Feasibility study of roller compacted concrete with recycled aggregates as base layer for light-traffic roads~~Feasibility study of roller compacted concrete with recycled aggregates from CDW to form a base layer for light-traffic roads~~

Commented [ALU1]: Título sugerido por el editor de la revista.

A. Lopez-Uceda[1], J. Ayuso[1,*], J. R. Jiménez[1], A. P. Galvín[1] & I. Del Rey[1]

[1]*Construction Engineering. University of Cordoba.UCO-Ed. Leonardo Da Vinci - Campus of Rabanales, 14071 - Cordoba, Spain*

[(*)] Corresponding author: Tel.: +34 957 218452; fax: +34 957 218550. E-mail address: ir1ayuje@uco.es (Jesús Ayuso).

Abstract

This research aims to produce roller compacted concrete (RCC) using recycled aggregates (RAs) from construction and demolition waste (CDW) with low cement content. Previous research has confirmed that RA performs favourably when applied to a road base layer as a granular material or as a cement-treated granular material. In addition, previous studies have made progress in analysing the feasibility of using RCC with different types of RA, such as recycled concrete aggregate (RCA) and recycled pavement aggregate (RPA). Under this framework, we determined the feasibility of using RCC with a 100% coarse RA incorporation ratio and low cement content in the base layer of light-traffic roads. For that purpose, two series of RCC mixtures were produced with different cement contents: 150 and 250 kg/m^3. Each series consisted of RCC mixtures with three different types of RA, specifically, one RCA and two mixed recycled aggregates (MRA). The percentage of ceramic particles in the RA ranged from 2.5 to 23.4%. The mechanical properties (e.g., the compressive strength, splitting tensile strength and elastic modulus) and drying shrinkage were studied in the RCC specimens produced. The results support the feasibility of using RCC with a 100% coarse RA incorporation ratio and low cement content to form light-traffic-road base layers, such as residential streets, sidewalks and bike lanes.

Commented [ALU2]: El revisor 3 indica que : **"The results of the physical and mechanical properties obtained in the most relevant research are not reflected in the abstract"**

Words: 4764

1. Introduction

In the European Union, waste resulting from the construction sector, i.e., construction and demolition waste (CDW), composed approximately one-third of the 800 million tonnes of waste in 2012 (European Commission, 2012). The European recycling policy, Directive 2008/98/CE, mandates that countries must re-use, recycle and recover at least 70% of CDW by weight by 2020. The recycling rate, determined by the percentage of total produced CDW that is processed as recycled aggregate (RA), ranges between 10% and 90% in European countries (EU-27), corresponding to a mean value of less than 50%. Spain is one of the countries with the lowest recycling rate of less than 15% (European Commission, 2011). The use of RA has been promoted as a priority to ensure that this rate increases.

Worldwide demand for the second most exploited natural resource, construction aggregate, is expected to increase at a rate of 5.2% annually in 2019 (Fredonia Group, 2016). The use of RA in civil projects reduces construction aggregate consumption and solves other problems associated with construction, such as landfill disposal.

Two major types of RA are characterised by the nature of its constituents: recycled concrete aggregate (RCA) must contain Portland cement-based fragments and natural unbound aggregates in a minimum proportion of 90% by mass, and mixed recycled aggregate (MRA) must contain less than 30% of masonry rubble (Agrela, 2011). In Spain, RCA and MRA represent approximately 15% and 80% of the total produced RA, respectively (GERD, 2012).

The use of RA in civil projects is diverse. Jiménez (2013), Cardoso (2015) and Vieira (2016) have each reviewed the various RA geotechnical unbound applications, such as backfilling, base and sub-base layers on roads and pavement on unpaved roads, highlighting the feasibility of its use.

Other applications of RA exist, such as cement-treated granular material (CTGM) ~~or incorporated aggregate in concrete manufacturing~~. Within CTGM ~~three~~two types of materials are distinguished: soil-cement (SC) and~~,~~ gravel-cement (GC), both with a cement content ranging between 3% and 7% ~~and rolled compacted concrete (RCC)~~. Xuan et al. (2012) determined that the mechanical properties of SC~~CTGM~~ improved as the cement amount used and compaction degree increased and as the RA ceramic content decreased. Del Rey et al. (2016) studied the feasibility of using ~~CTGM consisting of a~~the fine fraction of MRA and RCA treated with cement as a road base layer. The Spanish General Technical Specifications for Road Construction (PG-3) called this material soil-cement 20 mm (SC-20). The differences between the two types of RA (MRA and RCA) used in SC~~soil-cement~~ ~~CTGM~~ manufacturing were compared in terms of their mechanical and durability performance; that study found that there was no statistically significant difference between the two. Agrela et al. (201~~2~~4) conducted a study of a practical application that used a MRA (fine and coarse fraction) treated with cement~~-based CTGM~~ as the base layer in the construction of a road in Málaga (Spain), PG-3 ~~,~~called this material soil-cement 40 mm (SC-40). ~~CTGM containing~~ MRA treated with cement exhibited favourable mechanical behaviour, which was confirmed by continuing satisfactory performance of this infrastructure after two years. Grilli et al. (2013) incorporated reclaimed asphalt as aggregate in SC20, obtaining a general weakening in indirect tensile strength and unconfined compressive strength respect to those SC produced with natural aggregates.

Silva et al. (2015a, 2015b), through an extensive literature review, concluded that the compressive and tensile strength decreases as the RA content incorporated into concrete increases; the magnitude of the decrease depends on the RA type, size and origin.

A use of RA in civil applications that, to our knowledge, has not been widely studied is roller-compacted concrete (RCC), which is a mixture of water, cement and aggregate (fine

Commented [ALU3]: He incluido este artículo pq es del RM&PD. Tb he encontrado este artículo, que es del RM&PD que podría ser interesante, pero no lo encuentro en internet. Nguyen, M. L., Balay, J. M., Di Benedetto, H., Sauzeat, C., Bilodeau, K., Olard, F., ... & Bonneau, D. (2017). Evaluation of pavement materials containing RAP aggregates and hydraulic binder for heavy traffic pavement. *Road Materials and Pavement Design*, *18*(2), 264-280.

Commented [JAM4]: Debes decir que tipo de material era.

and coarse fraction), placed with compacting equipment, is commonly defined as "zero-slump" concrete consolidated by roller-compaction methods. The amount of cementitious material recommended for RCC ranges between 208 and 356 kg/m^3, corresponding to 10% and 17% of dry mass of aggregates, respectively (ACI Committee 325, 2001). RCC has been widely used for sub-base and concrete pavement construction. Its use reduces the cost of transporting, placing, and compacting concrete. It has also been used for building commercial parking areas, industrial storage facilities, parking pavements, container ports and dock storage areas (Gao et al., 2006, Yerramala and Baku, 2011).

The studies conducted on the hybrid RA-RCC mixture have focused on the incorporation of recycled pavement aggregate (RPA). Settari et al. (2015) found that RPA incorporation in RCC degraded the mechanical properties with respect to a control mixture, which is consistent with the results of Modarres and Hosseini (2014), Fakhri and Amoosoltani (2017) and Abut and Yildirim (2017). Researchers such as Modarres and Housseine (2014) studied the influence of RPA and rice husk ash on RCC, varying the cement content between 9% and 14%. Others, such as Vahedifard et al. (2010), studied the effects of various binder mixes on RCC with a content of approximately 235 and 275 kg/m^3 cementitious material content.

López-Uceda et al. (2016) studied the use of RCA as a coarse fraction of RCC. The study found that RCC with 175 kg/m^3 with full incorporation of RCA could be used as a base layer in urban area roads, while RCC at 250 kg/ m^3 and a 50% ratio of incorporated RCA could be applied to road bases with higher resistance requirements. Courard et al. (2010) found that the maximum solid compactness varies between 250 and 175 kg of cement per m^3 in RCC mixtures with full coarse RCA replacement. The authors also found that the 7-day compressive strength for a maximum contribution of a unit quantity of cement corresponded to the mixture with an RCC content of 200 kg/m^3.

~~The studies conducted on the hybrid RA-RCC mixture have focused on the incorporation of recycled pavement aggregate (RPA). Settari et al. (2015) found that RPA incorporation in RCC degraded the mechanical properties with respect to a control mixture, which is consistent with the results of Modarres and Hosseini (2014) and Fakhri and Amoosoltani (2017). Researchers such as Modarres and Housseine (2014) studied the influence of RPA and rice husk ash on RCC, varying the cement content between 9% and 14%. Others, such as Vahedifard et al. (2010), studied the effects of various binder mixes on RCC with a content of approximately 235 and 275 kg/m^3 cementitious material content. The amount of cementitious material recommended for RCC ranges between 208 and 356 kg/m^3, corresponding to 10% and 17% of dry mass of aggregates, respectively (ACI Committee 325, 2001).~~

The target of the present research is to study the feasibility of using MRA ~~different types of RA (one RCA and two MRA)~~ as a full replacement for the coarse fraction of RCC with two low and different cement contents (150 and 250 kg/m^3) to form base layers for light-traffic roads, such as bike lanes, residential streets and sidewalks~~.~~. The ~~two types of RA, called~~ MRA, ~~(RCA and MRA)~~ used in the present study are the most widely produced by Spanish CDW plants, and to the best of the authors' knowledge, there has not been studied the MRA incorporation in RCC. ~~.~~ Thus, it is imperative to incorporate these materials to diversify their technical applications.

2. Materials

2.1. Cement

Portland cement (CEM II/A-V 42.5 R) with a fly ash content of 17% was used in this investigation. The fly ash ~~cement~~ incorporated to the cement used was produced from the emissions of a local coal-fired power plant. The fly ash content in RCC generally ranges from 15% to 20% of the cement composition (ACI Committee 325, 2001). The properties of the cement are shown in Table 1.

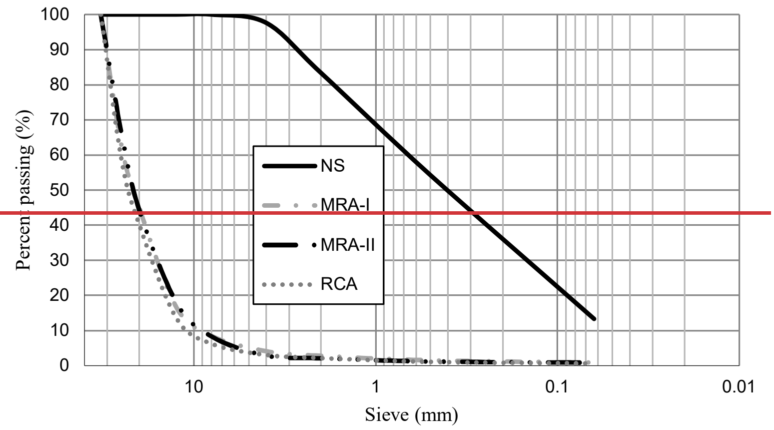
2.2. Aggregates

As coarse fraction, four different aggregates were used;Two RA were used in this study as a coarse fraction from a CDW treatment plant of Andalusia (southern Spain); one natural limestone coarse aggregate (NG) in the range 8-32 mm from crushed rocks; one RCA, whose origin was primarily from concrete demolition, and two different MRA (MRAI and MRAII), which were obtained via the demolition of residential buildings. The RA used came from a nearby CDW treatment plant and their The size range were of the three RA used was 8-32 mm. NG and RCA aggregates were used to contrast the results. As fine fraction; a Natural limestone sand (NS) was used as a fine fraction, with a maximum size of 4 mm. . The particle size distributions of the aggregates used are shown in Figure 1.

[t]Figure 1 near here[t]

Commented [ALU5]: Habría que indicar que el NG y el RCA se han usado para contrastar los resultados.

Commented [JAM6]: Yo pondría un solo material que sería la combinación de las dos granulometrías



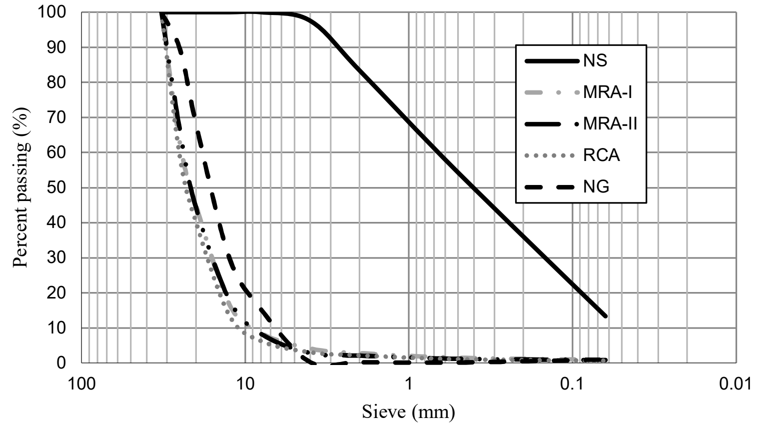


Figure 1 - Particle size distribution

Table 2 shows the key properties and compositions of the aggregates. The two MRA (MRA-I and MRA-II) presented a lower-surface saturated density and higher water absorption relative to the RCA. The water-soluble and acid-soluble sulphate contents of the RCA and the two MRA complied with Spanish Code specifications (Ministry of Development, 2015). NG y NS presented usual properties to natural aggregates.

Table 1. Main physical and chemical properties, and composition of aggregates used.

Properties	NG	RCA	MRAI	MRAII	NS	Test methods

Commented [ALU7]: Había pensado en poner lo siguiente.

The percentages of ceramic particles in the RA were, 2.5%, 11.4% and 23.4% corresponding to RCA, MRAI and MRAII respectively. Despite of the fact that RA usually presents heterogeneous composition, the RA studied in our research were representative in terms of its ceramic composition of the RA produced in Spain.

Habría que usar alguna referencia que justificara esto … es sólo una idea..

Esto no lo ha revisado Jesús

Commented [JAM8]: Idem a anterior comentario un solo material

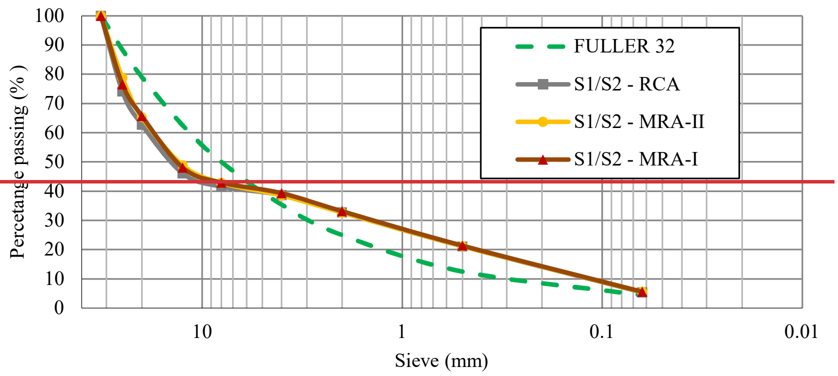
Dry density (g/cm^3)	2.63	2.22	~~2.~~2.16	~~2.~~2.08	~~2.~~2.61	UNE - EN 1097 – 06:2014
Water absorption (%)	0.8	6.1	7.4	9.2	0.9	UNE - EN 1097 – 06:2014
Los Angeles abrasión test		36.6	35.3	37.0	-	UNE - EN 1097-2:2010
Flakinesss index		5.7	9.4	14.3	-	UNE - EN 933-3:2012
Total sulphur content (% S)	0.1	0.6	0.5	0.6	0.1	UNE - EN 1744-1:2013
Composition (%)						UNE-EN 933-11:2009
Bituminuos		1.7	1.5	1.1	-	
Ceramic particles		2.5	11.4	23.4	-	
Concrete and mortars		58.7	55.3	50.8	-	
Natural aggregates	100	36.8	31.4	24.1	100	
Gypsum		0.0	0.1	0.2	-	
Others (Wood. glass. plastic and metals)		0.2	0.3	0.4	-	

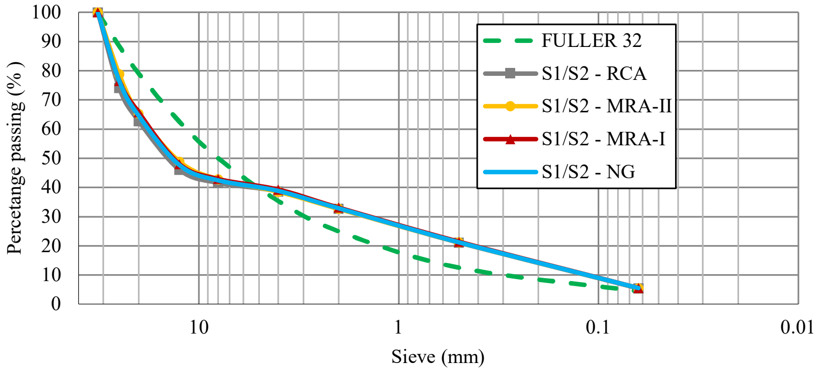
[t]Table 1 near here[t]

2.3. Dosage and mixing process

The aggregate gradation of the mixtures was determined by approximating them by a Fuller curve to seek the maximum compactness in the aggregate mixture and to fill the voids of the granular skeleton (Figure 2).

Figure 2 - Fuller and mixtures distributions.





[t]Figure 2 near here[t]

Two different series were produced, one for each cement content used (150 and 250 kg/m^3). The proportions of the 6 RCC mixtures produced and their designations are listed in Table 2. To determine the water necessary to produce the RCC mixtures, the Proctor Modified was carried out for each mixture, explained in 3.1. section. The water content required were higher as the amount of ceramic content increased in each serie. The serie with a cement content of 250 kg/m^3 demanded more water than the serie with 150 kg/m^3.

Table 2 - Composition of the mixtures

	Proportions								
	NS		NG		RCA		Cement		Water
Samples	(kg/m^3)	(%)*.*	(kg/m^3)	(%)*.*	(kg/m^3)	(%)*.*	(kg/m^3)	(%)	(kg/m^3)
S1-NG	792.0	35.2	1305.0	58.0			150	6.8	139.9

S1-RCA	765.2	35.1			1264.4	58.0	150	6.9	152.6
S2-NG	729.6	32.0	1299.6	58.0			250	11.1	148.2
S2-RCA	700.6	31.7			1259.7	57.0	250	11.3	163.5

. percentage of the element respect to total dry mass

~~Table 2 - Composition of the mixtures~~

	Proportions								
	NS		MRA-I		MRA-II		Cement		Water
Samples	(k~~K~~g/m^3)	(%)*.*	(k~~K~~g/m^3)	(%)*.*	(k~~K~~g/m^3)	(%)*.*	(k~~K~~g/m^3)	(%)	(k~~K~~g/m^3)
~~S1-RCA~~	~~765.2~~	~~35.1~~	~~-~~	~~-~~	~~-~~	~~-~~	~~150.0~~	~~6.9~~	~~152.6~~
S1-MRAI	752.5	35.0	1247.0	58.0	-	-	150~~.0~~	7	176.3
S1-MRAII	732.9	34.9	-	-	1208.0	58.0	150~~.0~~	7.1	180.6
~~S2-RCA~~	~~700.6~~	~~31.7~~	~~-~~	~~-~~	~~-~~	~~-~~	~~250.0~~	~~11.3~~	~~163.5~~
S2-MRAI	686.7	31.5	1242.6	57.0	-	-	250~~.0~~	11.5	161.3
S2-MRAII	661.4	31.2	-	-	1208.4	57.0	250~~.0~~	11.8	175

. percentage of the element respect to total dry mass

[t]Table 2 near here[t]

The scheme of the mixing procedure is presented in Figure 3.

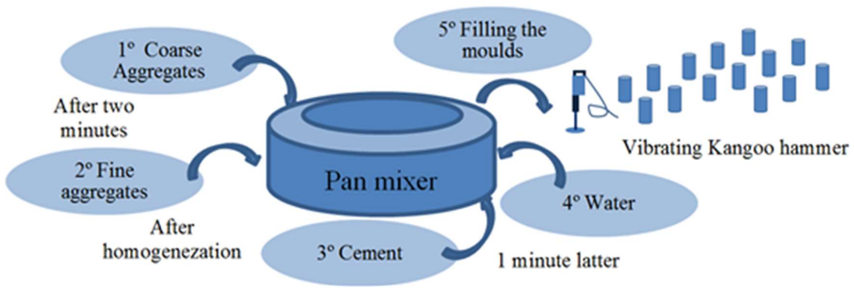


Figure 3 - Mixing procedure.

[t]Figure 3 near here[t]

3. Experimental tests

3.1. Compaction tests

An analysis of the mixture compaction characteristics was performed according to the UNE-EN 13286-2:2011 modified Proctor test. A cylinder mould (Ø 152.5 × 129.8 mm) was used. The relationship between the moisture and dry density was obtained.

The compaction time for all specimens was calculated using a vibrating Kango hammer in accordance with the Spanish Standard 310/90 NLT. The specimens were compacted using the optimum moisture content determined through the modified Proctor test. Different compaction energies were applied by varying the time of application of the load exerted by the vibrating hammer (5, 12 and 20 seconds). Compaction was applied in three layers in a Ø 152.5 × 129.8 mm Proctor mould. The vibrating hammer time sufficient to produce 98% of the maximum dry density obtained in the modified Proctor test was obtained.

3.2. Mechanical property tests in hardened RCC

The mechanical tests were conducted using cylinder moulds (Ø 150 × 300 mm). The compressive strength and the splitting tensile strength tests were performed according to UNE-EN 13286-41:2003 and UNE-EN 12390-6:2010, respectively. For each test, six moulds were filled in five layers, and each layer was compacted with the previously calculated optimal vibrating hammer time (Mardani-Aghabaglou and Ramyar, 2013). After approximately 24 hours, the specimens were demoulded and stored in a moist chamber at 18-22 °C and a relative humidity above 95%. After 7, 28 and 90 days, three specimens were tested for each curing age.

The development of the elastic modulus in the RCC mixtures was investigated using the stress-strain relationships of the mixtures in the strength tests and identifying the tangent of the modulus of elasticity obtained according to UNE 83316:1996. For this test, each of the three specimens was stored for 28 days prior to the testing under the aforementioned conditions.

3.3. Drying shrinkage

To study the drying shrinkage, specimens were manufactured in cylindrical moulds

(Ø 150 × 300 mm) in the same way as in mechanical property tests. After 24 hours, after the specimens were demoulded, six generatrixes were drawn at 60°, and the specimens were stored in a dry chamber at 22-25 °C and 46-54% relative humidity. The evolution of height over time was measured in each generatrix using a digital sliding gauge with an accuracy of ±0.005 mm. The height of each specimen was determined at 7, 28, 56 and 90 days as the average of the six generatrix measurements (Agrela et al., 2014). Each reported result represents the average of two specimens.

4. Results and discussion

4.1. Compaction tests

The maximum dry density and its corresponding optimum moisture for each mixture are presented in Table 3. The maximum dry density values ranged from 2.28~~1~~ to 2.10 g/cm^3. The highest values of maximum dry density are matched to the mixes produced with NG, ~~RCA~~. The results show that the higher the ceramic particle content, the more water is required and the lower the maximum dry density. These results agree with certain results reported by Xuan (Xuan et al., 2012, and Xuan et al., 2014). In addition, the observations suggest that the series S2 mixtures exhibit a higher maximum dry density than the S1 mixtures, likely because of the greater cement amount; these results agree with those of Hazaree et al. (2011), who obtained an increase in dry density with increasing cement content up to 300 kg/m^3.

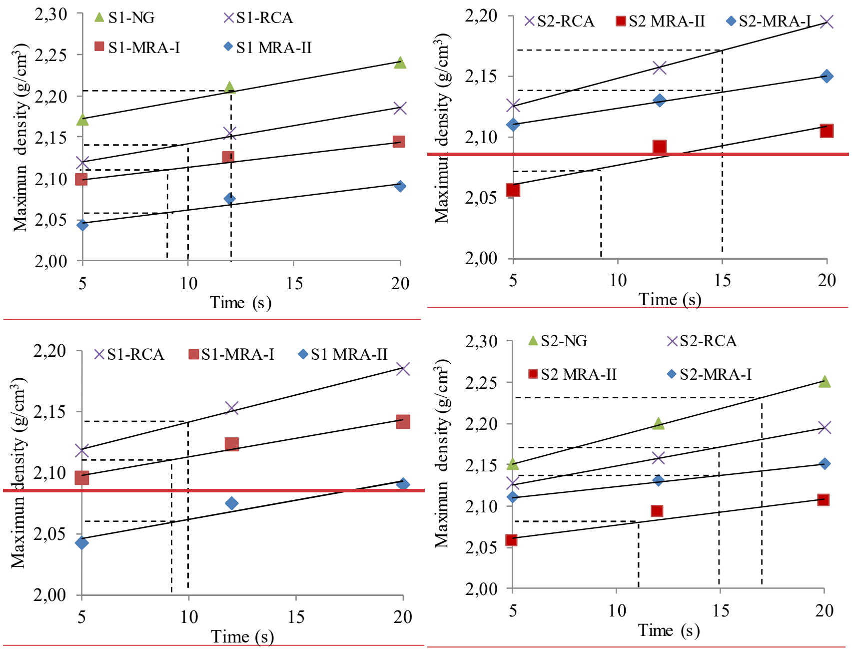
Table 3. Proctor Modified test values

Samples	Max. dry density (g/cm^3)	Optimum moisture (%)
S1-NG	2.25	6.0
S1-RCA	2.18	7.0
S1-MRAI	2.15	8.2
S1-MRAII	2.10	8.6
S2-NG	2.28	5.5
S2-RCA	2.21	7.4
S2-MRAI	2.18	7.4

S2-MRAII	2.12	8.4

[t]Table 3 near here[t]

Figure 4 shows the density results for each vibrating hammer time. The S1-RCA and S2-RCA mixtures had a slope similar to that reported by Agrela et al. (2014), who used CTGM produced with RCA and a low cement content.



a) b)

Figure 4 - Vibrating hammer time of the series; a) S1; b) S2

[t]Figure 4 near here[t]

4.2. Mechanical properties in hardened RCC

Table 4 shows the mean values of the compressive strength, splitting tensile strength and modulus of elasticity and their standard deviation at different curing ages. The Belgian Guideline RW99 establishes the minimum standards for RCC that can be used in road foundations. A compressive strength of 20 MPa and 30 MPa after 90 days must be reached for a minimum cement content of 200 kg/m^3 and 250 kg/m^3, respectively. The four~~three~~ mixtures of the series S2 complied with the requirement of 20 MPa at 90 days for a cement content of 250 kg/m^3, which is higher than the indicated 200 kg/m^3. Expect to S2-MRAII mixture, whose mean value is 19.5 MP, but its standard deviation is 0.82, so it could de said that could meet the requirement. ~~.~~The Spanish Guide of Recycled Aggregates from CDW (GERD, 2012) defines the standards for the use of RCC made with RA in base pavements. In areas with a high density of heavy vehicles, a minimum compressive 28-day strength of 20 MPa and a minimum splitting tensile strength of 3.3 MPa must be met. The S2-NG mixture complied with these requirements after 90 days. The S2-RCA and S2-MRA-I mixtures complied with the compressive strength requirement at 90 days but did not comply with the splitting tensile strength required. The compressive strength results for all mixtures were over 10 MPa at 28 days, complying with the requirement for RCC with RA composition established in the Catalogue of Pavements and Work Units with RA from CDW (Public Works Agency of the Regional Government of Andalusia, 2017) for the use of this material in residential streets and similar civil works (fewer than 50 heavy vehicles per day).

Commented [ALU9]: No sé si es necesario incluirlo, n ha comentado nada ningún revisor.

Table 4 - Mean values of the mechanical properties

	Compressive strength (MPa)						Splitting tensile strength (MPa)						M.E. (GPa)	
	7		28		90		7		28		90		28	
Mixtures	days	s.d.	days	s.d.	days	s.d.	days	s.d.	days	s.d.	days	s.d.	days	s.d.
S1-NG	13.1	*0.97*	15.8	*0.99*	18.3	*1.27*	1.49	*0.17*	2.02	*0.19*	2.12	*0.19*	17.6	*1.16*
S1-RCA	10.1	*0.75*	12.9	*0.62*	14.9	*0.99*	1.21	*0.10*	1.66	*0.14*	1.77	*0.17*	14.2	*1.55*
S1-MRAI	9.6	*0.71*	12.0	*1.00*	13.9	*1.24*	1.08	*0.12*	1.51	*0.08*	1.58	*0.11*	13.1	*1.31*
S1-MRAII	6.6	*0.54*	11.3	*0.90*	13.3	*0.58*	1.05	*0.11*	1.43	*0.15*	1.48	*0.15*	11.9	*1.10*
S2-NG	19.8	*1.72*	26.8	*2.14*	29.8	*1.86*	2.45	*0.23*	3.21	*0.21*	3.36	*0.25*	19.5	*1.10*
S2-RCA	16.2	*0.88*	23.4	*1.19*	26.2	*1.25*	2.01	*0.08*	2.67	*0.09*	2.75	*0.11*	16.0	*1.09*
S2-MRAI	14.7	*0.83*	21.4	*0.46*	24.0	*0.82*	1.91	*0.06*	2.58	*0.13*	2.61	*0.16*	15.6	*0.73*
S2-MRAII	11.0	*0.83*	18.4	*0.46*	19.5	*0.82*	1.84	*0.06*	2.48	*0.13*	2.50	*0.16*	14.2	*0.73*

[a]Note: Standard deviations (s.d.) given in italics.

[t]Table 4 near here[t]

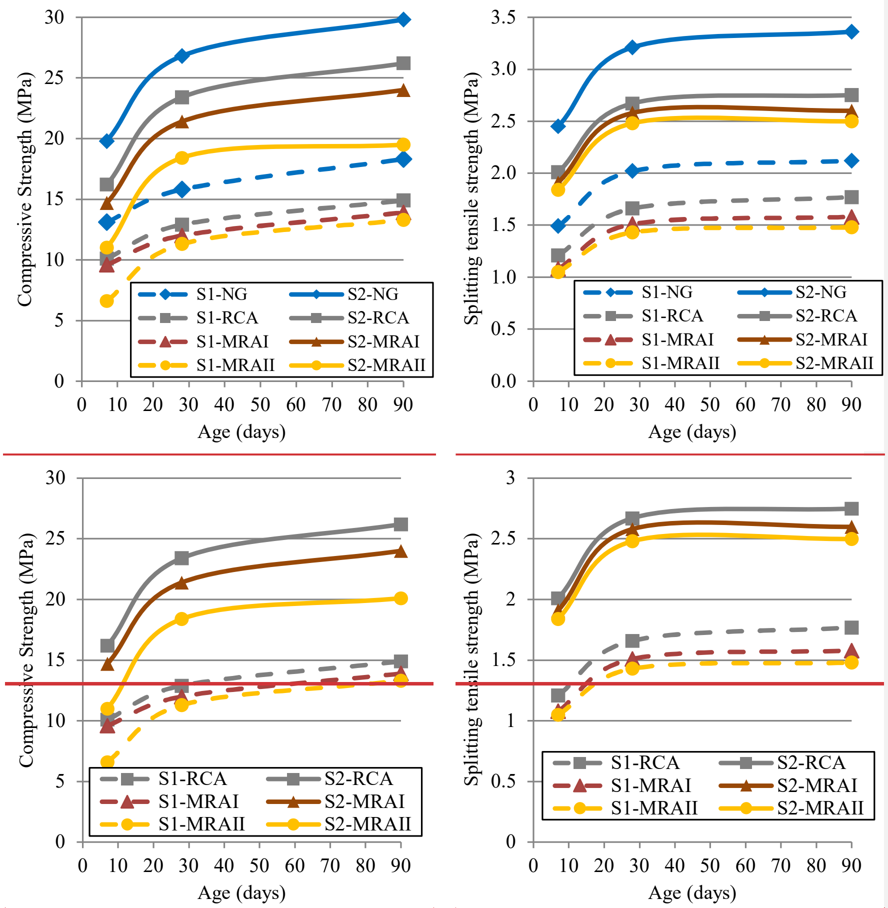
An increase in the mechanical properties studied showed that as the cement content rose, the mean compressive strength test results at 28 days for series S1 was 13~~12.1~~ MPa, whereas for series S2 it was 2~~1~~2.5~~.1~~ MPa. This result is 29.7~~34~~% lower than that obtained by Lee et al. (2013), who found a compressive strength of 32 MPa for RCC with natural aggregates and 250 kg of cement per m^3 after 28 days. The mean compressive strength, at different ages, of RCA, MRA-I and MRA-II mixes were 16.1~~7.8~~%, ~~and~~ 22.6~~2~~% and 35.2% less than those of the NG~~RCA~~, respectively. These values are consistent with those of Xuan et al. (2012), who concluded that the masonry content diminished compressive strength in CTGM, and contrasts with the results of Agrela et al. (2012), whose investigation into an actual use of RA in CTGM as sub-base layer indicated that CTGM containing RA with higher ceramic content reached a greater compressive strength after 7 days.

In the case of the splitting tensile strength, less reduction was found than in the compressive strength according to the type of RA. The mean values for RCA, MRA-I and MRA-II mixes were 17.6~~6.7~~%, 23.1% and 26.4~~10.7~~% less than those of the NG~~RCA~~, respectively. These reduction are lower and less scatter than those of compressive strength. This finding can be explained by despite of the fact that RA incorporation caused weakening of CTMs in terms of resistance, ~~-~~after reaching the splitting tensile strength, the cement paste dominates over the coarse aggregate in supporting the concrete strength. Debied et al. (2009) obtained a 2.6 MPa splitting tensile strength for RCC with RCA as its coarse fraction and a 250 kg/m^3 cement content, similar to the results obtained in this study.

Regarding the modulus of elasticity, a lower reduction than in the compressive case was found with respect to RCA of the MRA-I and MRA-II mixes. For modulus elasticity~~the splitting tensile strength~~, the mean values for the MRA-I and MRA-II mixes were 18~~5~~.6~~0~~%,~~ and~~ 22~~14~~.6% and 29.6% lower than those of the NG, respectively~~, which is less than that found for the RCA~~. Lim and Zollinger (2003) studied the modulus of elasticity of CTGM with RCA and a cement content of 8% of dry matter. In the Lim-Zollinger research, the mean value of modulus of elasticity was 9.1 GPa, which is lower than that obtained in this research (14.2 GPa) and may be because that group replaced 100% of the fine and coarse aggregate fraction by RCA. However, Debied et al. (2009) obtained a modulus of elasticity of 22.6 GPa in RCC mixtures with RCA as the coarse fraction and with a cement content of 250 kg/m^3 (59% higher), which can be attributed to the high quality of their cement (CEM I 52.5N).

As for the evolution of compressive strength over time (Figure 5.a), the mean of the RCA and MRA-I mixtures after 7 days were 72.5% and 72.8% of the 28-day strength, respectively, whereas the MRA-II mixture reached 59.3% of that strength, and~~.~~ for the NG mixtures 77.2%. ~~-~~The relative compressive strength gain between 28 and 90 days was minor; all increases ranged between 9.2% for the S2-MRA-II mixture and 17.7% for the S1-MRA-II mixture. In the study of splitting tensile strength over time (Figure 5.b), the observations suggest that the mean value of all the mixtures of the 7-day strength was

743.26% ± 1.13% of the 28-day strength, whereas the gain between 28 days and 90 days was 3.3% ± 1.52.3%.



a) b)

Figure 5 - Strength evolution over time; a) compressive strength; b) and splitting tensile strength.

[t]Figure 5 near here[t]

Figure 6 indicates a correlation (R^2=0.863) between the compressive strength and splitting tensile strength, which was 10.32% of the compressive strength. This relationship is consistent with the results obtained by Lopez-Uceda et al. (2016), who studied RCC with different cement quantities and different RCA coarse incorporation ratios. Mardani-Aghabaglou and Ramyar. (2013) obtained 9% for the same relationship, studying RCC with different replacement levels of cement by fly ash (binder content of 250 kg per m^3) for the same ageing periods.

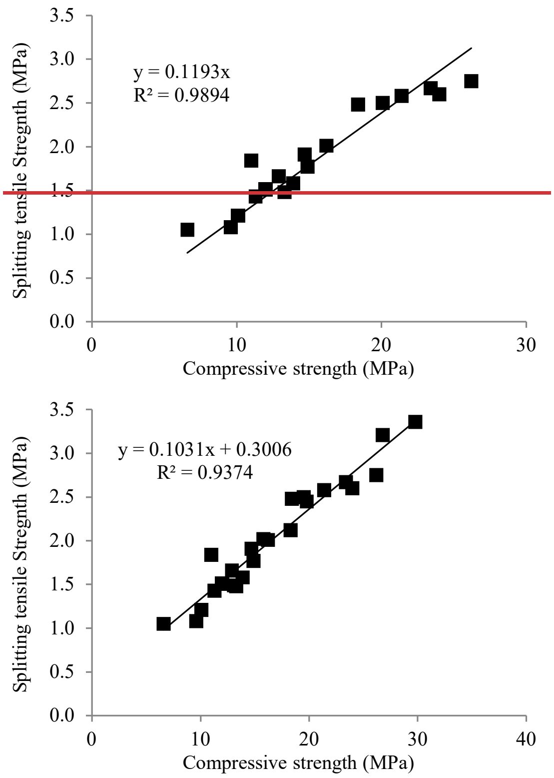


Figure 6 - Relation between compressive strength and splitting tensile strength.

[t]Figure 6 near here[t]

4.3. Drying shrinkage

The influence on the shrinkage was examined in a dry chamber of the type of RA used in RCC (Figure 3) over a period of up to 90 days for the RCC mixes. As expected, mixtures with NG showed less retraction than those with RA incorporation. The results were in accordance with those of Del Rey et al. (2015), who found no significant difference between retraction values at 90 days of CTGM with MRA and RCA; nevertheless, higher values were obtained (1000-1600 µm/m) by Del Rey et al. than in the present work. After curing in the dry chamber, the retraction was slightly higher in the MRA mixtures than in the RCA mixtures.

Pitman and Ragan (1998) recommended that the drying shrinkage values at 28 days range between 80 and 330 µm/m in RCC for pavement applications. This recommendation is consistent with the results obtained in the present research, which varied between 149~~60~~ and 309 µm/m for all mixtures. The results of shrinkage in the six mixtures with RA incorporation at 90 days varied between 420 and 541 µm/m, indicating relatively low scatter. Thus, the prediction shrinkage behaviour of RA in RCC with low cement content is not expected to be challenging to accommodate regardless of the RA type.

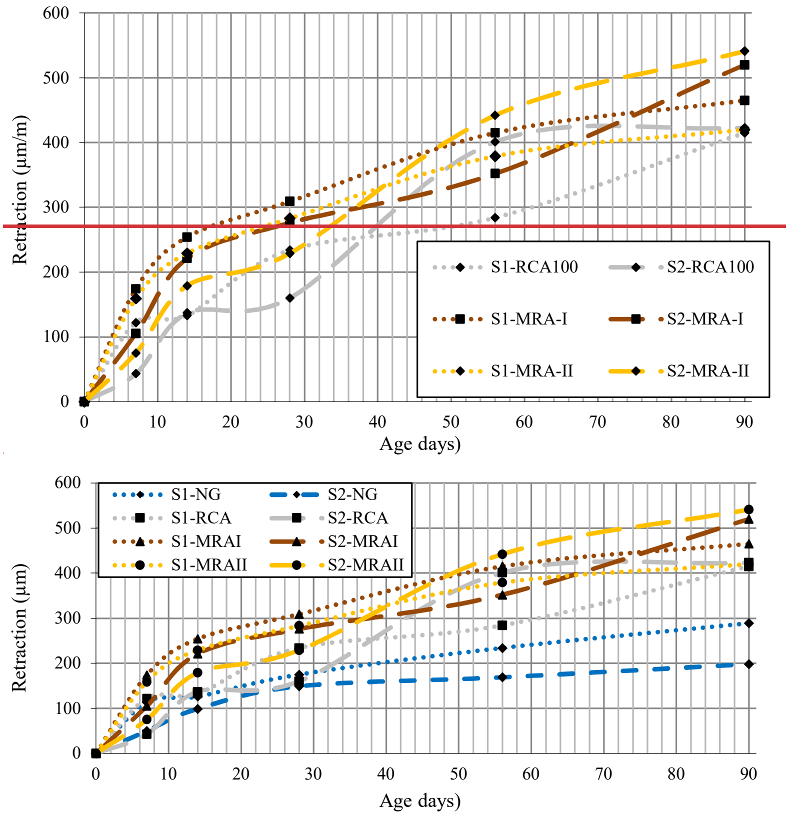


Figure 7 - Retraction evolution with age.

[t]Figure 7 near here[t]

5. Conclusions

In the present study, the mechanical properties and dimensional changes of RCC manufactured with different RA types and low cement content were analysed. Based on the experimental results obtained and the corresponding discussion, the following conclusions are drawn:

- The Proctor Modified test results indicate that a higher ceramic particle content in RA used as coarse fraction in RCC corresponds to greater ~~less~~ required water and a lower maximum dry density.
- The use of RA as the coarse fraction in RCC influences the mechanical properties; a greater percentage of ceramic particles of the RA corresponds to degraded mechanical properties as determined by the test results.
- A strong correlation exists between the compressive strength and splitting tensile strength in RCC mixtures. The splitting tensile strength was determined to be approximately 10.3~~2~~% of the compressive strength.
- The shrinkage behaviour of this RCC formulated with RA presented relatively little scatter, specifically in splitting tensile strength and drying shrinkage. This indicates~~ing~~ that its on-site use would not involve special requirements according to the type of RA used.

In conclusion, the feasibility of the RCC containing RA as its coarse fraction with a cement content of 150 kg/m^3 was confirmed. According to the acquired data, the compressive and splitting tensile strength after 28 days reached 10 MPa and 1.5 MPa, respectively. The MRA-II mixture failed to meet the splitting tensile strength requirement by only 2%. Thus, based on these values, this technical option could be a satisfactory solution for bike lanes and sidewalks with low strength requirements. RCC containing RA as a coarse fraction with a cement content of 250 kg/m^3 showed compressive and splitting tensile strength values higher than 20 and 2.5 MPa, respectively, at 28 days. The MRA-II mixture failed to comply with the splitting tensile strength requirement by only 0.8%. It would be convenient to limit the percentage of RA ceramic particles to 20%, given the influence of this percentage on the mechanical properties. This material could be used to construct the base layer of civil applications with relatively high strength requirements, such as residential streets or light-traffic roads (less than 50 heavy vehicles per day).

Therefore, the present study confirms that the use of RA from CDW can be diversified, provided that the physical and mechanical properties of the aggregate are meticulously controlled and characterised. Thus, the evidence suggests that apart from RPA, other types of RA used as MRA and RCA can be used in RCC manufacturing, which is expected to help avoid depletion of natural resources and expand the technical possibilities of using recycled materials in civil infrastructure projects such as light-traffic roads, residential streets, sidewalks and bike lanes.

Acknowledgements

The authors would like to thank the European Regional Development's Fund (ERDF) of the European Union for financial support via the project “Applications of recycled aggregates from construction and demolition waste (CDW) for the sustainable development of road infrastructure in central areas of Andalusia” from the “2007-2013 ERDF Operational Programme for Andalusia”. We also thank the Public Works Agency and Regional Ministry of Public Works and Housing of the Regional Government of Andalusia staff and researchers for their dedication and professionalism. The cement used in this research was freely provided by Votorantim Group.

References

Abut, Y., Yildirim, S. T. (2017). Structural Design and Economic Evaluation of Roller Compacted Concrete Pavement with Recycled Aggregates. In IOP Conference Series: Materials Science and Engineering (Vol. 245, No. 2, p. 022064). IOP Publishing.

ACI Committee 325 (2001). Report on roller compacted concrete pavements. American Concrete Institute: Farmington Hills, MI, USA.

Agrela F., Cabrera M. Galvín A.P., Barbudo A., Ramirez A. (2014). Influence of the sulphate content of recycled aggregates on the properties of cement-treated granular materials using Sulphate-Resistant Portland Cement. Construction and Building Materials, 68: 127-134.

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

Agrela, F., De Juan, M. S., Ayuso, J., Geraldes, V. L., Jiménez, J. R. (2011). Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete. Construction and Building Materials, 25: 3950-3955.

Cahier des charges-type RW 99 (Belgium Guidelines). Technical and administrative regulations for roads and highways, Wallonia Public Administration [in French]. www.qc.met.wallonie.be>.

Cardoso, R., et al. (2015) Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review. Waste Management, http://dx.doi.org/10.1016/j.wasman.2015.12.021.

Courard, L., Michel, F. Delhez, P. (2010). Use of concrete road recycled aggregates for Roller Compacted Concrete. Construction and building Materials, 24: 390-395.

Debieb F., Courard L., Kenai S., Degeimbre R. (2009). Roller compacted concrete with contaminated recycled aggregates. Construction and Building Materials, 23: 3382-3387.

Del Rey, I., Ayuso, J., Barbudo, A., Galvín, A. P., Agrela, F., de Brito, J. (2016). Feasibility study of cement-treated 0–8 mm recycled aggregates from construction and demolition waste as road base layer. Road Materials and Pavement Design, 17, 678-692.

European Commision (DG ENV). Final Report Task 2: Service Contract on Management of Construction and Demolition Waste Prepared by Bio Intelligent Service. 2011. Available online: http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf (accessed on 7 July 2017)

Fakhri, M., Amoosoltani, E. (2017). The effect of Reclaimed Asphalt Pavement and crumb rubber on mechanical properties of Roller Compacted Concrete Pavement. Construction and Building Materials, 137, 470-484.

Freedonia Group , 2016. Available on: http://www.freedoniagroup.com/World-Construction-Aggregates.html (accessed on 26 June 2017)

Gao, P.W., Wu, S.X., Lin, P.H., Wu, Z.R., Tang, M.S. (2006). The characteristics of air void and frost resistance of RCC with fly ash and expansive agent. Construction and

Building Materials. 20: 586-590.
Grilli, A., Bocci, E., Graziani, A. (2013). Influence of reclaimed asphalt content on the mechanical behaviour of cement-treated mixtures. Road Materials and Pavement Design, 14(3), 666-678.
Hazaree, C., Ceylan, H., Wang, K. (2011). Influences of mixture composition on properties and freeze–thaw resistance of RCC. Construction and Building Materials, 25: 313-319.
Jiménez, J. R. (2013). Recycled aggregates (RAs) for roads. Pacheco-Torgal, F., Tam, VWY, Labrincha, JA, Ding, Y. de Brito, J. (Eds.), Handbook of recycled concrete and demolition waste. Woodhead Publishing Limited, Cambridge, UK, 351-376.
Lee, S.W., Cho, Y.H., Park, C. (2014). Mechanical performance and field application of low cement based concrete under compaction energy. KSCE Journal of Civil Engineering, 18: 1053-1062.
Lim S., Zollinger D.G. (2003). Estimation of the compressive strength and modulus of elasticity of cement-treated aggregate base materials. Transportation Research Record, 1837: 30-8.
Lopez-Uceda, A., Agrela, F., Cabrera, M., Ayuso, J., López, M. (2016). Mechanical performance of roller compacted concrete with recycled concrete aggregates. Road Materials and Pavement Design, 1-20.
Mardani-Aghabaglou. A. Ramyar. K. (2013). Mechanical properties of high-volume fly ash roller compacted concrete designed by maximum density method. Construction and Building Materials, 38: 356-364.
Ministry of Development. (2015). Order / FOM / 2523/2014 amending certain articles of the General Technical Specifications for Road and Bridge Works, relating to basic materials, firms and pavements, and signs, markings and vehicle restraint systems (in Spanish). BOE No. 3:2015, 584–1096.
Modarres A., Hosseini Z. (2014) Mechanical properties of roller compacted concrete containing rice husk ash with original and recycled asphalt pavement material. Materials and Design, 64: 227–236.
NLT-310/90. Fabricación y curado de probetas cilíndricas de materiales granulares con productos de adición compactadas con martillo vibrante.
Pittman, D. W., Ragan, S. A. (1998). Drying shrinkage of roller-compacted concrete for pavement applications. Materials Journal, 95: 19-26.
Public Works Agency of the Regional Government of Andalusia (2017). Catalogue of

pavements and work units with RA from CDW. Spain [in Spanish]. (Available online: http://www.aridosrcdandalucia.es/rcd/wp-content/uploads/2017/03/Libro-catalogo-de-firmes-vers-impresa-en-pdf.pdf (accessed on 13 June 2017)

Settari, C., Debieb, F., Kadri, E.H., Boukendakdji, O. (2015). Assessing the effects of recycled asphalt pavement materials on the performance of roller compacted concrete. Construction and Building Materials, 101: 617-621.

Silva. R.V.; de Brito. J.; Dhir. R.K. (2015a). Tensile strength behaviour of recycled aggregate concrete. Construction and Building Materials. 83. 108–118.

Silva. R.V.; de Brito. J.; Dhir. R.K. (2015b). The influence of the use of recycled aggregates on the compressive strength of concrete: A review. European Journal Environmental Civil Engineering, 19: 825–849.

Spanish Waste Management Association (GERD). Spanish Guide of Recycled aggregates from CDW; Madrid, Spain, 2012

UNE 1097-6:2014 Test for mechanical and physical properties of aggregates - Part 6. Determination of particle density and water absorption.

UNE 83316:1996. Concrete tests. Determination of the modulus of elasticity in compression.

UNE EN 12390-6:2010. Testing hardened concrete - Part 6: Tensile splitting strength of test specimens

UNE-EN 1097-2:2010. Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation.

UNE-EN 1744-1:2013 Tests for chemical properties of aggregates - Part 1: Chemical analysis.

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

UNE-EN: 13286-2:2011 Unbound and hydraulically bound mixtures - Part 2: Test methods for laboratory reference density and water content. Proctor compaction.

UNE-EN:13286-41:2003 Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures.

Vahedifard, F., Nili, M., Meehan, C.L. (2010). Assessing the effects of supplementary cementitious materials on the performance of low-cement roller compacted concrete pavement. Construction and Building Materials, 24: 2528-2535.

Vieira, C. S., Pereira, P. M., de Lurdes Lopes, M. (2016). Recycled Construction and

Demolition Wastes as filling material for geosynthetic reinforced structures. Interface properties. Journal of Cleaner Production, 124: 299-311.

Xuan D. Houben L.. Molenaar A.. Shui Z. (2012). Mixture optimization of cement treated demolition waste with recycled masonry and concrete. Materials and Structures. 45: 143-151.

Xuan. D. X.. Schlangen. E.. Molenaar. A. A. A.. Houben. L. J. M. (2014). Influence of quality and variation of recycled masonry aggregates on failure behavior of cement treated demolition waste. Construction and Building Materials, 71: 521-527.

Yerramala, A., Babu, K.G. (2011). Transport properties of high volume fly ash roller compacted concrete. Cement and Concrete Composites, 33: 1057-1062.