the limit for maximum particle size. Despite the fact that the content of total sulfur compounds was not determined, the high values of water-soluble sulfates signify that the content in total sulfur compounds exceeded the PG-3 limits for this type of soil.

Table 2. PG-3 technical requirements for aggregates used in the construction of roadbeds (20)

PG-3 article and application		Soil classification	Particle size distribution	Maximum particle size	CBR
330 Embankment	Crown	Selected Soil (SS) Appropriate soils (AS)	#20>70% or #0.08>35%	-	≥ 5
	Foundation	Selected Soil (SS) Appropriate soils (AS) Tolerable soils (TS)		-	≥ 3
	Core			-	
332 Backfills	-	-	-	-	>10 > 20 backfill for engineering structures
333 Quarry-run fills	-	-	#20>70% or 30%>#0.08>35% #20<30% or #0.08≥10%	< 100 mm	-

Table 3. PG-3 technical requirements for soil used in the construction of roadbeds (20)

Requirements	Soil categories			
	Selected (SS)	Appropriate (AS)	Tolerable (TS)	Marginal (MS)[5]
Organic matter content (OM)	< 0.2 %	< 1 %	< 2 %	< 5%
Water-soluble salts content, including gypsum (SS)	< 0.2 %	< 0.2 %	-	-
Maximum particle size (D_{max})	< 100 mm	< 100 mm	-	-
Percentage of particles passing # 0.4 UNE	≤ 15 % < 75 %[1]	< 80 %	-	-
Percentage of particles passing # 2 UNE	< 80%[1]	-	-	-
Percentage of particles passing # 0.08 UNE	< 25 %[1]	< 35 %	-	-
Liquid limit (LL)	< 30	< 40	< 65	-
Plasticity index (IP)	< 10	> 40[2]	> 0.73 x (LL-20)[3]	> 0.73 x (LL-20)[4]
Free swelling test	-	-	< 3 %	< 5 %

[1] These values are only applicable if the percentage of particles passing # 0.4 UNE is higher than 15%.
[2] This value is only applicable if LL > 30.
[3] This value is only applicable if LL > 40.
[4] This value is only applicable if LL > 90.
[5] This type of soil cannot be included in the other categories, but fulfills the requirements included below.

The soluble salt content in the materials in a roadbed must be limited to prevent possible aqueous dissolutions which might lead to subsidence or loss of roadbed resistance (6). Water-soluble sulfate-based products are common contaminants in C&D waste (32) mainly due to the presence of calcium and sulfate ions associates with gypsum, especially in those aggregates from mixed debris. Manual selection before the crushing process removes large impurities, including gypsum. Nevertheless, since a high percentage of the smaller-size fraction passed into the crushing process, the mean sulfate content of our samples was higher than the percentage established in the PG-3 for water-soluble salts content (including gypsum). In consequence all samples were classified as Tolerable Soil.

When the results of the particle-size distribution of the samples were compared with the PG-3 limits (see Table 2), it was evident that fractions 001 and 002 did not fulfill the limits stipulated for embankments and backfills. In contrast, fractions 003 and 004 met the technical requirements for embankments (# 20> 70%), but not those for backfills.

When the CBR test was performed on fraction 001, the value obtained (81.47±49.74) exceeded the limit value established for embankments (≥ 5 for the crown and ≥ 3 for the foundations and core) and backfills (> 10 and > 20 for the backfilling of engineering structures). In this respect, our results were similar to those obtained in other studies. For example, Vegas *et al.* (6) obtained values of 47% - 107% for granular materials from recycled construction and demolition. The variability of this index could be due to varying quantities of fine particles as well as to the morphology of samples. For example, Poon and Chan (33) concluded that the presence of ceramic materials have resulted in lower values attributed to the lower particle density and higher water absorption and on the other hand Vegas (18) founded that this material could grow the value by the fact that brick particles act by slipping between the coarse grains, which confers to the materials a good compactness and a low water contents (19).

The result of the soil plastic limit test on sample 004 reflected its non-plastic state, which indicated the good performance of this material in relation to water content. Likewise, free swelling parameter was not performed on the samples in our study because the fractions were all coarse-aggregate. However, no swelling after immersion in water was detected in the CBR test development (30).

Fractions 001 and 002 thus fulfilled the requirements for backfills, whereas 003 and 004 could be used in embankments, though only for the core and foundations. However, they could not be used in the crown, which is the most critical layer of an embankment.

3.2. Characterization of materials for drainage fillers

Drainage filler consists of the spreading and compaction of drainage material in ditches, the backfill of engineering structure and any other area whose size does not permit the use of heavy equipment (7). The restrictions on the use of aggregate as drainage material depends on its properties as well as on those of the soil to be drained related on Table 4.

The results obtained for drainage material parameters indicated that none of the fractions tested could be used as drainage fillers. Despite the fact that the fractions fulfilled the requirements for cleanliness, resistance to fragmentation, plasticity and the sand equivalent index, some of the particle size requirements were not fulfilled. More specifically, fraction 001 did not fulfill the requirements related to F15 for all types of soil, as well as the uniformity coefficient of 16 in the case of blind drains. Fractions 002 and 003 did not fulfill the limits related to F15 (20 and 8 respectively) for all types of soils. Finally fraction 004 did not fulfill the limits for maximum aggregate size (8 mm) and the uniformity coefficient of 16 in the case of blind drains (see Table 5).

Cleanliness was a parameter not performed, but the result of plasticity test showed that the samples were non-plastic. Furthermore, their sand equivalent index value of higher than fifty indicated that the aggregates were not contaminated, and confirmed that their cleanliness level was sufficient for most applications (34), and sample 004 an index ranged from 64 to 79.

3.3. Characterization of materials for road structural layers

3.3.1. Artificial road granular structural layers

Graded aggregate can be defined as inert continuous granular material used in pavement layers (7). The PG-3 distinguishes the follow two types of aggregate (20): artificial graded aggregate ZA25, ZA20 and ZAD20, and natural graded aggregate ZN40, ZN25 and ZN20, in order to their particle size distribution.

Table 4. PG-3 technical requirements for aggregates used in the construction of drainage fillers (20)

Properties		Soil types		
		Non-cohesive soils	Cohesive soils	Blind drains
Cleanliness		Absence of clay, marl, organic material, and other foreign substances		
Resistance to fragmentation (LA)		< 40	< 40	< 40
Plasticity		non-plastic	non-plastic	non-plastic
Particle size distribution		#0.08<5%	#0.08<5%	#0.08<5%
Sand equivalent index		>30	>30	>30
Maximum particle size (mm)		< 76	< 76	20-80
Uniformity coefficient (F60/F10)		< 20	< 20	<4
Filter conditions	F_{15} (mm)	< 1	0.1-0.4	-
	F_{15}/d_{85}	<5	-	<5
	F_{15}/d_{15}	>5	-	>5
	F_{50}/d_{50}	<25	<25	<25
F_{85}	Perforated pipes	F_{85}/orifice diameter >1	F_{85}/ orifice diameter >1	F_{85}/ orifice diameter >1
	Open joint pipes	F_{85}/joint opening > 1.2	F_{85}/ joint opening > 1.2	F_{85}/ joint opening > 1.2
	Porous concrete pipes	F_{85}/d_{15} pipe aggregate >0.2	F_{85}/d_{15} pipe aggregate >0.2	F_{85}/d_{15} pipe aggregate >0.2
	Putlog holes	F_{85}/putlog hole diameter >1	F_{85}/ putlog hole diameter >1	F_{85}/ putlog hole diameter >1

Table 5. Percentage of aggregate passing through sieves series UNE EN 933-2 (24) and characteristics of filtering material

	Fraction			
	001	002	003	004
D_1	63	125	16	8
Characteristics of filtering material				
F_{60}	16	40	10	4
F_{10}	1	16	8	0.25
F_{60}/F_{10}	16	2.5	1.2	16
F_{15}	1	20	8	0.4
F_{50}	10	31.5	10	2
F_{85}	31.5	63	16	8

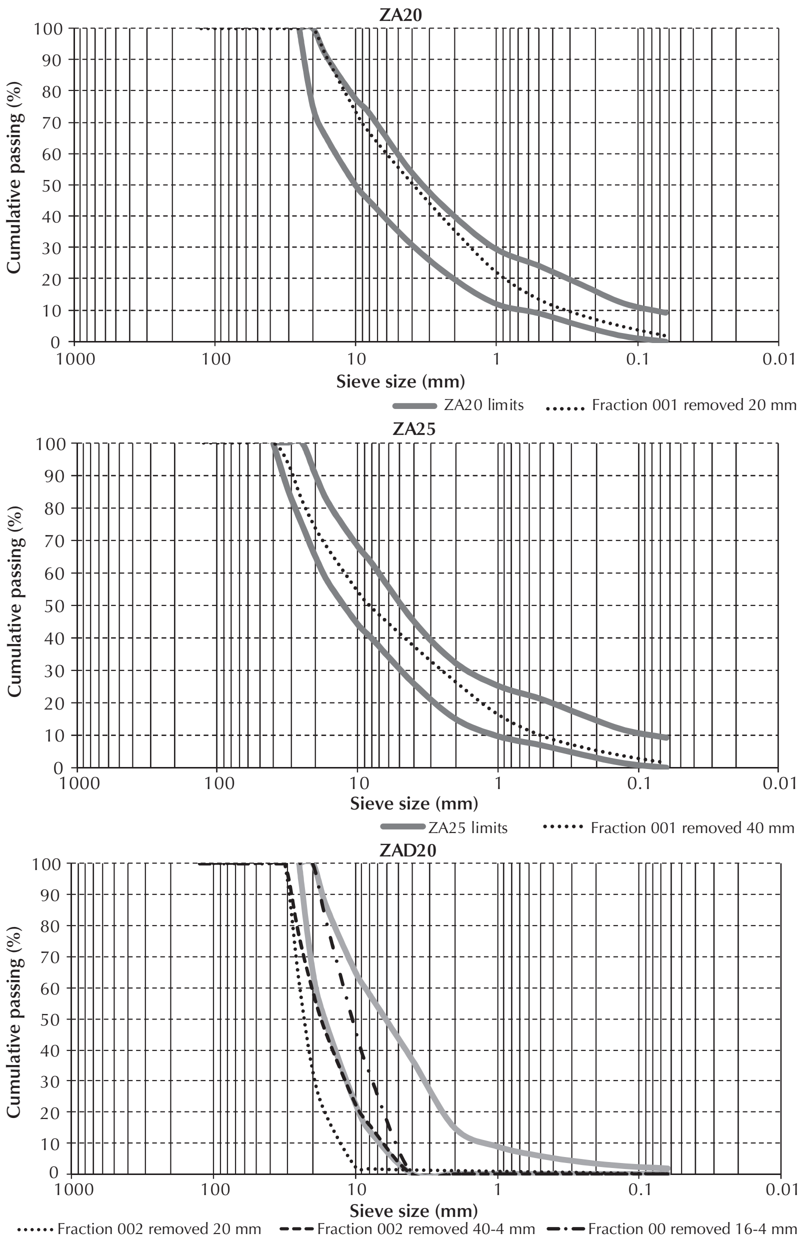
[1] Maximum size of the aggregate (D) is defined as the first sieve opening UNE EN 933-2 retaining more than 10% of the sample (Article 510 of PG-3) (20)

Table 6. PG-3 technical requirements for material used as artificial graded aggregate (20)

Properties		Limit
Sand equivalent value	Heavy traffic (T00-T1)	>40
	T2-T4 and hard shouldersT00-T2	>35
	Hard shoulders T3-T4	>30
Cleanliness coefficient		< 2
Maximum particle size	Base layers	20-25 mm
	Subbase layers	25-40 mm
Shape of particles. Flakiness index		< 35
Percentage of crushed particles (%)	T00-T0	100%
	T1-T2 and hard shoulders T00 and T0	≥ 75%
	Rest of cases	≥ 50%
Resistance to fragmentation (LA)	T00-T2	≤ 35
	T3-T4	≤ 30
Liquid limit (LL)	Hard shoulders T32-T4	< 30
	Rest of cases	Non-plastic
Plasticity index (IP)	Hard shoulders T32-T4	< 10
	Rest of cases	Non-plastic
Total sulfate content (SO_3)	Materials in contact with cement-treated layers	< 0.5%
	Rest of cases	< 1%

Table 7. Type of traffic (20)

Type	T00	T0	T1	T2	T31	T32	T41	T42
Medium Intensity – Daily (vehicles/day)	>4000	3999-2000	1999-800	799-200	199-100	99-50	49-25	<25



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1. Particle size distribution adjustment of samples 001 and 002 for artificial graded aggregates.

Table 6 and Figure 1 show the technical requirements to be fulfilled by such material. Due these applications include limits pertaining to the intensity of vehicle traffic supported by the road, the vehicle traffic classification is shown in Table 7.

The physical and mechanical properties requirements establish limit values for resistance to fragmentation, liquid limit, and the plasticity index. The samples were found to be non-plastic, and the Los Angeles test produced mean values of 29±2, lower than the limit, though one sample exceeded this value for use in roads with T3 and T4 vehicle traffic. This value was similar to the result obtained for other aggregates (35) (36) (37) (38). All samples were found to have a Los Angeles coefficient higher than 20, the typical value of high-quality natural aggregate (37) (39). The presence of ceramic waste and cement mortar attached to the aggregate particles in our samples resulted in a lower resistance to fragmentation (39) (40) (41).

Finally, the PG-3 (7) includes a limit value for sulfate content when the aggregate is to be used in an artificial granular layer. The mean value for all samples (1.52±0.46) exceeded the limit established in the regulations. Since previous studies obtained similar results, this seems to indicate that one of the critical properties of C&D waste for its use as granular material in structural unbound layers are sulfur compounds (6). The concentration of these compounds depends on the raw materials from which the materials are generated. This usually depends on whether the aggregate is composed of rubble segregated at the source. Recycled aggregates from concrete rubble and selected ceramic material show values which, in most cases, are below the limit established in the PG-3. However, aggregates from mixed rubble, generally associated with non-selective demolition (i.e. our samples), tend to have a total sulfur content exceeding the limits in the specifications. These high percentages are due to the presence of gypsum, which is part of the original rubble (6).

Regarding particle size, aggregates should have a maximum size of 20-25 mm for base layers and 25-40 mm for sub-base layers to avoid segregation during the execution of the road work. They should also show a continuous particle size distribution to obtain maximum compactness. Since the maximum sizes of the samples exceeded the limits established, none of the fractions studied fulfilled these requirements. The particle size distribution graphs of the four samples showed that fraction 001 was the sample that came closest to the limits established for ZA20 and ZA25. Nevertheless, a slight adjustment in coarse particle sizes would reduce the maximum particle size, and improve the characteristics of the fraction so as to better comply with particle size distribution requirements. In contrast, fraction 003 was the sample that best fit the limits established for ZAD20, though particle size adjustment would also be necessary to remove particles with larger sizes. Finally fractions 003 and 004 showed a poorer adjustment to particle size distribution requirements for all types of artificial road granular structural layers.

Figure 1 shows the adjustment that would be necessary to make the coarse aggregate fit the three requirements. In order to fulfill the requirements for the ZA20 application, it was found that all particles larger than 20mm should removed from fraction 001. Similarly, for the ZA25 application, all particles larger than 40mm should be removed from fraction 001. Finally, for the ZAD20, particles larger than 16mm and smaller than 4mm should be removed from fraction 002.

PG-3 geometrical technical requirements for aggregates (i.e. sand equivalent, maximum size, cleanliness coefficient, particle shape, and percentage of crushed particles) ensure the stability of the granular layer as well as the compactness and resistance to deformation of granular aggregates. On the one hand, the aggregates should be free of lumps of clay, loam, organic matter, or any other substance that could affect their durability. Consequently, limit values for sand equivalent and the cleanliness coefficient are stipulated in the PG-3. On the other hand, a high percentage of crushed particles and a low percentage of flakiness particles are also required. A high sand equivalent value (69.25±9.75) and the absence of organic matter content ensure clean aggregates. Since the samples studied were produced in a recycling plant with an impact mill, the particles tended to break into small blocks without generating slabs. This meant that it was entirely composed of crushed particles. In consequence, all samples fulfilled the limits established for geometrical properties.

It was possible to conclude that the critical properties for using recycled aggregates as artificial granular structural layers were particle size distribution and sulfate content. It was found that particle size distribution adjustment in the production process of recycled aggregates at the plant could improve the particle size of samples, especially in the case of the larger fractions (001and 002) (Figure 1). Furthermore, rubble segregation at the source or a manual selection process, before phase crushing at the treatment plant, could remove a high percentage of gypsum, associated with covering and decoration elements, from the original rubble.

3.3.2. On-site soil stabilization

Soil stabilization is defined as a process that improves a soil's resistance to deformation and durability, and decreases its susceptibility to water (7). This stabilization process can be mechanical (mixing soils of different types) or chemical (by adding substances such as lime and cement). Chemical stabilization is the most frequently used method (34). The technical requirements for stabilizing soils pertain to plasticity, organic matter content, and total soluble sulfates content are shown on Table 8.

Table 8. PG-3 technical requirements for aggregates used in soil stabilization (20)

Properties	Stabilization with lime			Stabilization with cement		
	S-EST1	S-EST2	S-EST3	S-EST1	S-EST2	S-EST3
Organic matter content (%)	< 2	< 1	< 1	< 2	< 1	< 1
Water-soluble sulfate content (%)	< 1	< 1	< 1	< 1	< 1	< 1
Plasticity index	≥12	12-40	-	-	≥40	≥40
Liquid limit	-	-	-	≥15	≥15	≥15

The samples studied did not contain any organic matter. However, none of the fractions fulfilled the plasticity limits. All the samples were non-plastic, but the PG-3 establishes minimum values for the plasticity index and the liquid limit (see Table 8). The soluble sulfate content (1.52±0.46) also exceeded the limit established (< 1%).

The particle grain-size limits established for soil stabilization with lime were not fulfilled in any cases. On the one hand, fractions 001 and 002 showed a percentage of particles passing # 80 mm below the 100% set. On the other hand, the percentage of particles passing # 0.063 mm was lower than the established limit (15%) for all the samples. However fractions 003 and 004 fulfilled the particle size distribution for the three types of soil (S-ST1, S-ST2, S-ST3) in the case of cement-stabilized soil. Fractions 001 and 002 showed percentages of particles passing # 80 mm lower than the established limit (100%).

This indicated that the samples were not suitable to be used in stabilized soil since they showed unsatisfactory values for all properties except organic matter content.

3.3.3. Cement-soil and cement-bound gravel

Aggregate treated with cement is a homogeneous mixture in the right proportions of granular material, cement, water, and in some cases, additives in order to make the mineral skeleton of the soil more cohesive (7). The requirements define the following two types: soil-cement SC40 and SC20 and cement-bound gravel GC25 and GC20.

Article 513 of the PG-3 describes granular materials that can be used for such purposes specifying the applicability of recycled aggregates from construction waste and demolition. It also distinguishes two types of granular materials (7): fine aggregate and coarse-grained aggregate. Since the samples in this study were classified as coarse-grained aggregate, only the limits for this type of fraction were analyzed. The technical requirements for soil-cement and cement-bound gravel pertain to particle size distribution, as well as to geometrical, physical-mechanical, and chemical properties (Table 9).

In relation to geometrical properties, coarse aggregates used in cement-bound gravel should fulfill the limit values for the sand equivalent index, cleanliness coefficient, particle shape, and percentage of crushed particles. In the case of soil-cement, the cleanliness coefficient limit value is included. A high sand equivalent value (69.25±9.75) and the absence of organic matter ensure clean aggregates. Since the samples studied were produced in a recycling plant with an impact mill, particles tended to break into small blocks without generating slabs. This ensured that 100% of the particles were crushed particles. Consequently, all samples fulfilled the limits established for geometrical properties.

Values for the liquid limit and plasticity index were included for coarse aggregates or for cement-bound gravel and soil-cement. In the case of cement-bound gravel, a limit value for resistance to fragmentation was also included.

Finally total sulfate and organic matter content should be lower than 1% for cement-bound gravel and soil-cement. Although all the samples were characterized by an absence of organic matter, the high water-soluble sulfate content (1.52±0.46) meant that the total sulfate content was higher than the limit in the original rubble.

The particle-size distribution graphs of the four samples show that fraction 001 was the sample that best fit the limits established for SC40, GC25 and GC20, and that fraction 004 best fit the limits established for SC20. However a slight adjustment in

Table 9. PG-3 technical requirements for aggregates used in cement-bound gravel and soil-cement (20)

Properties			Cement-bound gravel	Soil-cement
Sand equivalent value	GC20		>40	-
	GC25		>35	
Cleanliness. Percentage of clay lumps (%)	Coarse aggregate[1]		< 0.25	-
	Fine aggregate[2]		< 1	
Particle shape. Flakiness index	Roads	T00-T2	< 30	-
		T3-T4	< 35	
	Hard shoulders	In all cases	< 40	
Percentage of crushed particles (%)	Roads	T00-T1	≥ 75	-
		T2	≥ 50	
		T3-T4	≥ 30	
	Hard shoulders	T00-T2	≥ 50	
		T2-T4	≥ 30	
Liquid limit	T00-T2		Non-plastic	< 30
	Rest of cases		< 25	
Plasticity limit	T00-T2		Non-plastic	< 15
	Rest of cases		< 6	
Resistance to fragmentation (LA)	Roads	T00-T2	≤ 30	-
		T3-T4	≤ 35	
	Hard shoulders	In all cases	≤ 40	
Total sulfate content (%)			< 1	< 1
Organic matter content (%)			< 1	< 1

[1] Coarse-grained aggregate, defined as the portion of the total aggregate retained by the 4 mm sieve of UNE-EN 933-2 (24).

[2] Fine aggregate, defined as the portion of total aggregate passing by this sieve

coarse particle sizes would be necessary to improve the characteristics of fraction 001 in accordance with size distribution requirements. Fraction 001 would have been a good fit if SC40 sizes larger than 40 mm had been eliminated, although a defect in particle sizes between 4 and 16mm was detected. In the case of GC25, the removal of particles larger than 31.5 mm provided the best fit within the established limits. Finally, in the case of GC20, the removal of particles larger than 16mm for fraction 001 would be necessary to fulfill technical requirements (see Figure 2).

It was possible to conclude that the critical properties for using recycled aggregates as soil-cement and gravel-bound cement were particle size distribution and sulfate content. On the one hand, a particle size distribution adjustment in the production process of recycled aggregates in the plant could improve the particle size of samples, especially in the case of larger particles for fraction 001. On the other hand, the rubble segregation at the source or a manual selection process, before phase crushing in the plant, could remove a great percentage of gypsum associated with covering and decoration elements from the original rubble.

3.4. Characterization of materials for road surfaces

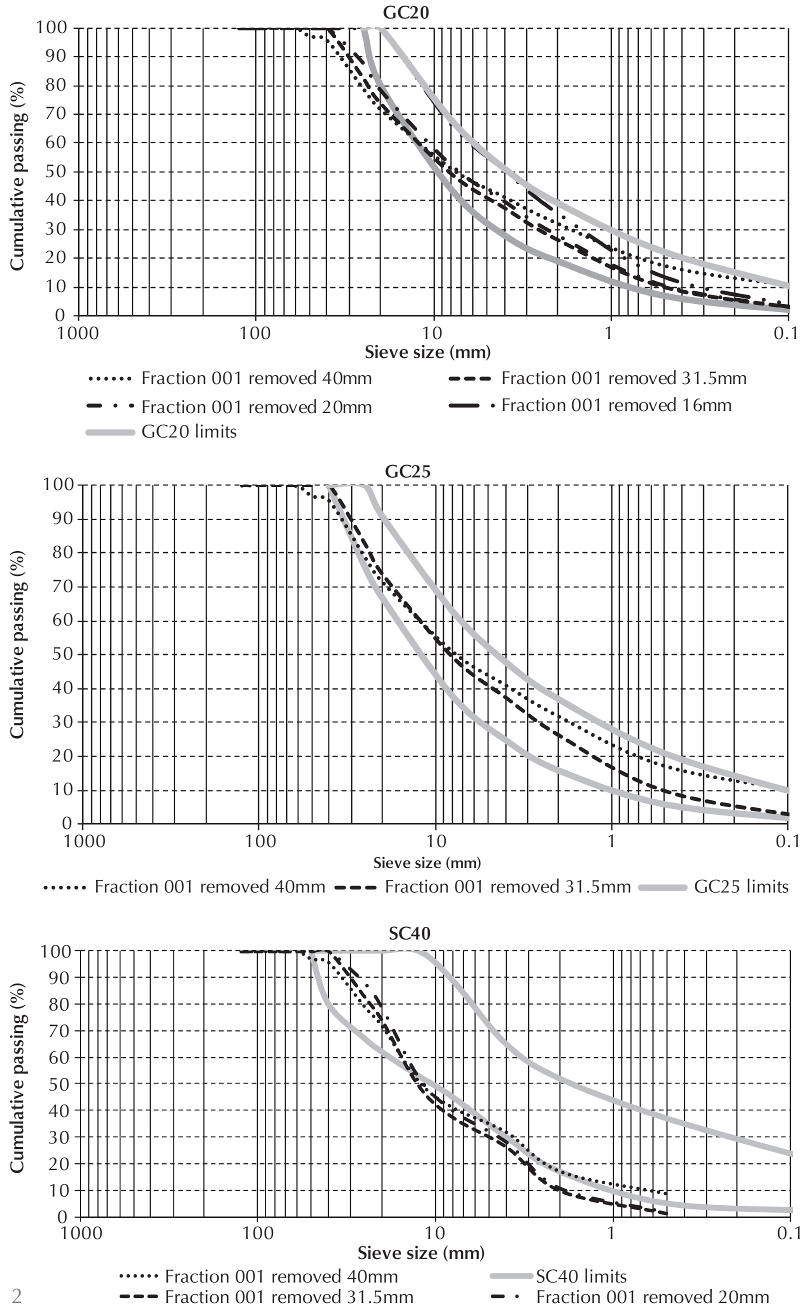
3.4.1. Prime coats and seal coats

A prime coat can be defined as the application of hydrocarbonate binder to a granular surface before an asphalt layer or surface course is spread over it (7). A seal coat is a thin asphaltic treatment on pavement layers treated with hydraulic conglomerate to make the surface impermeable.

The aggregate eventually used for prime coats and seal coats should be free of dust, dirt, clay lumps, vegetation, and other impurities. It should have a sand equivalent index higher than 40, and be non-plastic. In addition particles should be smaller than 4 mm, and the percentage of particles passing #0.063 mm should be lower than 15% (see Table 10).

Removing particles smaller than 4mm in fraction 004 would make it possible to obtain a fraction suitable for prime coats and seal coats, inasmuch as the maximum size would be smaller than 4mm and the percentage of particles smaller than 0.063mm would be 4.84%.

Since the materials studied were classified as coarse-grained aggregate, it would be necessary obtain a new fraction in the C&D waste plant with a more suitable particle size distribution. Regarding other features, the fine fraction of sample 004 had a sand equivalent index greater than 40 (69.25 ± 9.75) It was also non-plastic, and free of dust, dirt, clay lumps, and impurities. This indicated that reclassification of the fraction 004 in the plant would provide material suitable for prime coats and seal coats.



2

2. Particle size distribution adjustment of sample 001 cement soils and cement bound gravel.

Table 10. PG-3 technical requirements for aggregates used in prime coats and seal coats (20).

Property	Prime coat	Seal coat
Percentage of particles passing #4 mm sieve	100	100
Percentage of particles passing #0.063 mm sieve	< 15	< 15
Plasticity	Non-plastic	Non-plastic
Sand equivalent value	>40	>40
Cleanliness	Absence of clay, marl, organic material and other foreign substances	

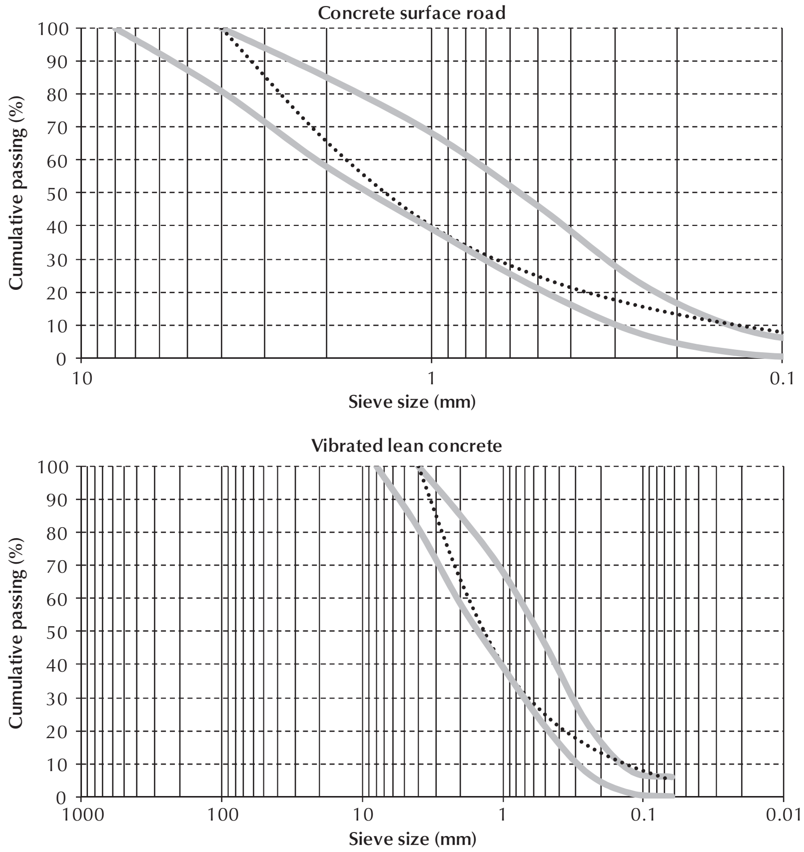
Table 11. PG-3 technical requirements for aggregates used in concrete pavement PG-3 (20)

Property	Concrete pavement		Vibrated lean concrete pavement	
	Coarse aggregate	Fine aggregate	Coarse aggregate	Fine aggregate
Sand equivalent value	-	>75 >80 frozen		>75 >80 frozen
Maximum particle size	< 40 mm		< 40 mm	
Particles shape. Flakiness index	< 35		<35	
Resistance to fragmentation (LA)	< 35		<35	

3.4.2. Concrete pavements

The PG-3 defines cement pavement as pavement composed of mass concrete slabs separated by transverse joints or by a continuous reinforced concrete slab, in both cases with longitudinal joints. It also defines vibrated lean concrete as the homogeneous mix of aggregates, cement, water, and additives used in base layers underlying concrete pavement. When it is applied at the road construction site, its consistency is such that internal vibrators are needed for its compaction (7). In this case, the regulations state that it is possible to use recycled aggregate.

Articles 550 and 551 of the PG-3 describe the granular materials that can be used for such purposes, and specify the applicability of recycled aggregates from construction waste and demolition. It also distinguishes two types of granular materials: fine aggregate and coarse aggregate. The technical requirements established for pavements made of concrete and vibrated lean concrete pertain to particle size distribution (including maximum particle size), geometrical properties (sand equivalent index and particle shape), and physical-mechanical properties (resistance to fragmentation) (Table 11).



3. Particle size distribution adjustment of sample 004 for concrete pavements and vibrated lean concrete.

In relation to technical requirements for coarse aggregates, the maximum particle size of fractions 003 and 004 fulfilled the limit established for pavements made of concrete and vibrated lean concrete since they showed values of 16 and 8 mm, respectively. Fractions 001 and 002 showed values of 63 and 125 mm, which were higher than the limit (< 40 mm) in both cases. Since our samples, were produced in a recycling plant with an impact mill, this meant that particles tended to break into small blocks without generating slabs. This guaranteed that 100% of the particles were crushed particles. In consequence, all samples fulfilled the limits established for geometrical properties. Finally, the Los Angeles test showed mean values (29±2) that were lower than the limit of 35 in both cases. This indicated that fractions 003 and 004 could be used in pavements made of concrete and vibrated lean concrete. In the case of samples 001and 002, maximum particle size of the recycled aggregates was not suitable although a particle sieve distribution adjustment in the production process of recycled aggregates in plant could improve this property.

In relation to the technical requirements for fine aggregates, only fraction 004 was considered since it corresponded to the definition of this type of aggregate. Its particle size distribution indicated that with a slight adjustment, a new fraction could be obtained at the C&D waste plant that would be more in consonance with the distribution established for this use (Figure 3). However, the most unsatisfactory property of this fraction was the sand equivalent index, whose value was lower (69.25 ± 9.75) than the limits established for fine aggregates in pavements made of concrete and vibrated lean concrete. It was thus possible to conclude that sample 004 could not be used for this purpose.

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4. CONCLUSIONS

1. This research studies the use of recycled aggregates from a C&D waste treatment plant located in the province of Granada (Spain), in road construction. Although this is one specific case, the results obtained were similar to those from other studies. Thus, the conclusions drawn can be extrapolated to aggregates presenting similar characteristics.

2. Although there are various studies on the use of recycled aggregates in road construction, these are mainly limited to low-level applications, such as the construction of sub-base layers and unpaved rural roads. Therefore, the suitability of recycled aggregates in other applications as listed in the Spanish General Technical Specifications for Roads and Bridge Works (PG-3) has been analyzed.

3. The mixed recycled aggregate fractions, analyzed according to the PG-3, presented similar geometric, physical-mechanical, and chemical properties, to those aggregates studied in previous research studies. However, these materials characterized as Tolerable Soils, did not fulfill all the PG-3 requirements for road construction, especially in relation to their particle-size distribution and sulfate content.

4. The Spanish standard recommends the use of recycled aggregates in road layer, cement-bound gravel, and lean concrete pavement. However, recycled aggregates could be apt for further road construction applications, such as prime coats, seal coats, soil-cement, and roadbeds, by modifying the manufacturing process in order to adjust the particle-size distribution and by removing the gypsum waste before the crushing process at the plant. Furthermore, on-site sorting of gypsum waste during construction or demolition processes will contribute to a higher quality of the recycled aggregates.

5. The use of recycled aggregates from C&D waste is of particular interest in order to provide a viable solution to the environmental problems derived from waste disposal. Using recycled aggregates also help to safeguard natural resources, reduces construction cost and increases the supply of sand and gravel.

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